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Research article

Selective activation of the rectus abdominis muscle during low-intensity and fatiguing tasks

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Abstract
In order to understand the potential selective activation of the rectus abdominis muscle, we conducted two experiments. In the first, subjects performed two controlled isometric exercises: the curl up (supine trunk raise) and the leg raise (supine bent leg raise) at low intensity (in which only a few motor units are recruited). In the second experiment, subjects performed the same exercises, but they were required to maintain a certain force level in order to induce fatigue. We recorded the electromyographic (EMG) activities of the lower and upper portions of the rectus abdominis muscle during the exercises and used spatial-temporal and frequency analyses to describe muscle activation patterns. At low-intensity contractions, the ratio between the EMG intensities of the upper and lower portions during the curl up exercise was significantly larger than during the leg raise exercise ($p = 0.02$). A cross-correlation analysis indicated that the signals of the abdominal portions were related to each other and this relation did not differ between the tasks ($p = 0.12$). In the fatiguing condition, fatigue for the upper portion was higher than for the lower portion during the curl up exercise ($p = 0.008$). We conclude that different exercises evoked, to a certain degree, individualized activation of each part of the rectus abdominis muscle, but different portions of the rectus abdominis muscle contributed to the same task, acting like a functional unit. These results corroborate the relevance of varying exercise to modify activation patterns of the rectus abdominis muscle.

Key words: Motor control, electromyography, biomechanics, exercise.

Introduction

The selective activation of the rectus abdominis portions in a variety of abdominal exercises has been observed using electromyography (EMG) (Escamilla et al., 2006; Moreside et al., 2008; Vera-Garcia et al., 2000; Walters and Partridge, 1957; Warden et al., 1999). However, other studies, also based on EMG measurements, have not found differences in the activation of the different portions (Clark et al., 2003; Hubley-Kozey and Vezina, 2002; Lehman and McGill, 2001).

Selective activation of different portions of the rectus abdominis muscle is theoretically possible because, in morphological terms, the rectus abdominis is a polygastric (literally, “with several bellies”) muscle with three to four portions on the left and right sides of the body. These portions are separated by connective tissue that partially or completely interrupts the muscle fibers of the rectus abdominis (Hollinshead, 1980; Woodburne, 1994). Both corpse dissection and electrical nerve stimulation have shown that different portions of the muscle can be innervated by different nerves as well as by a common nerve branch (Duchateau et al., 1988; Hammond et al., 1995; Pradhan and Taly, 1989; Sakamoto et al., 1996).

While the cited studies about the selective activation of the rectus abdominis muscle used different experimental procedures, all of them used surface EMG to analyze the signal amplitude during motor tasks of median to high intensity. The fact that some motor units of different portions of the rectus abdominis muscle share the same innervation may obviate selectivity in rectus abdominis muscle recruitment, potentially explaining why some studies (for example, (Clark et al., 2003; Hubley-Kozey and Vezina, 2002; Lehman and McGill, 2001)) have not observed differences in activation in the different portions of the rectus abdominis.

An approach that may be useful to examine with more detail the possibility of selective activation of different portions of the rectus abdominis muscle is to study the muscle activation in low-intensity tasks (in which only a few motor units are recruited). The rationale is that in a low-intensity task that relies disproportionately on different parts of the muscle to perform, the subject will require more motor units situated only in this portion while needing fewer motor units that share innervation with other portions. Therefore, the first goal of this study is to investigate the selectivity of muscular activity in different areas of the rectus abdominis muscle during low-intensity exercises. We hypothesize that during low-intensity tasks, the motoneurons of the rectus abdominis muscle select a specific spatial pattern of activation according to the features of the motor task.

Another technique that may help us understand these controversial results of selective activation of the rectus abdominis is to study the behavior of the different areas of the muscle under induced fatigue in specific abdominal tasks. In this way, the potential selective behavior of these portions would be captured through frequency changes rather than amplitude changes in the EMG signals. Understanding how the rectus abdominis muscle and its different parts are activated during fatiguing tasks could also help to clarify the function of this muscle in high-intensity sport activities. We hypothesize that different portions of the rectus abdominis muscle present different patterns of fatigue according to the muscle portions that are more activated more frequently in each specific motor task.

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Methods

We performed two experiments where we analyzed EMG activity of the upper and lower rectus abdominis (RA) muscle portions during two controlled isometric abdominal exercises: the curl up (supine trunk raise with feet flat on the floor and not held down) and the leg raise (supine bent leg raise). The curl up exercise is supposed to activate the upper portions of the RA more while leg raises should activate the lower portions (Kendall et al., 1993; Sarti et al., 1996). In the first experiment, subjects performed the exercises at a low-intensity level; they were instructed to maintain the abdominal exercise with the lowest possible activation. In the second experiment, the subjects performed the same exercises at high-intensity until they fatigued. Isometric tasks were chosen in order to decrease the effect of skin movement on the EMG signals. We then selected dependent variables that would capture the characteristics of the EMG signals from the rectus abdominis muscle portions according to the exercise, intensity, and presence of fatigue.

Subjects

Eleven healthy, male, adult volunteers took part in the first experiment (mean ± S.D.: age 24 ± 3 years; height 1.72 ± 0.09 m; mass 71 ± 13 kg; abdominal skinfold 12.0 ± 0.6 mm), and 10 healthy, male, adults volunteered in the second experiment (age 26 ± 8 years; height 1.72 ± 0.08 m; mass 71 ± 9 kg; abdominal skinfold 11.0 ± 0.5 mm). There was no difference between groups concerning all these measurements. None of the volunteers reported any history of neurological or muscle-skeletal disease, and they all had previous experience with abdominal exercising. This study was approved by the local ethics committee of the University of São Paulo, and all volunteers gave their written informed consent before participation.

Procedures

In both experiments, the subjects performed both exercises. During the curl up the subject was instructed to keep his trunk at flexion (15 degrees). The leg raise exercise required subjects to keep their legs at flexion using a hip flexion (15 degrees).

Activation of rectus abdominis portions in low-intensity tasks

In the first experiment, both exercises were performed in a low-intensity isometric contraction for 10 s. Before these trials, the subjects were instructed to perform maximum voluntary isometric contractions for 5 seconds against an external resistance for the curl up and leg raise exercises. The subjects performed three maximum contractions for each exercise and the maximum value was considered. The resistance was provided by restraining belts attached to the subjects as shown in Figure 1. All trials were separated by 5 min of rest and were performed in random order. These maximum voluntary isometric contraction trials were used to verify the low-intensity level of the contractions and for normalization purposes.

The EMG signals from two portions of the right side of the rectus abdominis muscle were amplified and bandpass filtered (10 to 500 Hz) with Nihon MEB 4200 (Nihon-Kohden, Japan) and digitized with a 2 kHz sampling rate. We used passive double-differential electrodes with three contact bars with a 0.5 cm distance between them in an effort to increase the recording selectivity (Mesin, 2009). Each bar was 1 cm wide and 0.09 cm thick. The first double-differential electrode was placed on the belly of the second portion under the muscle origin (upper portion), and the second electrode was placed on the portion under the umbilicus (lower portion). Both electrodes were attached to the body along the muscle fiber direction after the skin area had been prepared. The digitized EMG signals were bandpass-filtered from 40 to 500 Hz using a 4^{th} order Butterworth filter with zero lag. The high-pass cutoff frequency was necessary to attenuate the electrocardiogram signal. Thereafter, the envelopes of the signals were estimated using a moving root-mean square algorithm with a moving window of 500 ms.

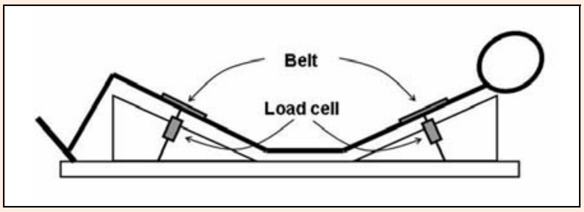


Figure 1. Illustration of the apparatus employed to measure the EMG activity during the curl up and leg raise exercises having the subject's force (measured by a load cell attached to the subjects' leg or chest) given as visual biofeedback in a monitor. Note that the subject's posture was never changed despite the exercise type.

The relationship between the activation of the two portions of the rectus abdominis muscle during the different tasks were compared by amplitude and cross-correlation analyses between the EMG signals that were recorded from the two portions. The comparison of the signal amplitudes from the different portions indicates whether one portion is activated more than another during the different tasks. To compare the amplitudes, we calculated a ratio by dividing the root-mean square (RMS) value of the EMG signal of the upper portion by the RMS value of EMG signal of the lower portion for each exercise. The cross-correlation between the signals served as an indicator of how much the signals are related during the different exercises (Kohn, 2006). Similarly, a comparison between the cross-correlation values will show whether this relationship varies for the different tasks. The signals were first whitened in order to temporally to uncorrelate each EMG signal, which is necessary for a correct interpretation of peaks in cross-correlation (Kohn 2006). Then, the cross-correlation function between the EMG signals was calculated with the function *xcov* (Matlab 6.5). The values were normalized by corresponding standard deviations, and a maximum lag of 200 ms was used. The maximum value of the cross-correlation function within this lag (± 200 ms) became the index of correlation between the signals.

Activation of the RA portions during fatiguing tasks-

During this experiment, the subjects were required to produce a force of 50% of their maximum voluntary isometric contraction force during the curl up and leg raise exercises for about 60s. These values were determined in pilot experiments to be sufficient to induce muscle fatigue in the subjects; *i.e.*, in this condition, the subjects were unable to maintain rectus abdominis muscle activation to produce the specified force level for more than 60 s. The force that was produced during the exercise was measured with a load cell that was attached to the subject's trunk or thighs and shown as visual feedback on a monitor in front of the subject (see Figure 1). The subjects performed the exercises in an adjustable apparatus in which body posture during periods of rest for both exercises was identical. The subjects performed the maximum voluntary isometric contraction trial for each curl up and leg raise exercise for 5 s in the same manner as described in the first experiment; and these trials were used to normalize the respective data from the tasks. Verbal encouragement and instructions were standardized. The subjects performed the tasks in random order with a 10 min resting period between all trials.

The force that was produced and the EMG activities of the upper and lower portions of the right side of the rectus abdominis muscle were acquired simultaneously during the exercises. The EMG signals were recorded with an 8-channel telemetric EMG system (Telemyo 900, Noraxon MyoResearch, USA). We used passive disposable dual Ag/AgCl snap electrodes with a 1-cm diameter for each circular conductive area and 2-cm center-to-center spacing. The electrodes were placed on the belly of each muscle along the muscle fiber direction after the skin area was prepared. EMG and force signals were acquired with a sampling rate of 1024 Hz. Data acquisition and visual feedback of force were managed using MyoResearch software (Noraxon MyoResearch, USA).

The digitized EMG data were first bandpass-filtered from 40 to 400 Hz using a 4^{th} order Butterworth filter with zero lag. The high-pass cutoff frequency was necessary to attenuate the electrocardiogram signal. For the maximal voluntary isometric contraction data, RMS values with a 1-s moving window for the EMG amplitude were estimated. Then, the maximum value from the maximal voluntary isometric contraction data was measured and used as a normalization factor for the respective EMG data. Both time and frequency characteristics of the normalized EMG data were analyzed, hence amplitude and frequency of the EMG data changed with fatigue, even before decrease of the muscle force (De Luca, 1997; Dimitrova and Dimitrov, 2003). For the temporal analysis, the EMG RMS values were estimated based on a 1-s moving window. A linear regression of the RMS-versus-time data was computed, and the slope of the straight line (indicating the rate of amplitude change per second) was used as a first index of fatigue (Dimitrova and Dimitrov, 2003). For the time-frequency analysis, EMG data were analyzed with a short-time Fourier transform applied to 1-s epochs. The median frequency of the spectrum for each epoch was computed, and the linear regression of the median frequencies versus time was determined. The slope of the straight line (indicating the rate of frequency change per second) was adopted as a second index of fatigue (Dimitrova and Dimitrov, 2003; Roy et al., 1995).

Statistical analysis

Normality and homogeneity of variances of the data were confirmed by the Kolmogorov-Smirnov and the Lilliefors tests, respectively. We performed a comparison between muscle portions for each task using paired t-tests for the ratios and cross-correlation values. Repeated measures ANOVA (2 x 2) was utilized to determine the effect of task and portion on the indexes of fatigue derived from the time and frequency analyses. Post hoc comparisons were performed using paired t-tests (only one extra comparison was necessary due to the simple design). To accommodate for this double testing performed here, a 0.025 level of significance was used for all statistical tests.

Results

Activation of rectus abdominis portions in low-intensity tasks

During the low intensity tasks, the RMS EMG amplitude of the upper and lower portions of the rectus abdominis muscle during the curl up and leg raise exercises averaged across subjects was 25±6% of their respective RMS EMG amplitude during the maximum voluntary isometric contractions.

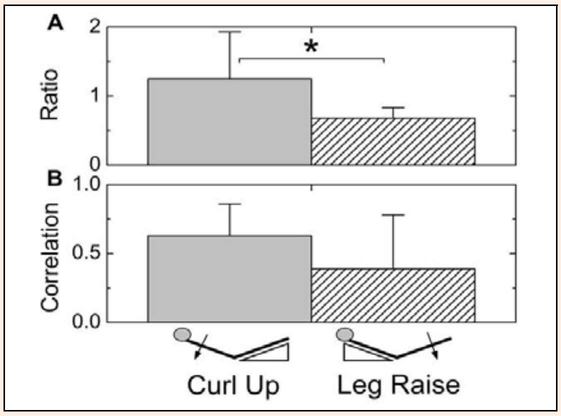
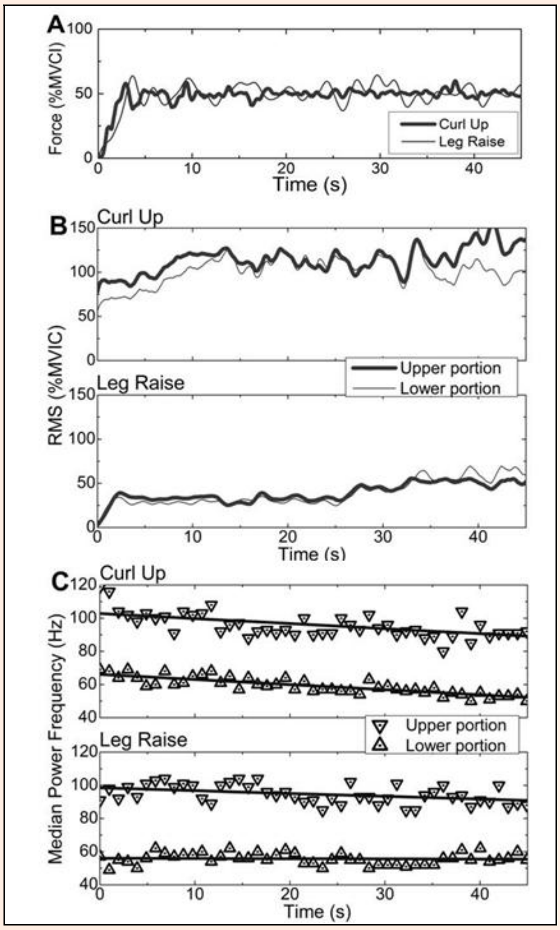


Figure 2. Mean and standard deviation of the ratio between the root-mean square (RMS) values (A) and of the cross-correlation value (B) of the upper and lower portions EMG data during the Curl Up and Leg Raise tasks (* p = 0.02).

The ratio between the RMS values of the upper and lower portions of the EMG data during the curl up exercise was significantly larger than during the leg raise exercise (mean ± SD for the curl up:1.25 ± 0.68 ; mean ± SD for the leg raise: 0.68 ± 0.15; $t(10) = 2.7$; $p = 0.02$), see Figure 2. The peak values of the cross-correlation function between the EMG signals of the upper and lower portions were high and indicated that the signals were statistically correlated and this correlation was not different between tasks (mean ± SD for the curl up: 0.6 ± 0.2; mean ± SD for the leg raise: 0.4 ± 0.4; $t(10) = 1.7$; $p = 0.12$).

Activation of the RA portions during fatiguing task

Figure 3 shows exemplary recording of the force and the corresponding time series of the moving RMS and the median frequencies of the EMG data for each muscle portion and exercise investigated for one subject.



Figures 3. Exemplary time-series from one subject during the Curl Up and Leg Raise abdominal exercises. The force signals (A), the moving RMS (B), and the EMG median frequencies (C) of the EMGs of the two rectus abdominis portions.

Figure 4 shows the mean and standard deviation across subjects of the indexes of fatigue for both time and frequency analyses. ANOVA only revealed an interaction effect between the task and rectus abdominis muscle portion in the index of fatigue based on the median frequency variable ($F(1,9) = 10.2$; $p = 0.01$). Post hoc analyses revealed that this index of fatigue of the upper portion was higher than that for the lower portion during the curl up exercise ($t(9) = -3.38$; $p = 0.008$) and that the upper portion presented a higher index of fatigue in the curl up exercise than in the leg raise exercise ($t(9) = -2.8$; $p = 0.02$).

Discussion

Our first hypothesis was indeed confirmed; at low-intensity contractions, the ratio between the EMG of the upper and lower portions during the curl up exercise was significantly larger than during the leg raise exercise. The difference in the ratio between RMS values of the EMG data of the upper and lower portions during the curl up and leg raise exercises suggests that the different portions were selectively recruited during these two tasks.

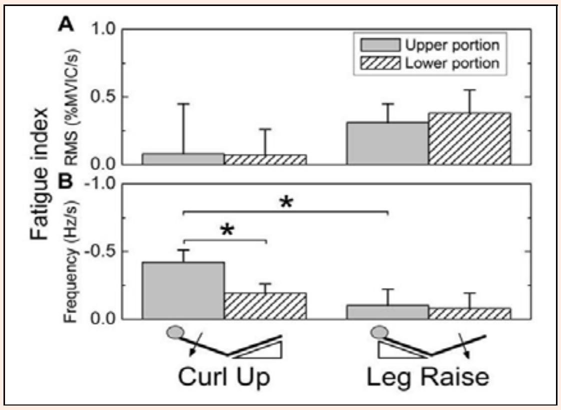


Figure 4. Mean and standard deviation of the root-mean square (RMS) fatigue index (A) and of the median frequency fatigue index (B) during the Curl Up and Leg Raise exercises for the two rectus abdominis portions (* $p < 0.025$).

However, the peak values of the cross-correlation function indicate that the EMG signals from the upper and lower portions were correlated during the curl up and leg raise exercises. This correlation between EMG signals of the upper and lower portions indicates the existence of a common neural command for both portions, in addition to individual neural commands for each area (with about 50% common command and 50% individual command). This interpretation can be described with a simple model (Kohn, 2006). Let $y(n) = \alpha x(n) + w(n)$ indicate the relation between the EMG signals x and y, where $x(n)$ and $y(n)$ indicate that the two EMG signals are in discrete-time and $w(n)$ is an independent random process. This random process embodies the individual commands for the two muscle portions, meaning that if $w(n)$ is zero, the EMG of a muscle portion is α times the EMG of the other portion (we are assuming no time delays, for simplicity). The cross-correlation peak value indicates what fraction of $y(n)$ is directly related to $x(n)$, meaning that when the cross-correlation peak is equal to 1, the two muscle parts are being driven by a common source. On the other hand, if the cross-correlation peak value is lower than 1, the proportion of individual drive is increased with respect to the common source. Finally, when the cross-correlation peak is zero, no common source exists, and each muscle portion is driven independently of each other.

These results suggest that a dual control system may be operating simultaneously on the different portions of the rectus abdominis muscle: one that activates two or more portions in a parallel way (a common drive) (De Luca and Erim, 2002) and another that provides independent control of the portions. That is, each portion of the rectus abdominis muscle can be partially controlled by the nervous system in an independent way while different portions simultaneously contribute to the same task, acting like a functional unit. This mathematical evidence for a common drive as well as independent control of the rectus abdominis portions is consistent with neuro-anatomical descriptions of rectus abdominis muscle innervations based on corpse dissection and electrical nerve stimulation (Duchateau et al., 1988; Hammond et al., 1995; Pradhan and Taly, 1989; Sakamoto et al., 1996). These studies have shown that different portions can be innervated by different nerves as well as by a common nerve branch, supporting the common drive and independent control of the rectus abdominis portions.

Our second hypothesis was that portions of the rectus abdominis muscle present different patterns of fatigue according to the muscle portions that are more activated in each specific motor task. This hypothesis was also confirmed; the fatigue condition captured by the rate of change in the frequencies of the EMG signals revealed differences between exercises and various rectus abdominis areas. The observation of a higher index of fatigue for the frequency variable (indicating a larger frequency decline) for the upper portion compared with the lower portion during the curl up exercise and the higher index of fatigue for the upper portion during the curl up than during the leg raise exercise corroborates the idea of task-dependent selective fatigue in the rectus abdominis muscle. However, such differences were observed only for the median frequency of the EMG data. The index of fatigue based on the moving RMS of EMG amplitude was much more variable than the index of fatigue based on the median frequency, as shown by the standard deviations in Figure 4. Such variability in fatigue conditions confirms earlier results from Dimitrova and Dimitrov (2003), who reported that EMG amplitude is not a reliable measurement to detect neuromuscular fatigue.

A unique finding of this study is that by investigating very controlled tasks (low-intensity and fatiguing isometric abdominal exercises without changing body posture) and employing specific signal processing tools through cross-correlation function and time-frequency analysis, we observed that both common drive and independent control of the rectus abdominis muscle are present during rectus abdominis activation. This dual presence may explain why different studies have found selective activation of the rectus abdominis muscle (Escamilla et al., 2006; Moreside et al., 2008; Vera-Garcia et al., 2000; Walters and Partridge, 1957; Warden et al., 1999) while others have not (for example, Clark et al., 2003; Hubley-Kozey and Vezina, 2002; Lehman and McGill, 2001).

We speculate that variations in the intensity of abdominal exercises, subject differences in the rectus abdominis neuroanatomical innervation, or subject variation on recruiting different rectus abdominis motor units might cause either the common drive or the independent control to dominate the other. Further research is needed to elucidate these issues.

Conclusion

We conclude that changes in body position and exercise intensity create different demands for the control of different portions of the rectus abdominis muscle, which corroborates the relevance of exercise variation to modify muscle activation patterns.

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Key points

- Selective activation of the rectus abdominis muscle is possible because this muscle has different portions (which can have different motor fibers in series) which can be innervated by different nerves as well as by a common nerve branch.
- Changes in body position and exercise intensity create different demands for the different portions of the rectus abdominis muscle.
- Exercise variation seems to be valid to modify the activation patterns of the rectus abdominis muscle.

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