Original Contribution

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Muscle Maintenance by Volitional Contraction against Applied Electrical Stimulation

TAKESHI NAGO, YUICHI UMEZU, NAOTO SHIBA, HIROO MATSUSE, TAKASHI MAEDA, YOSHIHIKO TAGAWA*, KENSEI NAGATA AND JEFFREY R BASFORD**

*Rehabilitation Center, Kurume University, Kurume 830-0011, *Department of Mechanical and Control Engineering, Kyushu Institute of Technology, Kitakyushu 804-8550, Japan and **Department of Physical Medicine and Rehabilitation, Mayo Clinic Rochester, Rochester MN 55905, USA*

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Summary: Muscle training exercises are needed for muscular endurance during spaceflight. This study was designed to investigate effects of volitional contraction against applied electrical stimulation on the muscular endurance of the proximal upper extremity. Thirteen healthy sedentary men were allocated into two groups. One group participated in a hybrid (HYB) exercise regimen in which the biceps brachii was stimulated as he volitionally extended his elbow, and the triceps brachii was stimulated as the volitionally flexed his elbow. The second group underwent a similar regimen in which the electrical stimulation (ELS) was alternatively delivered to the biceps brachii and then to the triceps brachii with the limb fixed. Forty-second surface electromyography (EMG) recordings at 50% maximum voluntary contraction (MVC) were made as baseline data at just before starting the training regimen, and again conclusion. The median frequency (MF) and mean power frequency (MPF) slopes with time were determined using power spectrum analysis. There were statistical significance only for the triceps in which the MF and MPF slopes in the HYB Group became less negative over the period of study (from −45.7±14.7 and −47.0±8.6%/min at baseline to −36.9±10.7 and −36.8±7.0%/min at the end of training, respectively). The corresponding values for these slopes in the ELS Group showed opposite tends with less marked changes of borderline significance for MF and of statistical significance for MPF. These results suggested that the HYB exercise regimen was capable of producing an improvement in triceps but not biceps brachii.

Key words electric stimulation, exercise, muscle endurance, upper extremity

INTRODUCTION

It is known that muscular strength and endurance decrease during spaceflight [1]. Some muscle training regimen is therefore necessary that is both effective and convenient during spaceflight [2].

Resistance exercises are an effective and economical approach to increasing muscle bulk and strength. Gains in strength of as much as 40-100% over 10-12 weeks of training are common even in people who are sedentary, deconditioned or elderly [3,4]. However, there are times when conditions such as immobilization and the low gravity environment of space flight limit the applicability of resistance training and other approaches become necessary. In space flight, especially, the number of slow twitch fibers considerably decrease [5]. As one countermeasure, neuromuscular electrical stimulation (NMES) could be explored for

Address for corresponding author: Takeshi Nago, M.D., Rehabilitation Center, Kurume University, 67 Asahi-machi, Kurume 830-0011, Japan. Tel: +81-(0)942-31-7568 Fax: +81-(0)942-46-6002 E-mail: nago_takeshi@kurume-u.ac.jp

Abbreviations: ELS, electrical stimulation; EMG, electromyography; FFT, fast fourier transform; HYB, hybrid; MF, median frequency; MPF, mean power frequency; MVC, maximum voluntary contraction; NMES, neuromuscular electrical stimulation; ROM, range of motion; SD, standard deviation.

utilization.

NMES, unfortunately, suffers from a number of limitations among which are recruitment patterns that preferentially favor fast twitch fibers [6] and those muscles located near the stimulating electrodes. Another issue that may be particularly important for training to higher levels of function is that NMES strengthening typically does not utilize the reciprocal limb movements that are involved in the activities of everyday life.

An exercise program that involves volitional muscle contraction by applied electrical stimulation may provide an optional regimen. Such regimen would involve electrically stimulated muscles to provide resistance against volitional contraction of the muscle antagonists [7]. This "hybrid" technique would, thus, incorporate the advantages of reciprocal limb movements and muscle contractions without the need for external stabilization or resistance.

Research has found hybrid exercise as capable as or more effective than conventional weight training alone or NMES alone in increasing muscle bulk and strength [8,9]. No study has yet been performed, however, to evaluate the relative impact of these approaches on the fatigue resistance of the strengthened muscles.

The present study was therefore designed to address this lack, by assessing the effects of a hybrid electrical stimulation-volitional muscle contraction exercise regimen versus conventional NMES, on the endurance in the muscles of the proximal upper extremity.

MATERIALS AND METHODS

The IRBs of Kurume University and the Japanese National Space Development Agency approved the clinical design of this study protocol. Following approval, informed consent was obtained from a convenience sample of 13 healthy self-identified right hand dominant sedentary men (age, 22.3±2.3 standard deviation (SD) yr; height, 168.9±5.3 cm; and weight, 64.9±8.8 kg) who had reviewed the goals of the study and agreed to participate. Subjects were required to have normal musculoskeletal examinations and histories; right hand dominance in accordance with the Edinburgh Inventory [10]. Subjects meeting the above criteria were then randomized into two groups matched in age, in weight, and in height. One group, the Hybrid (HYB) exercise Group (HYB, n=7) participated in a combined electrical stimulation-volitional contraction exercise program and the other, the electrical stimulation (ELS) Group (n=6), took part in a conventional (isometric) NMES program.

Exercise

Subjects trained 3 times a week for 8 weeks. Each exercise session consisted of the participant lying supine and voluntary or electrically performing 10 sets of 10 reciprocal elbow flexion and extension contractions with their non-dominant left upper extremity. Contractions were 2 sec in duration and sets were separated by 1-min rest intervals. An exercise session required 15 min and 40 sec to complete.

HYB Group: Exercises were performed in the supine position with the subject's biceps brachii stimulated as the volitionally extended the elbow; the reverse occurred (i.e., the triceps brachii was stimulated) as the volitionally flexed their elbow [9]. The range of motion (ROM) of the joint was measured using a goniometer, and was restricted to an arc that extended from 15 to 105° elbow flexion. The subject changed the direction of his muscle contractions, in accordance with a tone emitted by the stimulator.

ELS Group: Subjects in this group also lay supine in the manner described above. The procedures and the number of session were identical as in the HYB Group with the exception that the subjects were each instructed to avoid volitional contraction of the muscle and the left elbow was immobilized in a brace at 60° flexion.

Equipment: The HYB training apparatus consisted of an electrical stimulator, surface electrodes, and a joint motion sensor that triggered stimulation of the antagonist once it sensed the initiation of a volitional contraction [9]. Low impedance gel-coated electrodes (Sekisui Plastics Co., Tokyo, Japan) placed over the motor points of the biceps and triceps brachii have been previously described [7,9].

Stimulation parameters

Waveform: Stimulation parameters were based on a standard Russian waveform in which a 5 kHz carrier frequency was modulated at 20 Hz (2.4 ms on, 47.6 ms off) to deliver rectangular biphasic wave pulses [7].

Intensity: Stimulation intensities were set at the value of the threshold intensity plus two-thirds the difference between the maximum comfortable intensity and the threshold intensity [7-9], with the isometric contraction force limited to 25-30% of the maximum voluntary contraction (MVC). Output power was <10W, the current intensity was <10 mA/cm^2, and the voltage was <80V.

Evaluation

Strength: Muscle strength of each subject was evaluated one week before the regimen as a baseline and also evaluated one week after the regimen for an endpoint. Subjects were each evaluated during a baseline session that was undertaken within one week prior to his entering the study protocol, as well as during the one week after the end of the program. Maximal isometric elbow flexion and extension torques were obtained with the subject sitting in a Kin-Com apparatus (Chattanooga Group, Inc., TN, USA) with the left elbow positioned at 60° flexion. Each subject was then asked to produce a maximal isometric elbow flexion and extension and encouraged to monitor his own efforts on a video screen. The maximum voluntary contraction was defined as the mean of three measurements at 1-min intervals.

Endurance: Muscle fatigue was assessed in a standardized manner. Since a >40% MVC is reported to be necessary for successful surface electromyography (EMG) power density spectral analysis of fatigue in the upper extremities [11], we chose to perform testing at 50% MVC. A consistent procedure was followed which began with the subject first sitting in a relaxed manner for 2-3 min and then performing a preliminary/training series of 40-sec isometric elbow flexion and extension contractions at the 50% MVC in the manner described in the strength determination section above. Isometric endurance testing of elbow flexion and extension were then performed with video feedback in a manner similar to that of the training sessions. The duration of each session was more than 15 min, after having measured the flexion and measured the extension.

EMG recording: The skin over the bellies of the left biceps and triceps brachii was first cleansed with an alcohol swab. Next, a pair of 10-mm-diameter 20-mm-center-to-center separation silver-silver chloride bipolar surface electrodes was placed over the motor end-points of each of the two muscles. The biceps and triceps EMG activities were continuously monitored during their respective 40-sec testing durations. The EMG signals were amplified, digitized at a sampling rate of 2000 Hz, and stored on memory cards in an ME 3000P EMG analysis system (Mega Electronics, Ltd, Helsinki, Finland). Records were downloaded and analyzed off-line using the manufacturer's proprietary software (MegaWin software 2006 version 2.0, Mega Electronics, Ltd, Helsinki, Finland). The EMG preamplifier sensitivity was set at 1 μV, and the frequency bandwidth at 20-500 Hz.

Evaluation of muscle fatigue: EMG power spectral frequency analysis was used to evaluate skeletal muscle endurance [12-20]. The median frequency (MF) and the mean power frequency (MPF) indices were derived from the raw EMG signals and plotted against time using the ME3000P Fast Fourier Transform (FFT) spectral analysis program. The MF and MPF slopes per unit time over the 40-sec 50%-MVC elbow flexion and extension testing periods were calculated from the following formula: % slope=[(final frequency – initial frequency)/time]×100. The values were normalized and expressed as a percentage of the individual's baseline prior to further analysis and comparison between the groups.

Data analysis

Statistical analyses were performed with Stat-View, Version 5.0, for Windows (SAS, Cary, NC, USA). Data were expressed as mean ± standard deviation (SD). Changes in MF and MPF spectral frequency distributions during the 40-sec isometric contraction tests were assessed using the Pearson's product moment correlation test. Inter-group differences between the MF and MPF slopes in the HYB and ELS Groups were examined for statistical significance using Student's unpaired t-test. Intra-group changes in each parameter between their baseline and endpoint determinations were examined for statistical significance using Student's paired t-test. A P-value at less than 0.05 was considered to denote statistical significant.

RESULTS

The groups were matched and did not differ in a statistically significant manner in terms of age, height, and weight. All the 13 subjects attended and completed all the training and evaluation sessions.

Spectral power analysis

The slopes of MF and MPF decreased linearly between the baseline and endpoint period in elbow flexion and extension endurance testing sessions in all subjects (by Pearson's product moment correlation coefficient) (in all cases $p<0.01$).

The baseline MF and MPF slopes in the biceps during elbow flexion did not statistically differ between the groups ($p=0.19$, and $p=0.43$, respectively). Intra-group analysis among the HYB Group revealed nosignificant changes between the baseline values (MF −32.9±5.3, and MPF −33.3±6.8%/min) and the values at the end of training (MF −40.0±21.9, and MPF −38.2±13.9%/min) ($p=0.40$, and $p=0.45$, respec-

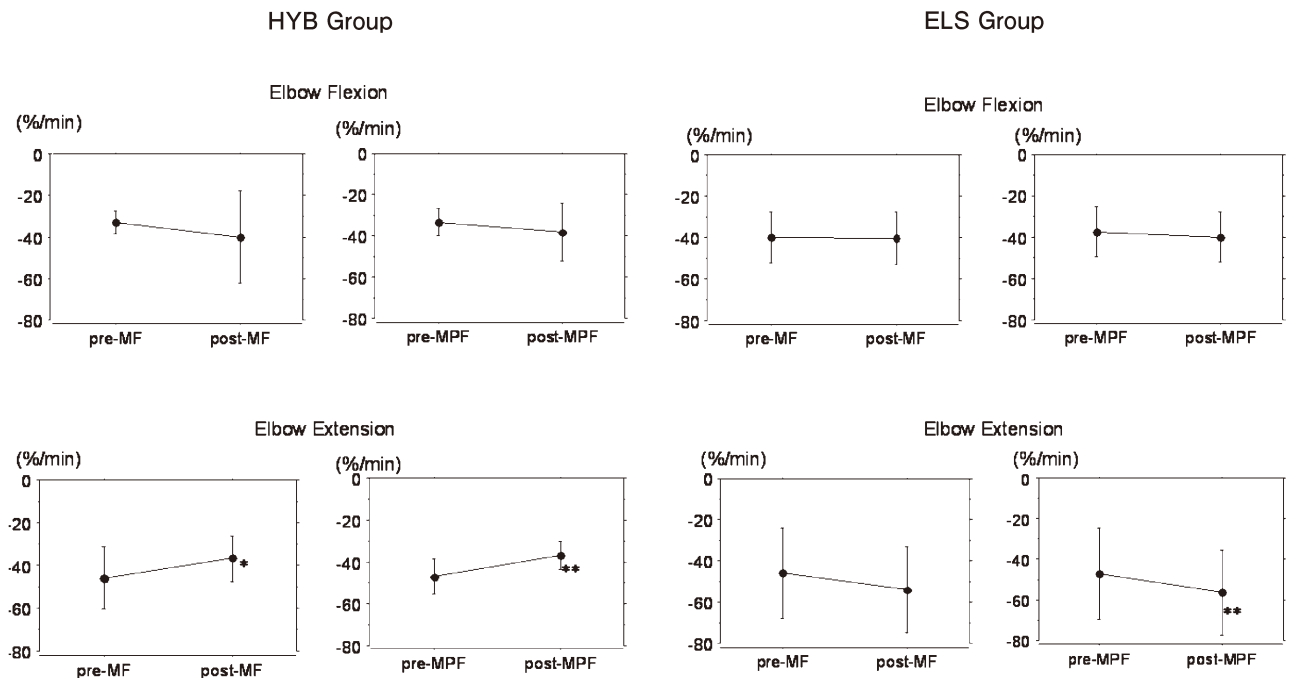

Fig. 1. Left Panels. HYB group. Comparison of MF and MPF slopes (means ± SD) of the biceps during elbow flexion and triceps during extension before (pre) and after (post) four weeks of HYB training. While training had no effect on the MF (p=0.40) or MPF (p=0.45) slopes of the biceps, it did produce statistically significant improvements in both of these quantities in the triceps (*MF: p=0.03, **MPF: p<0.01). Right Panels. ELS group. Comparisons of MF and MPF slopes (means ± SD) of the biceps during elbow flexion and the triceps during extension before (pre) and after (post) four weeks of ELS training. While training had no effect on biceps MF and MPF slopes during elbow flexion (MF: p=0.95, MPF: p=0.60) it did produce a statistically significant worsening of the MPF slope (p<0.01) and a borderline worsening in the MF slope (p=0.054) during elbow extension.

tively) (Fig. 1, Upper Left). Intra-group analysis of the ELS Group revealed a similar pattern of no significant difference between the baseline values (MF −39.9±12.3, and MPF −37.7±12.1%/min) were statistically indistinguishable from those recorded at the end of training (MF −40.3±12.6, and MPF −39.9±12.1%/min) (p=0.95, and p=0.60, respectively) (Fig. 1, Upper Right). Analysis revealed that these nonsignificant intra-group changes were accompanied by similar nonsignificant inter-group changes (MF p=0.97, MPF p=0.80).

The baseline values of the MF and MPF slopes in the triceps during elbow extension did not differ between the groups in a statistically significant manner at baseline (p= 0.95, and p= 0.99, respectively). These slopes improved following training in the HYB Group (from −45.7±14.7 and −47.0±8.6%/min at baseline to −36.9±10.7 and −36.8±7.0%/min at the end of training) (p=0.03, and p<0.01, respectively) (Fig. 1, Lower Left). The corresponding values for these slopes in the ELS Group however became steeper following training (from −46.8±21.8 and −47.1±22.4%/min, to −54.0±21.2 and −56.4±21.1%/min) with change in MF slope approaching (p=0.054) significance and that in MPF slope showing statistical significance (p<0.01) (Fig. 1, Lower Right). Inter-group comparison between the HYB Group and the ELS Group demonstrated these findings in changes improved muscular endurance in the triceps in the HYB Group relative to the changes in the ELS Group (p<0.05).

DISCUSSION

The findings from this study indicated that while a HYB exercise regimen resulted in an improvement in the resistance of the triceps to fatigue (as determined from MF and MPF slopes). Training with a comparable electrical stimulation strengthening regimen has been associated with a decrease in triceps endurance. The present study found that neither the HYB nor the ELS training had a beneficial effect on the resistance of the biceps to muscular fatigue.

The discrepancy between the responses in the training in the biceps and triceps is intriguing as the

two muscles were stimulated at the same relative intensity (threshold intensity + 2/3rds the difference between the maximum comfortable intensity and the threshold intensity). It is possible that the reason for the difference may lie in the different fiber composition of the two muscles: the triceps has a higher proportion of slow twitch fibers than the biceps in monkey [21,22], and at least one recent report has suggested that gains in strength by electrical stimulation in fast twitch rich muscles comes at a cost of decreased endurance in human lower extremities [17]. The finding that the fatigue resistance of the triceps in the HYB Group improved with training while that of the ELS Group worsened may have a similar root cause. Elder reported in human that while the medial head of triceps was found to be mainly composed of slow twitch fibers, fast twitch fibers were found to be more prevalent than slow twitch fibers in the lateral and long heads of triceps as well as the biceps brachii using fresh cadaver [23]. The opinion of researchers varies by their specimens or subjects, and it is difficult to arrest these results equally. Further study should be necessary to determine on the fiber distribution.

Also, it is possible that the reason for the difference may lie in the different strength of the two muscles: the maximal elbow extension torques were bigger than the maximal elbow flexion torques [7,9]. Muscular strength training requires an exercise load of strong intensity; on the other hand, muscular endurance training requires an exercise load of low intensity [24]. I believe that because the electrically stimulated eccentric contraction preferentially recruits fast twitch fibers, the concentric contraction of the HYB regimen contributes to improve muscular endurance. For muscular endurance improvement, in this study, the concentric exercise load for the triceps might be appropriate, but for the biceps might be too big. Kramer [25] reported the male subjects demonstrated significantly greater electrically stimulated knee extension torque values as well as maximal voluntary knee extension torque values than did the female subjects. It would be necessary in muscle maintenance to regulate electrical stimulation intensity to each muscle.

Using MF and MPF slopes as a measure for muscular endurance deserves some discussion. The choice may be arguable but seems appropriate as physiological research confirms an association between muscle fatigue and shifts in firing rates towards lower values [7,12-20]. Moreover, regression analyses between the MF and MPF slopes with time were capable of detecting differential responses in the fiber types: with slow twitch fibers showing more resistance to fatigue than the fast twitch fibers [26,27].

Another concern involves the spectral analysis for the upper extremities: other reports have examined the muscles of the back and lower extremities. However, studies on the muscle in the upper extremities also appear in the literature. For example, an investigation by members of this group found that the MF and MPF slopes in the triceps brachii of wheelchair marathoners displayed an improved endurance relative to wheelchair naïve ambulatory control subjects [20]. It is also significant that another recent upper extremity study [28] has revealed that the fast twitch fiber rich biceps reveals a steeper degradation in its firing frequency than the slow twitch rich triceps [21,22,26].

HYB regimen was capable of producing an improvement in the muscular endurance of the triceps brachii, however, the changes in fiber type by HYB approach inconclusive in this study. Further research is necessary to investigate the improvement of muscular strengthening and endurance on other muscles as well as change in their fiber types. We also hope to continue the study of the long-term effects of this exercise, and to refine the HYB approach.

CONCLUSIONS

Our HYB exercise regimen was capable of producing an improvement, and conventional electrical stimulation of worsening, in the muscular endurance of the triceps brachii. Neither approach, however, appears to have a significant effect on the fatigue resistance of the biceps brachii.

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