# Muscular Fatigue and Recovery Following Alternating Isometric Contractions at Different Levels of Force

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**The purpose of this study was to document the amount and rate of muscular fatigue during alternating levels of isometric contraction similar to that found during the Simulated Aerial Combat Maneuver (SACM). In addition, the time needed to recover from such an exercise was examined. Twenty males between the ages of 22 and 35 years performed an isometric contraction of their right quadriceps muscle at alternating levels of tension (20 and 50% maximum voluntary contraction) until exhaustion. The time at each contraction level was 10 s. After each exhaustive exercise bout, subjects were assigned to one of six recovery intervals (10, 20, 40, 60, 120, and 240 min) followed by a repeat of the exhaustive exercise. All subjects were tested under each of the six recovery intervals. Results showed that the amplitude (RMS) of the myoelectric signal increased while the frequency content of the signal (MPF) decreased over the course of the fatiguing activity. Endurance time (ET) was found to be significantly ($p < 0.05$) recovered (90.96%) within 60 min after stopping the exercise. Although MPF returned to its prefatigue value within 10 min of rest, the RMS value had still not recovered after 4 h.**

PILOTS OF HIGH performance aircraft are frequently required to perform in a high-gravitational stress ($+G_z$) environment. It is imperative in these situations that the pilot maintain complete mental and physical control of the aircraft. Among the current methods employed to assist pilots to withstand the high $+G_z$ forces is the Anti-G Straining Maneuver (AGSM). The AGSM requires the pilot to perform near-maximal activation of numerous muscle groups in response to the acceleration stress (4). Although the AGSM has been found to significantly contribute to the tolerance of sustained $+G_z$ stress, it is considered to be extremely fatiguing (2,4). It is obvious that as the muscles involved in the AGSM become fatigued, their effectiveness is diminished. Failure to accomplish an effective AGSM, therefore, could lead to impaired performance and even loss of consciousness (LOC).

Research in the area of $+G_z$ tolerance has typically employed what is called the Simulated Aerial Combat Maneuver (SACM). This is a protocol conducted on a human centrifuge which attempts to simulate the levels and durations of $+G_z$ exposure that would be encountered during aerial combat. It typically consists of alternating levels of accelerative stress of 10-s durations at either 4.5 and 7 or 5 and 9 $+G_z$, depending upon the cockpit configuration and/or the support devices used. The nature of the SACM requires the subjects to alternate the level of their AGSM in response to the changing $+G_z$ stress. Although a number of investigations have been conducted in the area of muscle fatigue and recovery, they have all dealt with either an isotonic exercise at a constant workload or an isometric contraction at a constant level of tension (5,11,17,19). No published articles could be found dealing with alternating levels of tension in the same exercise. Such alternating tension levels would be similar to those found during an SACM.

The purpose of this study was to document the amount and rate of muscle fatigue during alternating levels of isometric contraction similar to that found during an SACM. In addition, the time needed to recover from such an exercise was investigated. This information will allow researchers to better understand the musculoskeletal demands required of high $+G_z$ acceleration stress and will assist in the development of exercise programs to further improve a pilot's G-tolerance.

## MATERIALS AND METHODS

### *Subjects*

Twenty male volunteers between the ages of 22 and 35 years (mean = 26.7) participated in this study. The

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majority of data available on muscle performance during the SACM is reported on males. Since the purpose of this study was to compare our results to those during the SACM, only males were chosen for this study. Subjects with a history of a musculoskeletal or neuromuscular condition that would prevent them from performing sustained isometric contractions of their quadriceps femoris muscle were excluded from the study. Demographic information on the subjects used in this study given as mean (±SD) is as follows: age, 26.70 year (3.54); height, 176.91 cm (6.17); weight, 79.25 kg (8.39); and mean MVC, 122.66 kg (19.82). This study was approved by the Committee for the Protection of Human Subjects at Northern Arizona University and all subjects signed an informed consent form prior to participation.

### *Instrumentation*

The isometric force exerted by the right quadriceps femoris muscle group was recorded using a Cybex II isokinetic dynamometer (Cybex Inc., Ronkonkonma, NY). The subjects were positioned in a chair with their hips in 80° of flexion and their right knee in 60° of flexion (Fig. 1). Stabilizing straps were used to maintain this position during all experimental testing. EMG activity from the vastus lateralis muscle was recorded using bipolar Ag-AgCl surface electrodes (IN-VIVO Metric, Healdsburg, CA) having a recording diameter of 4 mm and an inter-electrode distance of 25 mm. The electrodes were arranged parallel to the muscle fibers and positioned so that the recording electrodes were proximal and distal to the muscle's motor point. Day-to-day consistency in the placement of the electrodes was assured by first electrically determining the motor point on the first day of the experiment and then marking that point with a permanent marker for use on subsequent days. The myoelectric signal was band-pass filtered to 5 and 500 Hz and digitized at 1000 samples per second using an analog-to-digital converter (Scientific Solutions, Inc., Solon, OH) and a microcomputer.

### *Experimental protocol*

All subjects were tested on six separate occasions. Each test session consisted of: 1) assessment of the subject's maximal voluntary isometric strength (MVC); 2) continuous isometric contraction of the quadriceps femoris muscle until exhaustion; 3) a prescribed recovery period, and finally; 4) repetition of the exhaustive isometric exercise bout following the predetermined recovery period.

MVC was calculated as the mean force generated during three successive isometric contractions of the right quadriceps femoris muscle (9). Each contraction lasted approximately 3 s and a rest interval of at least 30 s was provided between contractions. At the conclusion of the final rest period, subjects performed the exhaustive exercise bout which consisted of contracting their right quadriceps femoris muscle continuously at alternating tension levels of 20 and 50% of their previously determined MVC. The amount of time at each tension level was 10 s (Fig. 1). These tension levels and durations were selected because they approximate those required by the SACM (1). Subjects continuously alternated between the two tension levels until exhaustion. For this study, exhaustion was defined as the point when the subject could not achieve and/or maintain the desired tension level. Both the target and subject-produced tension levels were displayed on an oscilloscope (Model TEK 2221, Tektronix, Inc., Beaverton, OR) to provide feedback to the subject and ensure that the desired muscle tension was produced and maintained (Fig. 1). The total time spent by each subject performing the alternating contraction was recorded as the subject's Endurance Time (ET).

Following the completion of the exhaustive exercise, subjects were assigned one of the following six recovery intervals: 10, 20, 40, 60, 120, or 240 min. The order in which recovery intervals were administered was counterbalanced. At the conclusion of the prescribed recovery interval, the subject again performed the exhaustive exercise. Each subject received all six recovery intervals with at least 24 h elapsing between successive tests.

### *Data Management*

From digitized samples of the EMG signal, root mean square (RMS) and median power frequency (MPF) of the power spectral density function were calculated at 1-s intervals for the entire exercise bout. The RMS values were normalized to the electrical activity recorded during the performance of the MVC. The RMS and MPF values were then averaged over each 10-s contraction period. To compensate for varying durations of muscle contraction between subjects, the data were normalized to each subject's ET. The above procedures resulted in a mean RMS and MPF value every 10% of the subject's total contraction time for both the 20% and 50% MVC contraction levels. These amplitude and frequency data were finally subjected to a repeated measures analysis of variance (ANOVA). The dependent variables tested in this study were RMS, MPF, and ET. An alpha level of 0.05 was used for all tests of statistical significance. Between-day reliability across all subjects for MVC, ET, RMS, and MPF was assessed using a type two interclass correlation coefficient (ICC) (12).

## RESULTS

### *Reliability*

The variables of MVC and ET were found to have between-day ICC values of 0.961 and 0.922, respectively. The variable RMS and MPF had between-day ICC values of 0.823 and 0.777. According to Landis, these values represent almost perfect between-day reliability (12).

### *Endurance Time*

The mean initial (prefatigue) ET for each of the six sessions are shown in Fig. 2. Although a progressive increase is evident over the six conditions, no statistically significant difference ($p > 0.05$) was found. Comparison of ET prior to, and immediately after the exhaustive exercise bout showed that there was a statistically significant difference ($F = 12.50$, $df = 1,19$; $p = 0.002$). The mean prefatigue ET was 174.02 s (SD

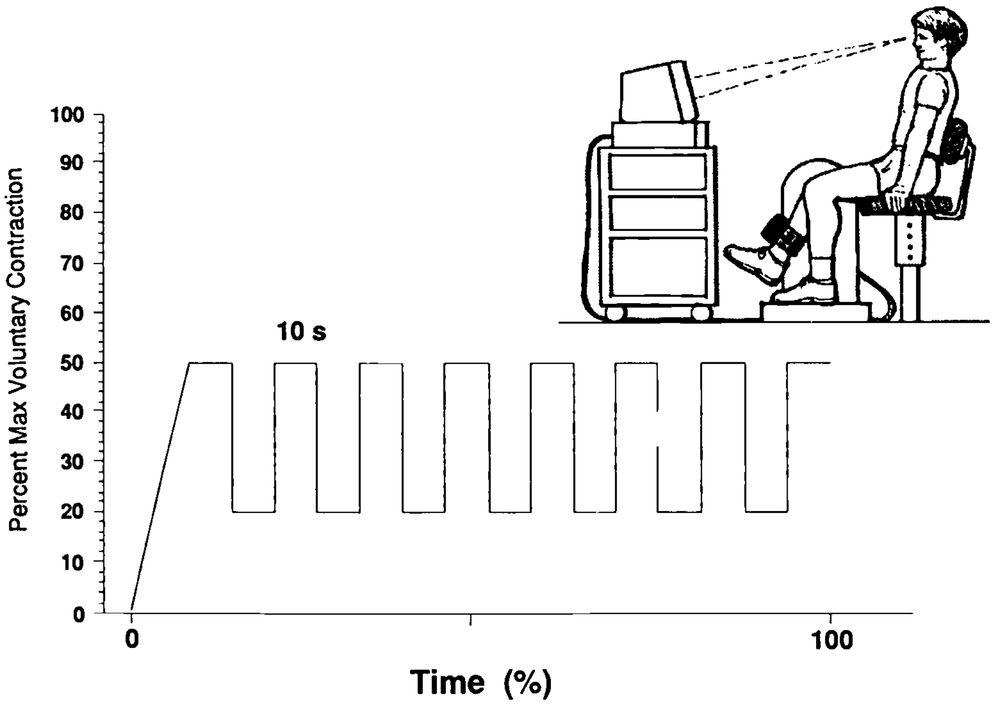


**Fig. 1. Schematic diagram of the experimental setup and testing protocol.**

= 48.57) while the mean postfatigue ET was 156.8 s (SD = 52.17). In addition, a statistically significant difference ($F = 5.20$, df = 5,95; $p < 0.001$) was found between the six recovery intervals. Finally, the ANOVA indicated a significant ($F = 3.49$, df = 5,95; $p = 0.006$) interaction existed between the six recovery intervals and the prefatigue and postfatigue values. A post hoc analysis using Tukey's HSD test showed mean postfatigue ET was significantly different ($p < 0.05$) from mean prefatigue ET only at the 10-, 20-, and 40-min recovery intervals. At the 60-min recovery interval, group mean ET for the postfatigue was 90.96% of the prefatigue value. Although not statistically significant, none of the postfatigue ET values fully recovered to their prefatigue level (Table I).

### *Electromyographic Changes*

*EMG amplitude:* Results of the ANOVA for changes in EMG amplitude showed that regardless of the contraction level, RMS values increased significantly ($F = 55.88$, df = 10,190; $p < 0.001$) from beginning to the end of the fatiguing activity. Also, the ANOVA demonstrated there was a significant difference ($F = 112.27$, df = 1,19; $p < 0.001$) between the RMS values at the two contraction intensities tested. Finally, there was a significant interaction ($F = 61.91$, df = 10,190; $p < 0.001$) between the contractile intensity and the time of contraction. The responses at each of the two contraction levels are seen to be quite different (Fig. 3). The slope of the regression line is steeper when the muscle is contracting at 50% of the subject's MVC (Fig. 3). The increase observed at 50% MVC, when averaged across all time periods, was 234.6%, while at 20% MVC it was only 124.8%. Finally, Tukey post-hoc analysis showed that postfatigue RMS values were significantly higher ($p < 0.05$) compared to their prefatigue values at each of the six recovery intervals.

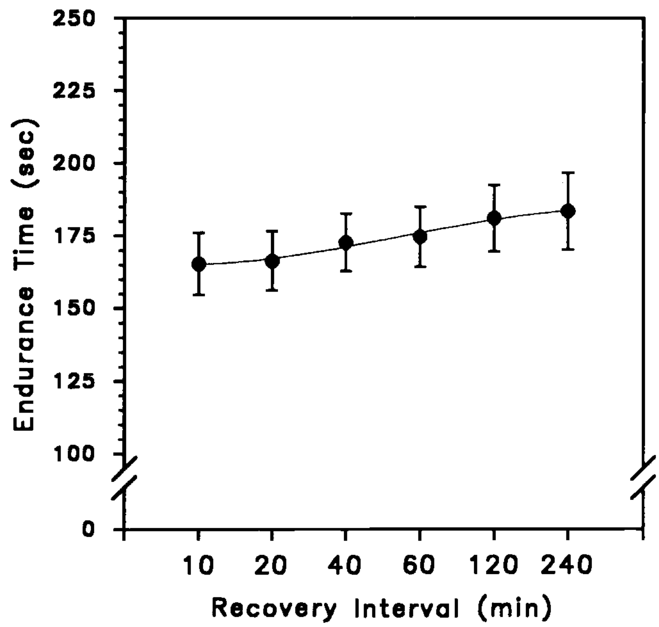


**Fig. 2. Mean (n = 20) Pre-fatigue endurance times for each of the six experimental recovery intervals. Error bars represent SE.**

*EMG frequency:* The results of the ANOVA for changes in EMG frequency showed that regardless of the contraction level, MPF values decreased significantly ($F = 98.86$, df = 10,190; $p < 0.001$) during the course of the fatiguing activity. As with EMG amplitude, there was a statistically significant difference ($F = 47.18$, df = 1,19; $p < 0.001$) between the muscle's response at the two contractile intensities (Fig. 4). Again, a significant interaction ($F = 3.27$, df = 10,190; $p = 0.001$) was found between contractile intensity and the time during the fatiguing exercise. Fig. 4 shows a

TABLE I. MEAN (±SE) PREFATIGUE AND POSTFATIGUE ENDURANCE TIMES AND PERCENTAGE OF ENDURANCE TIME RECOVERED DURING EACH OF THE SIX EXPERIMENTAL RECOVERY INTERVALS. (n = 20).

| Interval (min) | Pre-fatigue (s) | Post-fatigue (s) | Recovery (%) |
|---|---|---|---|
| 10 | 165.45 (10.68) | 132.48 (9.07) | 80.01* |
| 20 | 166.45 (10.19) | 143.55 (11.03) | 86.24* |
| 40 | 172.83 (9.86) | 151.13 (11.61) | 87.44* |
| 60 | 174.76 (10.34) | 158.97 (9.55) | 90.96 |
| 120 | 181.18 (11.39) | 177.93 (11.73) | 98.96 |
| 240 | 183.49 (13.15) | 176.74 (14.07) | 96.32 |

* $p < 0.05$.

slightly more rapid decline in the muscle's MPF at 50% compared to 20% MVC from 70–100% of the contraction time. At the 50% MVC contraction level, MPF decreased 13.0%, whereas the overall decrease during muscle tension at 20% MVC was 12.2%. Notably, at the end of the fatiguing activity, both values are nearly identical (Fig. 4). Tukey post hoc analysis showed that there was no significant difference ($p < 0.05$) between pre- and postfatigue MPF for any of the six recovery intervals.

## DISCUSSION

### *Endurance Time*

The mean prefatigue ET of 174.02 s (SD = 48.57) obtained in the present study is similar to G-tolerance times reported in the literature for SACM's of 4.5 and 7.0 $G_z$ (2,4,20). This finding of similarity of endurance time lends support, first, to the estimates by Burton and his colleagues regarding the level of isometric muscle contraction required during the execution of the SACM at 4.5 and 7.0 $G_z$ (2). This finding also indicates that, at least under some controlled conditions, research regarding muscular activity during acceleration stress can be performed at 1 $G_z$ with reasonably good success. Such research would be advantageous because it would be less expensive and would allow tighter research controls.

Although the physical activity performed in the present study has not been previously studied, comparison of ET recovery rates with past literature does show similarities. The majority of previous reports indicate that following an exhaustive isometric exercise, recovery of ET is exponential with an initially steep rate of recovery (5,16,19,24). The observed initial rapid recovery of ET has been theorized to be the result of the restoration of blood flow to the muscle (19), the rapid removal of hydrogen ions and lactic acid (6), or the resynthesis of phosphocreatine (14). Others indicate that rate of recovery is dependent upon the capillary density of the contracting muscle (22). In addition to

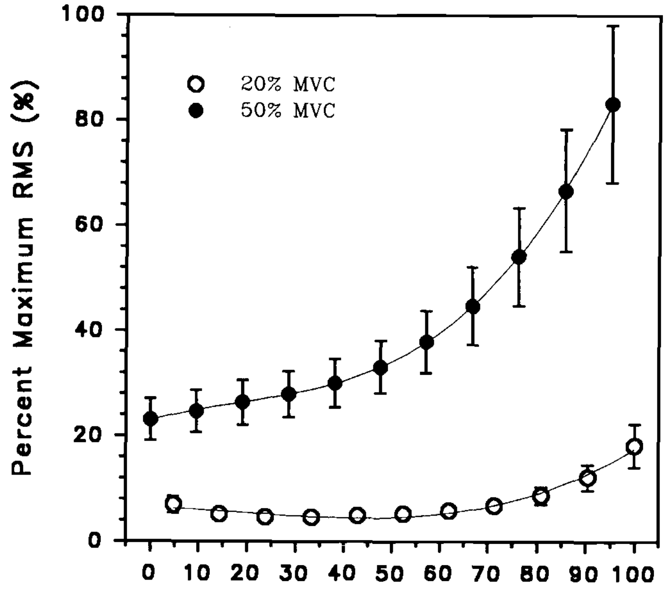


**Fig. 3. The effect of contraction intensity on mean (n = 20) percent of maximum RMS during the fatiguing isometric contraction. Error bars represent SE.**

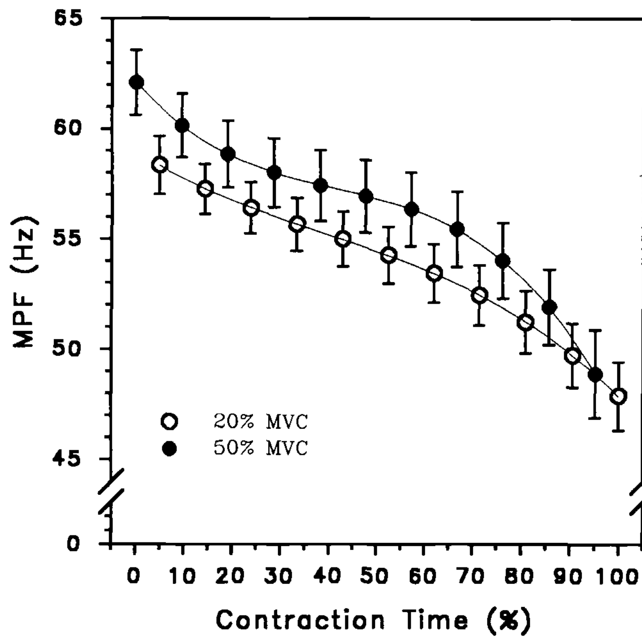


**Fig. 4. The effect of contraction intensity on mean ( n = 20) MPF during the fatiguing isometric contraction. Error bars represent SE.**

this initial rapid recovery, the literature indicates recovery of ET is approximately 80% complete after 10–12 min (16) and then plateaus to 85–90% after 40 min (5,24). Our results (Table I) are nearly identical to these previous studies. It is possible that a 10% decrement in endurance time while performing a critical flight maneuver could be catastrophic. Therefore, based upon these findings, pilots should not engage in repeated executions of the SACM. Certainly, additional research needs to be conducted in this area.

### *Electromyographic Changes*

*EMG amplitude:* The significant differences in normalized RMS values of the myoelectric signals at 20 and 50% MVC were not surprising. It has been known for some time that the amplitude of the EMG signal is related (linearly or non-linearly) to the amount of force produced by a muscle (23). Thus, as the level of contraction increases, so does the amplitude of the EMG signal. This is certainly the case in the present study.

Alterations of the RMS values throughout the fatiguing exercise (Fig. 3) have been reported in the literature by numerous other investigators (13,16,17). However, the exact pattern of the increase is dissimilar. Although the majority of researchers have shown the increase is exponential or logarithmic in shape (16), others have reported a linear relationship (13,17). The different response patterns for 20 and 50% MVC (Fig. 3) seen in this study have been observed by other researchers (3). As with endurance time, it is possible that the more dramatic changes in RMS at 50% MVC are related to the presence of muscle ischemia. Blood flow is occluded at contraction intensities greater than 40% MVC and contributes to the rapid build-up of lactic acid (21,25).

Recovery data for EMG amplitude indicates that even after 4 h, initial exercise values have not fully returned. Kroon and Naeije reported a similar result, finding EMG amplitude had not returned to pre-exercise levels after 25 h (10). Kramer and associates also reported amplitude was not recovered for several hours following a fatiguing activity (8). On the other hand, Inbar et al. and Stull et al. showed that EMG amplitude recovers within a matter of minutes (19). Several factors may account for the discrepancy between this study and that of Inbar et al. and Stull et al.—the uniqueness of the type of fatiguing contraction performed in the present study or possibly the increased measurement sensitivity of the present study resulting from the relatively large number of subjects tested.

*EMG frequency:* The MPF differences at two contraction intensity levels has been observed previously by Stulen in 1980 (18). Higher frequency signal composition, seen at 50% MVC, is most likely related to the recruitment and firing patterns of the muscle's motor units. It has been suggested in the literature that MPF of a muscle may be related to the muscle's motor unit firing rate (15), but not necessarily from motor unit synchronization (7). As was pointed out previously, fatiguing exercise results in motor unit recruitment and an increased firing rate to maintain the desired level of tension. This enhanced firing rate not only increases the observed amplitude of the EMG signal, but its frequency content as well.

The observed decrease in the frequency content of the EMG signal during the course of the fatiguing exercise has also been well documented in the literature (11,22,25). However, there is no agreement whether or not the decrease is linear or non-linear. The amount of decrease has been reported to be as much as 25 to 50%, which is much greater than the 12.6% reported in the present study. This discrepancy is most likely the result of the alternating contraction intensities used in this study. Alternating muscle contractions at 20% MVC possibly allowed blood flow to be restored to the muscle for short periods of time, thus partially dissipating lactic acid and dampening the overall effect observed in the rate of MPF decline. This argument is somewhat supported by an examination of Fig. 4. As can be seen, the rate of decline increased during the later portion of the exercise and suggests that lactic acid accumulates over the course of the exhaustive exercise. These changes in the myoelectric signal may be related to the altered pH of the tissue caused by increased production of lactic acid and its subsequent dissociation to lactate and hydrogen ions (21,25).

Unlike the previous discussion of EMG amplitude, the literature is in agreement with regard to the rate of recovery of MPF following a physically exhaustive activity. Previous investigations have shown that MPF recovers very quickly and is fully recovered in approximately 5 min or less (11,17). The results of the present investigation lends even further credence to these studies. The cause of the rapid return of MPF to their pre-exercise values has been shown to be closely associated with the return of localized blood flow and the removal of lactic acid (25).

## CONCLUSIONS

The results of this study employing exhaustive exercise, at alternating contraction levels of 20 and 50% MVC, are similar to previous research using single intensity isometric fatiguing exercises. The following conclusions can be drawn from our data: 1) The ET from the type of contraction performed in the present study closely resembles the G-tolerance times reported in the literature during an SACM at 4.5 and 7.0 $G_z$. As such, this protocol could be used to further study the muscular demands of performing the SACM. 2) Recovery of ET is 90.96% complete by 60 min and 98.96% complete by 120 min. The implication of this finding is that pilots will have diminished muscular capacity to perform successive SACM's if done within an hour's time. 3) EMG amplitude (RMS) increases exponentially while frequency (MPF) decreases slightly throughout the exhaustive exercise bout. 4) Recovery of a muscle's MPF is rapid, less than 10 min. Amplitude, on the other hand, is still elevated above its initial level 4 h after stopping the exhaustive exercise.

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REFERENCES

1. Balldin UI, Myhre K, Tesch PA, Wilhelmsen U, Anderson HT. Isometric abdominal muscle training and G tolerance. Aviat. Space Environ. Med. 1985; 56:120–4.
2. Burton RR, Whinnery JE, Forster EM. Anaerobic energetics of the simulated aerial combat maneuver (SACM). Aviat. Space Environ. Med. 1987; 58:761–7.
3. Clamann HP, Broecker MS. Relation between force and fatigability of red and pale skeletal muscles in man. Am. J. Phys. Med. 1979; 58:70–85.
4. Epperson WL, Burton RR, Bernauer EM. The influence of dif-

ferential physical conditioning regimens on simulated aerial combat maneuvering tolerance. Aviat. Space Environ. Med. 1982; 53:1091–7.
5. Funderburk CF, Hipskind SG, Welton RC, Lind AR. Development of and recovery from fatigue induced by static effort at various tensions. J. Appl. Physiol. 1974; 37:392–6.
6. Jones DA. Muscle fatigue due to changes beyond the neuromuscular junction. Ciba Found. Symp. 1981; 82:178–96.
7. Jones NB, Lago PJA. Spectral analysis and the interference EMG. IEEE Proc. 1982; 129:673.
8. Kramer H, Lun A, Mucke R, Kuchler G. Changes in mechanical and bioelectrical muscular activity and in heart rate due to sustained voluntary isometric contractions and time required for recovery. Part I: contractions at constant level of bioelectrical activity. Electromyogr. Clin. Neurophysiol. 1979; 19: 381–6.
9. Kroll W. Reliability theory and research decision in selection of a criterion score. Res. Q. 1967; 38:412–9.
10. Kroon GW, Naeije M. Recovery following exhaustive dynamic exercise in the human biceps muscle. Eur. J. Appl. Physiol. 1988; 58:228–32.
11. Kuorinka I. Restitution of EMG spectrum after muscle fatigue. Eur. J. Appl. Physiol. 1988; 57:311–5.
12. Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics 1977; 33:159–74.
13. Lind AR, Petrofsky JS. Amplitude of the surface electromyogram during fatiguing isometric contractions. Muscle Nerve 1979; 2:257–64.
14. Metzger JM, Moss RL. Shortening velocity in skinned single muscle fibers. Influence of filament lattice spacing. Biophys. J. 1987; 52:127–31.
15. Moritani T, Muro M, Nagata A. Intramuscular and surface electromyogram changes during muscle fatigue. J. Appl. Physiol. 1986; 60:1179–85.
16. Petrofsky JS. Quantification through the surface EMG of muscle fatigue and recovery during successive isometric contractions. Aviat. Space Environ. Med. 1981; 52:545–50.
17. Petrofsky JS, Glaser RM, Phillips CA, Lind AR, Williams C. Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. Ergonomics 1982; 25:213–23.
18. Stulen FB. A technique to monitor localized muscular fatigue using frequency domain analysis for the myoelectric signal. [PhD Thesis] Cambridge, MA: Massachusetts Institute of Technology, 1980.
19. Stull GA, Clarke DH. Patterns of recovery following isometric and isotonic strength decrement. Med. Sci. Sports Exer. 1971; 3:135–9.
20. Tesch PA, Balldin UI. Muscle fiber type composition and G-tolerance. Aviat. Space Environ. Med. 1984; 55:1000–3.
21. Tesch PA, Karlsson J. Lactate in fast and slow twitch skeletal muscle fibers of man during isometric contraction. Acta Physiol. Scand. 1978; 103:413.
22. Tesch PA, Wright JE. Recovery from short term intense exercise: its relation to capillary supply and blood lactate concentration. Eur. J. Appl. Physiol. 1983; 52:98–103.
23. Thorstensson A, Karlsson J. Fatigability and fibre composition of human skeletal muscle. Acta Physiol. Scand. 1976; 98:318–22.
24. Yates JW, Kearney JT, Noland MP, Felts WM. Recovery of dynamic muscular endurance. Eur. J. Appl. Physiol. 1987; 56: 662–7.
25. Zwarts MJ, Arendt-Nielsen L. The influence of force and circulation on average muscle fibre conduction velocity during local muscle fatigue. Eur. J. Appl. Physiol. 1988; 58:278–83.