Muscle-specific endurance of the trapezius muscles using electrical twitch mechanomyography

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Abstract

Background: Symptoms of fatigue and pain are often reported for the trapezius muscle in the shoulder. The present study evaluated endurance in the trapezius muscles of healthy participants using electric twitch mechanomyography (ETM).

Methods: Surface electrodes and a tri-axial accelerometer were placed over the left trapezius muscle. Muscles were stimulated for 3 min each at 2 Hz, 4 Hz and 6 Hz. Maintenance of acceleration during muscle twitches was used to calculate an endurance index (EI). Subjects ($n = 9$) were tested on two separate days to assess reproducibility of the trapezius EI measurements. The endurance measurements were made on the wrist flexor and vastus lateralis muscles for comparison. Near infrared spectroscopy was used to measure muscle oxygenation (HbO_2) during the stimulation protocol ($n = 8$).

Results: Mean (SD) EI was 84.9% (8.7%), 63.3% (19.1%) and 41.7% (20.0%) for 2 Hz, 4 Hz and 6 Hz, respectively. The coefficients of variation were 7.4%, 11.3% and 24.0% for 2 Hz, 4 Hz and 6 Hz, respectively. EI values were significantly lower in the trapezius compared to arm and leg muscles ($p < 0.05$). HbO_2 values were unchanged from resting values with electrical stimulation.

Conclusions: The EI as measured by ETM may provide a reproducible method of evaluating function in trapezius muscles that is not influenced by oxygen saturation.

Keywords

accelerometry, muscle fatigue, near infrared spectroscopy, shoulder muscles

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Introduction

Fatigue and pain of the shoulder muscles is a common problem in clinical and healthy populations.¹ Daily and occupational activities associated with shoulder loading and overuse can result in fatigue of the shoulder muscles and may be associated with the development of pain.^{2–6} Furthermore, clinical populations such as individuals with neurological injuries may experience significant overuse, fatigue and pain of the shoulder muscles.^{7,8} Therefore, it is important to evaluate the ability of shoulder muscles to perform repetitive submaximal activity without the development of fatigue.

Muscle fatigability is a term used to describe the inability of a muscle to sustain repeated contractions.⁹

Voluntary exercise protocols have been used to evaluate fatigability in the shoulder muscles.^{10–12} However, interpretations of these tests are limited by the potential presence of reduced central activation and desynchronization of muscle group activation. Furthermore, previous studies have evaluated fatigue in the shoulder muscles by measuring changes in electromyography (EMG) signals during voluntary contractions.^{4,13} The advantage of surface EMG as a marker of fatigue

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is that it is noninvasive and localized to specific muscle areas. The disadvantages are that the changes in median frequency and amplitude are indirect measures of muscle contractile function, and may not correlate with changes in perceived fatigue¹⁴ or cross-bridge cycling.

Electrical twitch mechanomyography (ETM) has recently been used to evaluate fatigability in the upper extremity muscles of persons with neurological disease.¹⁵ This approach uses low frequency surface neuromuscular electrical stimulation to produce twitch contractions and a triaxial accelerometer to measure the acceleration of muscle movement. With the development of muscle fatigue, the acceleration declines, and the acceleration that remains at the end of the stimulation is used to calculate an endurance index (EI). Acceleration from muscle movement has been used in previous studies, and changes in muscle acceleration have correlated well with changes in muscle force production.^{16–19}

The trapezius muscles are commonly evaluated in studies of shoulder muscle fatigue and pain.^{20,21} Studies have found that trapezius muscles are a tender point in patients with fibromyalgia^{21,22} and are affected by a variety of activities including carrying backpacks,³ carpet weaving²³ and flying helicopters.² Furthermore, the trapezius muscles are important in wheelchair propulsion and facilitating a respiratory task in clinical populations.^{24,25} The purpose of the present study was to evaluate the utility and reproducibility of the EI as measured by ETM as a method of assessing muscle fatigue in the trapezius muscles of the shoulder. Three sets of experiments were performed. First, endurance indices were performed on two occasions and coefficient of variation and interclass correlation coefficients were determined. Second, endurance indices were determined on the forearm and vastus lateralis muscles of the same participants for comparison. Finally, oxygen saturation was monitored using near infrared spectroscopy (NIRS) to determine if contraction-induced ischaemia occurred during electrical stimulation.

Materials and methods

Nine healthy participants (seven males and two females) participated in the present study. Participants had a mean (SD) age of 22.4 (2.6) years, height of 1.79 (0.13) m and body weight of 72.8 (12.7) kg. Participants had no prior history of shoulder injuries. The study was conducted with approval of the Institutional Review Board at the University of Georgia (Athens, GA, USA) and all of the subjects provided their written, informed consent before testing.

Experimental design

Each participant was tested on three separate days by the same tester. On one day, the EI was determined for the trapezius and vastus lateralis muscles. On another day, the EI was determined on the trapezius and the forearm/wrist flexor muscles. On another day, oxygen saturation was measured in the trapezius muscles. The order of testing for the three days was varied for different participants and all experiments were completed within 2 weeks for each participant.

Endurance index measurements

For the trapezius muscle testing, the subjects were positioned prone on a padded table (Fig. 1). Two electrodes (5 cm × 5 cm) were placed with on the exposed shoulder such that the accelerometer could be placed over the middle of the trapezius muscle. The muscles were stimulated using submaximal current levels that ranged from 25 mA to 35 mA with pulse durations/intervals of 200 μ s/50 μ s. A wireless tri-axial accelerometer (WAX3; Axivity, Newcastle upon Tyne, UK) was used to measure the acceleration of muscle twitch contractions.

Figure 1. Experimental set-up for the trapezius muscle endurance test. The stimulation electrodes are white and the accelerometer is black, located between the electrodes.

The protocol consisted of 3 min each of electrical stimulation at 2 Hz, 4 Hz and 6 Hz sequentially with 5 s of no stimulation between each stage. The surface accelerometer measured the surface oscillations resulting from the muscle twitches via wireless Bluetooth transmission. Muscle twitch acceleration was quantified as the resultant acceleration (A_r) from all three axes ($A_r = \sqrt{X^2 + Y^2 + Z^2}$). Raw acceleration data was analyzed using custom written routines in MATLAB R2014b (MathWorks Inc., Natick, MA, USA). Peak to peak (p-p) analysis was employed to determine the magnitude of acceleration measured during each contraction. The EI was calculated as the percentage of movement at the end of the fatigue test compared to the initial peak value.

For the forearm and vastus lateralis muscles, the accelerometer was placed in the centre of the belly of the muscles and the stimulation electrodes placed proximally and distally on the same muscle. The participant lay supine on a padded table during the forearm measurements, with the upper extremity secured at the wrist to prevent unintended rotation of the arm during stimulation.¹⁵ For the vastus lateralis measurement, the participant sat upright, with the lower extremities extended (knee joint = 0°). The current used during stimulation was similar to that used for the trapezius muscles (25 mA to 35 mA).

Oxygen saturation during the EI test

For the trapezius muscles, the participant was in a seated position with their arms and head resting comfortably at shoulder level. A NIRS device (Portamon; Artinis Medical Systems, Elst, The Netherlands) was secured to the subject using an elastic band. The location was approximately the same location as the accelerometer placement. Muscle oxygenation (HbO₂), deoxygenation (HHb) and blood volume (tHb) measures were collected at a sampling rate of 10 Hz with separation distances of 3 cm and 4 cm. The same 2 Hz, 4 Hz and 6 Hz protocol was performed, followed by 60 s of voluntary shoulder shrugs. Shoulder shrugs were performed continuously without relaxing when holding weights of 4.54 kg (female) or 6.81 kg (male) in each hand with the elbow at full extension. Shoulder shrugs were performed to induce ischaemia and lower oxygen saturation to a minimum oxygen saturation level for comparison with the oxygen levels during twitch contractions. Data collection continued after the shoulder shrug exercise to allow for hyperaemia and maximal oxygen saturation values to be recorded. Oxygen saturation (HbO_{2diff} as the difference signal of HbO₂ and HHb) was calculated at rest, during the last 30 s of each stimulation level, at the lowest point of the

shoulder shrugs, and at the highest point after the exercise. Values of oxygen saturation for rest and the stimulation levels were calculated as a percentage of the range between the low values during the contractions (assumed to be 0% oxygen saturation) and the highest values during reactive hyperaemia (assumed to be 100% oxygen saturation).

Statistical analysis

Measures of EI and oxygen saturation at each frequency were compared using repeated measures analysis of variance (ANOVA). Pairwise comparisons of stimulation frequency and muscle group were made using Bonferroni corrections for multiple comparison. Comparison of measures of endurance between muscles was performed using a two-way repeated measures ANOVA. Data are presented as the mean (SD). Reliability was tested using coefficients of variation (CV) and intraclass correlation coefficients (ICC) using Cronbach's α based on standardized items. $P < 0.05$ was considered statistically significant.

Results

Representative acceleration values for a single participant for the three different muscles are shown in Fig. 2. The EI values for the trapezius vastus lateralis, and wrist flexor muscles are shown in Fig. 3. There was a significant main effect of stimulation frequency on the EI, with measures of EI significantly lower at each stage of increasing frequency (<0.001) indicating the presence of fatigue. There was also a significant main effect for muscle group, with significant pairwise comparisons between the trapezius muscles and the wrist flexor ($p = 0.005$) and vastus lateralis ($p = 0.001$) muscles. EI values in the trapezius muscles for the two test days are shown in Fig. 4. Table 1 shows average values and ICC and CV values for the different stimulation frequencies.

Representative NIRS measurements of oxygen saturation (HbO_{2diff}) for a single individual are shown in Fig. 5. Oxygen saturation in the trapezius muscle dropped significantly with isometric shoulder contractions but did not change during electrical stimulation at any frequency compared to resting values ($p > 0.05$ for all comparisons). The results for the nine participants are shown in Fig. 6.

Discussion

The present study demonstrates the viability of using ETM for evaluating muscle endurance in the trapezius muscles. The primary findings of the present study are

Figure 2. Representative examples of muscle acceleration during electrical stimulation at 2 Hz, 4 Hz and 6 Hz. (a) trapezius muscle. (b) Forearm muscles. (c) leg muscles.

that an EI can be measured for the trapezius muscles and the EI values have reasonable reproducibility. Furthermore, the EI values for the trapezius muscle in asymptomatic participants are lower than EI values from muscles in the leg and arm. Our findings suggest that EI as measured by ETM may have potential for evaluating the development of muscle fatigue in the shoulders associated with occupational activities and pathology. There are currently no data available on mitochondrial capacity for the trapezius muscles. However, muscle biopsies have been performed on the trapezius muscles and there appears to be a high percentage of slow oxidative (66%) and fast oxidative fibres (22%).²⁶ Based on these findings, the trapezius

muscle should be relatively fatigue resistant. The reports of fatigue and tenderness in a variety of occupation conditions suggest that either the metabolic demands of these activities on the trapezius muscle are relatively large or that these muscles are not as fatigue resistant as their fibre type composition suggests.^{6,27–29}

In previous studies, fatigue of the trapezius or shoulder muscles have been measured as perceptions of fatigue or changes in surface EMG signals.^{14,30} Standardized tests to identify fatigability in the trapezius muscles usually involve performing functional tasks based on activities of daily living.^{14,30} Sustained or repetitive tasks have also been performed.^{10,20,22,31}

Figure 3. Average endurance index (EI) values for the leg, arm and trapezius muscles. Significant differences between trapezius muscle EI and leg muscles are indicated by an asterisk (*) and significant differences between arm and trapezius muscles are indicated by a hash symbol (#). Values are the mean (SD).

Figure 4. Endurance index values for the first and second day for each participant.

Table 1. Measures of variability for the endurance index (EI) measurements.

	Stimulation frequency		
	2 Hz	4 Hz	6 Hz
EI first (%)	84.2	63.0	40.9
EI second (%)	89.6	69.4	44.9
CV (%)	7.4	11.3	24.0
ICC	0.33	0.89	0.83

CV, coefficient of variation; ICC, interclass correlation coefficient.

These tasks involved voluntary movements that can be limited by motivation or reduced central activation.²² ETM has the advantage of using twitch electrical stimulation, which does not require a maximal voluntary effort, and it is not influenced by factors such as inter-rater variability or the height and weight of the participant relative to the task. In addition, ETM uses an accelerometer to measure changes in muscle movement rather than force or EMG measurements.^{15,19} By measuring muscle movement, we were able to directly measure muscle contraction without the use of ergometers and high force, voluntary contractions. Changes in EMG signals have also been used to evaluate fatigue/endurance in the trapezius and other muscles, although measurements of muscle activation are an indirect measure of muscle performance and do not always correlated with force development or movement.^{32–34} Measuring acceleration also allows for the use of shortening contractions (muscle twitches), which are known to have higher rates of cross-bridge turnover and ATP use than isometric contractions.^{35,36} The use of twitch contractions with muscle movement increases the metabolic cost of the contractions and makes tests of muscle endurance more likely to reflect the metabolic capacity of the muscle being tested.

One of the concerns with any fatigue test related to muscle metabolism is that the muscle contractions may limit oxygen delivery. Several previous studies have evaluated oxygen levels in the trapezius muscles during exercise.^{37,38} Because we have found that sustained isometric contractions lower oxygen levels to similar values as cuff-induced ischaemia (unpublished observations J Murrow, J Brizendine, K McCully), we used a sustained contraction to calibrate our NIRS signals. Other studies have used laser Doppler methods to

Figure 5. Representative oxygen saturation values (HbO_2Diff) for the trapezius muscles at rest, during electrical stimulation and during a short duration of shoulder shrugs with arm weights. Values are given in optical density units.

Figure 6. Average oxygen saturation values (HbO_2) for the trapezius muscles at rest and during electrical stimulation. Units are as a percentage of the signal change during a sustained isometric contraction. Values are the mean (SD).

evaluate microcirculation in the shoulder area.³⁹ It is not clear whether the penetration depth of the laser Doppler method is sufficiently deep to provide results comparable to the results with NIRS. The lack of desaturation of oxygenated haemoglobin/myoglobin suggests that twitch contractions do not limit oxygen delivery, and the EI measured during twitch contractions is not limited by contraction-induced decreases in blood flow.

The present study addressed the capacity of the trapezius muscle to sustain contractions under conditions where blood flow is not limiting. Although muscle ischaemia may lead to the development of pain symptoms in the trapezius muscle, we found that the

trapezius muscles have relatively lower endurance even when oxygen delivery is sustained. In agreement with these findings, Elcadi et al.³⁷ did not find evidence that muscle fatigue in the trapezius muscles was related to low oxygen saturations during controlled submaximal voluntary exercise. Additional studies will be needed to address the contribution of ischaemia to fatigue of the trapezius muscles during exercise or daily activities, and whether ischaemia or muscle metabolism is more closely related to the development of pain.

One of the limitations to the present study was that we only tested younger subjects without a history of shoulder muscle tenderness or weakness. This was performed aiming to develop the methodology. Future studies will be needed to evaluate the utility of the EI measurements in patient populations. Because submaximal electrical stimulations are used and the participant does not have to perform any activity other than to lie motionless, it is possible that the test can be applied to a wide variety of patient populations. The variability of the EI measurements in the present study is difficult to compare with other methods of measuring muscle endurance in the trapezius. The CV% values for the trapezius EI were higher than that found for the forearm muscles, with a CV% of 2.5%, 7.4% and 4.3% for the three stimulation frequencies.⁴⁰ This mostly likely reflects the higher signal to noise values for the forearm muscles (Fig. 2) and the greater ability to immobilize the forearm compared to the shoulder. The ICC values were low for the 2-Hz stimulation, reflecting the lack of fatigue at that frequency. For the 4-Hz and 6-Hz stimulations, the ICC values were above 0.8, indicating reasonably good reproducibility. Future studies can be designed to account for the variability of the measurements. The sample size used in the present study was

relatively small and, although promising, future studies will be needed to confirm findings obtained in the present study.

In conclusion, we found that the trapezius muscles have lower EI values compared to leg and arm muscles in young healthy participants without a recent history of pain in the shoulder. We chose to compare our trapezius muscle results with those of the forearm and vastus lateralis muscles because we have previously evaluated muscle oxidative capacity in those muscles.^{15,41,42} The EI values were reasonably reproducible. The stimulation protocol showed no evidence of limiting oxygen delivery, and thus the test should reflect oxidative metabolism rather than contraction-induced limited blood flow. The twitch EI test has the potential to evaluate muscle dysfunction in patients with pain in the shoulder and other clinical populations. The value of the EI as a measure of muscle fatigability will depend on future studies evaluating the utility of this methodology in clinical populations.

Declaration of Conflicting Interests

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Ethical Review and Patient Consent

The study was conducted with approval of the Institutional Review Board at the University of Georgia (Athens, GA, USA) and all of the subjects provided their written, informed consent before testing.

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