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Original Article

Muscle endurance and power spectrum of the triceps brachii in wheelchair marathon racers with paraplegia

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Objective: To investigate differences in triceps brachii endurance and electrical activity between elite marathon and recreational wheelchair athletes with paraplegia.
Design and methods: Nine male elite wheelchair athletes between 20 and 46 years of age (average 29.0 ± 8.2 years) with complete (ASIA-A) T4–L1 paraplegia were compared to a group of six male height- and weight-matched recreational wheelchair athletes with similar ages and injuries. Right triceps brachii maximum voluntary contraction (MVC), as well as the duration of the ability to maintain a 50% MVC were determined for all subjects. Median frequency (MF) and mean power frequency (MPF) were evaluated with fast Fourier transform spectrum analysis. MF and MPF rates of change were calculated and compared with the Student's *t*-test.
Setting: Department of Rehabilitation Medicine, University of Occupational and Environmental Health, Japan.
Results: Right triceps brachii MVCs of the marathoners (42.4 ± 8.8 N m (range 33–55 N m)) and recreational athletes (41.6 ± 9.3 N m (range 32–56 N m)) did not differ significantly ($P = 0.63$). Endurance, however, did. All of the athletes, but none of the control subjects, were able to maintain a 50% MVC contraction of the right triceps brachii for 2 min (the average contraction duration in the latter group was 75.5 ± 16.2 s). MF and MPF of the triceps brachii decreased linearly in both groups, but the slopes in the marathoners (-8.9 ± 4.6 (-3.8 to -16.4) and -9.7 ± 4.6 (-4.0 to -17.2)%/min, respectively) were statistically less steep than those in the recreational athletes (-22.3 ± 8.2 (-9.6 to -31.4) and -21.2 ± 6.4 (-11.4 to -28.6)%/min, respectively).
Conclusion: Elite marathoners and active wheelchair users have similar triceps brachii strength. The marathoner's triceps brachii, however, display a significantly improved endurance and a slower decline of MF and MPF with time than do those of their recreational athlete control group.
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Keywords: wheelchair; marathon; athlete; strength; endurance; rehabilitation

Introduction

Sir Ludwig Guttman introduced wheelchair-based competitive sports and recreation into spinal cord injury (SCI) rehabilitation at the end of World War II.[1] Much has happened since those early days at Stoke Mandeville. Wheelchair sports are now gaining acceptance by the public and have matured to the point where world-class athletes routinely compete at the national and international events. Marathon racing is emblematic of these activities and, at its highest levels, involves highly trained athletes capable of completing the 26.2-mile distances of a marathon in 1 h and 40 min. In view of this level of competition, it is not surprising that the racers train intensively, make physiological adaptations to their sports, and constantly strive to improve their equipment and training strategies.

These efforts have not gone unnoticed. There is a broad and growing literature on the biomechanics and physiology of wheelchair propulsion.[2] It is known, for

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example, that people who propel wheelchairs have a higher incidence of upper-extremity pain and dysfunction than the nondisabled population.[2–4] Wheelchair racing, because of its high intensities and stroke repetition rates, has been the focus of particularly intense scrutiny. Much has been learned and a number of physiological changes have been isolated and studied in racers. Thus, while it is controversial how much torque-generating characteristics may vary between wheelchair-dependent individuals and the ambulatory population,[2] differences may be clearer in more highly trained individuals or for different physiologic systems. Zeppilli *et al*,[5] for example, found that wheelchair athletes had a larger caliber upper-extremity vasculature and a significantly smaller diameter lower-extremity system than nondisabled controls when normalized for body surface area (BSA). In addition, wheelchair long distance racers, who trained intensively, had larger abdominal aortas and inferior vena cavas than wheelchair basketball players. In other words, endurance training appears to lead to a generalized increase in the capacity of arterial and venous conductance vessels.[5]

The effect of endurance training on the muscles is also a center of intense interest in sports physiology. A number of recent studies have used electromyographic (EMG) power spectral analysis to evaluate skeletal muscle endurance. These investigations have shown that muscle fatigue (and hence endurance) is associated with a shift in the frequency content towards lower values. These analyses also reveal strong relations between maximum voluntary contraction (MVC), rates of decline in power spectrum frequencies, and time to fatigue.[6] Regression analyses between the frequency slope and endurance time also show intersubject variations that may be related to muscle fiber-type proportions with slower rates of decline associated with increased concentrations of Type II fibers.[7] Most EMG power spectrum analysis reports emphasize the muscles of the back. Investigations of the muscles of the extremities seem far more limited. This relative lack of investigation is particularly prominent in the upper extremities and the muscles involved in wheelchair propulsion.

We wished to help rectify this imbalance by studying upper-extremity power spectrums in highly trained and recreational athletes. In particular, we compared the characteristics of the brachialis strength and EMG power spectrums of elite wheelchair marathon athletes with paraplegia with those of a sample of recreational athletes matched in terms of age, height, injury and weight.

Methods

Subjects

This study involved a convenience sample of nine male volunteers with complete (ASIA-A) T4–L1 SCI who participated in the 17th Oita International Wheelchair Marathon Race on November 1997 in Oita, Japan. Subjects had no other medical problems, and were elite wheelchair marathon racers, whose best times were all less than 2 h 20 min. All trained regularly, typically more than 1.5 h per day, 6 days per week, and all had participated in wheelchair marathons for more than 3 years. Informed consent was obtained from all subjects.

Control subjects

Six men with ASIA-A paraplegia (T7–L1) that participated in recreational wheelchair basketball team served as an age-, height-, weight- and injury-matched control sample. Their anthropometric characteristics of both groups are shown in Table 1. Informed consent was obtained from all participants.

Isometric exercise of elbow extension

A standardized procedure was followed that began with the subjects resting quietly for 10 min in a sitting position. The subjects were then placed in a supine position with their shoulders firmly secured to an adapted bed and their right arm and forearm supported in the horizontal plane with their elbow in 50° of flexion and their forearm in a neutral position (Figure 1). The elbow was aligned with the axis of the rotation of a Cybex II isokinetic dynamometer (CYBEX International, Inc., USA) that had a strain gauge transducer mounted on its shaft (Figure 1). The subjects were then asked to produce a maximal isometric elbow extension and encouraged to monitor their efforts on a video screen. The maximum torque obtained in the three efforts for a 1-min interval was defined as the MVC. The subjects next rested a 2- to 3-min interval and then performed a preliminary/training test of isometric elbow extension at the 50% MVC level for 1 min. This static elbow extension test was repeated for a 2-min interval after a 15-min rest period. All testing was done with video feedback used in the manner outlined for the MVC determinations.

EMG recording

The skin over the right triceps brachii was first cleansed with an alcohol swab. Next, a pair of silver–silver chloride bipolar surface electrodes (10 mm diameter, 20 mm separation) was placed over the belly of the

Table 1 Anthropometric measurements

	Marathon group (n=9)	*Control group (n=6)*
Age (years)	29.0±8.2	27.5±8.9
Height (cm)	168.3±12.9	168.2±6.3
Body weight (kg)	60.1±12.2	59.5±7.2
Spine lesion	T4–L1	T7–L1

Values reported as mean±SD

Figure 1 The figure shows a subject's isometric triceps brachii MVC being measured with a Cybex II dynamometer. Note the visual feedback provided by the monitor. The 2-min, 50% MVC trails were performed in the same manner

muscle. The myoelectrical signals from right triceps were continuously monitored during the elbow extension 2-min holding test as well as for a minute before and after the trail. The signal was amplified, digitized at a sampling rate of 2000 Hz, and stored on memory cards with one channel and 1 MB in an ME 3000P EMG analysis system (Mega Electronics, Ltd, Finland). These records were then downloaded into a personal computer (Toshiba, Japan), and analyzed off-line using proprietary software (ME3000P Professional version 1.2). EMG preamplifier sensitivity was set at 1 μV. The frequency band was 20–500 Hz.

Evaluation of muscle fatigue

Median frequency (MF) and mean power frequency (MPF) indices were derived from the raw EMG signal as described above and plotted against time during the test using the ME3000P fast Fourier transform spectral analysis program. The rate of change in each parameter (the slope of MF and MPF per unit time) over the 2-min elbow extensor-holding period was calculated and analyzed. MF and MPF slopes were calculated from the following formula: % slope = ((final frequency−ini-initial frequency)/exercise time) × 100. Values were normalized and expressed as percentage of baseline to permit pooling and comparison between the groups. The validity of this method was confirmed by the EMG specialists.

Statistical analysis

The Stat-View Ver. 4-1.1 statistical analysis program (Abacus Concepts, Inc., USA) was used to examine differences between the subjects. Changes in MF and MPF slope during the endurance test were examined for statistical significant differences using the Student's *t*-test. A $P < 0.05$ denoted the presence of a statistically significant difference. Data were expressed as mean ± SD.

Results

All nine wheelchair marathon subjects completed the 2-min, 50% MVC trials. No control subject, however, was able to complete theirs: the average time that this group could maintain a continuous 50% MVC elbow extension was 75.5 ± 16.2 (range: 49–114) s. The mean MVC of the athletes and the controls, 42.4 ± 8.8 (range: 33–55) N m and 41.6 ± 9.3 (range 32–56) N m, respectively, did not differ in a statistically significant manner. MF and MPF decreased linearly during the test in both groups (Figure 2). MF and MPF slopes in the athletes were −8.9 ± 4.6 (−3.8 to −16.4) and −9.7 ± 4.6 (−4.0 to −17.2)%/min, respectively (Figure 3). These slopes in the recreational athlete controls were −22.3 ± 8.2 (−9.6 to −31.4) and −21.2 ± 6.4 (−11.4 to −28.6)%/min (Figure 3), respectively, and each was significantly

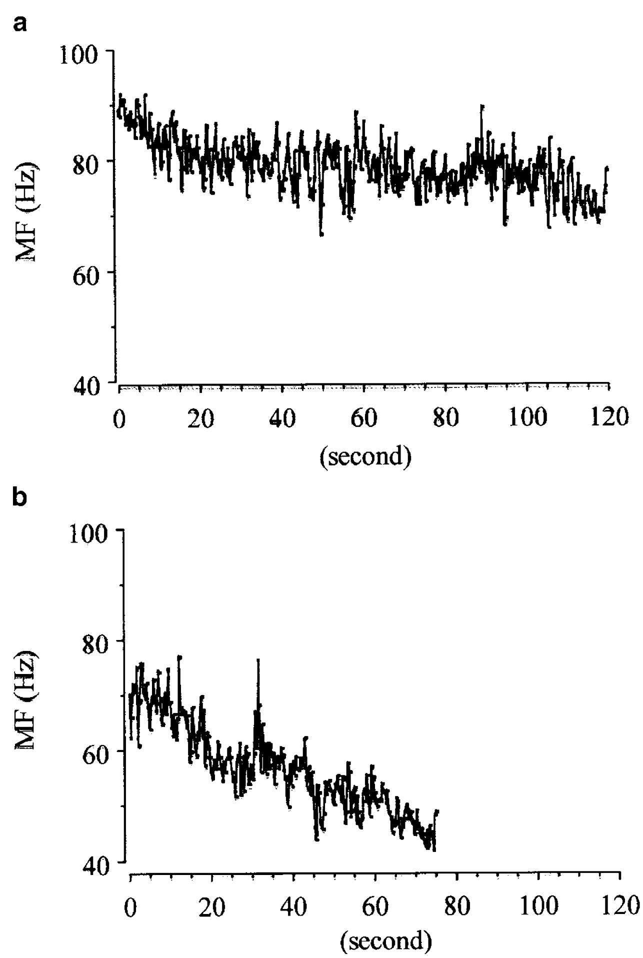

Figure 2 Changes in the MF in (**a**) a representative 27-year-old marathoner and (**b**) a 35-year-old recreational athlete control subject. The progressive and linear decrease in MF is a measure of fatigue and is more marked in the control subject

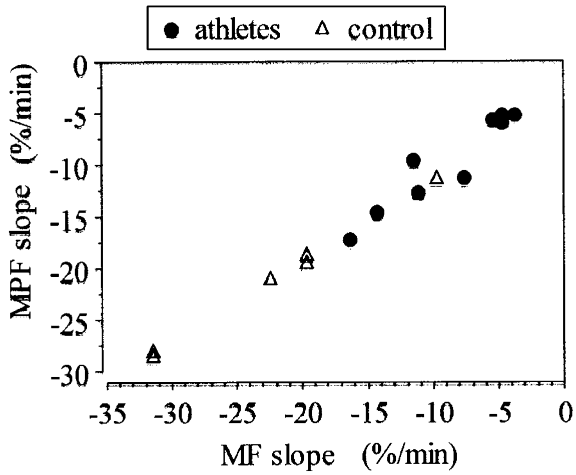

Figure 3 Individual data for the marathon racers and recreational athlete control subjects are plotted against MF and MPF slopes. Note that the data of the recreational athletes tend to group itself in the graph's left lower quadrant

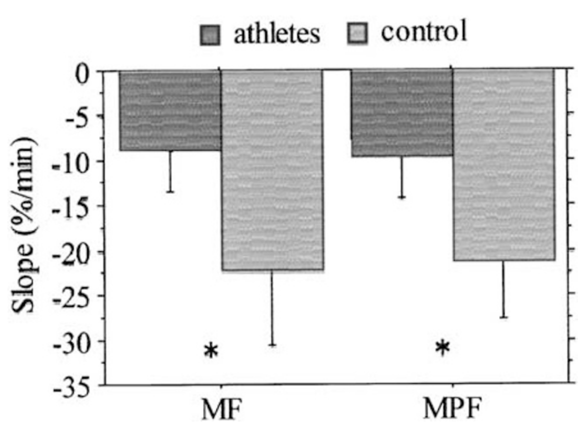

Figure 4 Comparison of the slopes (means $\pm$SD) of MF and MPF in the marathoners and the recreational athlete control groups during the 50% MVC trials. Note that the magnitude of the slopes of both MF and MPF are significantly greater in the control than the athlete group. (MF: $P=0.0013$, MPF: $P=0.0012$)

steeper ($P=0.0013$ and 0.0012) than those in the marathon group (Figure 4).

Discussion

Wheelchair sports participation has grown markedly since Sir Ludwig's pioneering introduction 60 years ago. Today, people compete for enjoyment, comradeship and the conditioning benefits of exercise. A small number train far more intensively and reach a world-class status that manifests itself in outstanding performance and corresponding physiological adaptation. These latter individuals have been the focus of our study.

Although cardiopulmonary capability is obviously important, muscle strength and endurance are also essential if one is to compete effectively. In our study, we confirmed that the highly trained marathoners had MVCs indistinguishable from those of recreational level peers. Not surprisingly, however, the marathoners displayed a higher level of endurance than their controls: each was able to maintain a 50% MVC triceps contraction for at least the 2-min duration of their trial, while none of the control subjects was able to do so. Spectral analysis quantifies this observation. First of all, we found that the MF and MPF slopes decreased significantly faster in the recreational athletes than in the marathon racers. This finding agrees with recent research in the trunk musculature that also reveals a slower rate of frequency decrease with time is association with an increased level of muscle endurance.[8,9]

EMG power spectral analysis has focused primarily on muscle fatigue of the back muscles.[8–10] There have, however, been a few studies that have involved the quadriceps in nondisabled people,[6,11] which have shown that this muscle is difficult to study and that load reproducibility is challenging. We considered these difficulties.

Our knowledge of brachial muscle endurance and EMG power spectral analysis is limited. Recently, however, Krivickas *et al*[12] reported that EMG spectral analysis was useful to evaluate muscle endurance of upper limb and that muscles with white fiber predominance have faster rates of frequency reduction with time. These authors also noted that it is important to set loads for correct evaluation of muscle fatigue. In particular, as a $>$40% MVC in the upper extremities is reported to be necessary for successful surface EMG power density spectral analysis of fatigue,[13] we chose loads of 50% MVC.

Muscles fiber types and characteristics that are typically assessed by histochemical means can also be assessed to a certain extent with the EMG power spectral analysis.[14] In particular, as might be expected, muscles with a greater percentage of fast glycolytic and fast oxidative glycolytic fibers exhibit a more rapid reduction of MF over the course of a contraction than those with a higher concentration of Type II fibers. Thus, the slower rates of decline in the slopes of MF and MPF that we found in the marathon athletes support the ideas that fiber-type composition can be predicted on the basis of MF and that the arm muscles of wheelchair marathon racers have gained a higher predominance of red muscle fibers.

Conclusion

The reduced slopes of MF and MPF found in wheelchair marathoners in this study reflect the improved endurance of the triceps brachii of these individuals. It is interesting that the MVCs of the two groups did not differ significantly – a finding that seems to support the observation that you should 'train for your sport'.

References

1 Ogata H. A review of wheelchair marathon and tennis. *Sangyo Ika Daigaku Zasshi* 1994; **16:** 201–217.
2 Kotajarvi BR, Basford JR, An K. Upper extremity torque production in individuals with paraplegia. *Arch Phys Med Rehabil* 2002; **83:** 441–446.
3 Sie IH, Waters RL, Adkins RH, Gellman H. Upper extremity pain in the postrehabilitation spinal cord injured patient. *Arch Phys Med Rehabil* 1992; **73:** 44–48.
4 Nichols PJR, Norman PA, Ennis JR. Wheelchair user's shoulder. *Scand J Rehabil Med* 1979; **11:** 27–32.
5 Zeppilli P *et al*. Echocardiographic size of conductance vessels in athletes and sedentary people. *Int J Sports Med* 1995; **16:** 38–44.
6 Mannion AF, Dolan P. Relationship between myoelectric and mechanical manifestations of fatigue in the quadriceps femoris muscle group. *Eur J Appl Physiol Occup Physiol* 1996; **74:** 411–419.
7 Merletti R, Roy S. Myoelectric and mechanical manifestations of muscle fatigue in voluntary contractions. *J Orthop Sports Phys Ther* 1996; **24:** 342–353.
8 Ng JK, Richardson CA. Reliability of electromyographic power spectral analysis of back muscle endurance in healthy subjects. *Arch Phys Med Rehabil* 1996; **77:** 259–264.
9 Mannion AF, Connolly B, Wood K, Dolan P. The use of surface EMG power spectral analysis in the evaluation of back muscle function. *J Rehabil Res Dev* 1997; **34:** 427–439.
10 Umezu Y, Kawazu T, Tajima F, Ogata H. Spectral electromyographic fatigue analysis of back muscles in healthy adult women compared with men. *Arch Phys Med Rehabil* 1998; **79:** 536–538.
11 Taylor AD, Humphries B, Smith P, Bronks R. Electrophoretic separation of myosin heavy chain isoforms in the human m. vastus lateralis: references to reproducibility and relationships with force, electromechanical delay, fibre conduction velocity, endurance and electromyography. *Arch Physiol Biochem* 1997; **105:** 10–18.
12 Krivickas LS *et al*. Is spectral analysis of the surface electromyographic signal a clinically useful tool for evaluation of skeletal muscle fatigue? *J Clin Neurophysiol* 1998; **15:** 138–145.
13 Bernardi M, Solomonow M, Baratta RV. Motor unit recruitment strategy of antagonist muscle pair during linearly increasing contraction. *Electromyogr Clin Neurophysiol* 1997; **37:** 3–12.
14 Kupa EJ, Roy SH, Kandarian SC, De Luca CJ. Effects of muscle fiber type and size on EMG median frequency and conduction velocity. *J Appl Physiol* 1995; **79:** 23–32.