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Diagnostic Ultrasound Shows Preferential Activation of Rectus Abdominis Segments with Exercises Targeting Upper Versus Lower Segments

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ABSTRACT

International Journal of Exercise Science 16(1): 1077-1086, 2023. Preferential activation of rectus abdominis sections during crunch or leg lifts has long been disputed. The objectives of this study were to both explore the activation of the rectus abdominis during these exercises. This study used a randomised independent measures design utilising both EMG and diagnostic ultrasound to record changes in rectus abdominis activity. Fifteen participants each performed multiple repetitions of a 45° crunch, a 90° sit-up, and finally a 90° leg raise, sufficient for an 8-second ultrasound recording utilising M-mode of all four unilateral abdominal segments during each of the exercises, resulting in 12 images per participant. There was a significant interaction between segment number and type of exercise when testing for percent difference ($F_{6, 440} = 4.718$, $p < .01$, $\eta^2 = .065$). The mean thickness change of abdominis during a crunch manoeuvre was greater than the leg raise by 36.39 ± 3.21 % ($p < .01$). The mean thickness during the sit-up was also greater than the leg raise (32.49 ± 3.04 %). Rectus abdominis shortening and thickening was observed in all the exercises tested but was most pronounced in the abdominal crunch. Muscle recruitment seems to be biased closer to the load.

KEY WORDS: Upper abdominal, lower abdominal, leg lift, sit up, preferential activation

INTRODUCTION

The lumbopelvic-hip complex, most commonly referred to as the core, is a group of structures comprised of the spine, abdominal structures, hips and pelvis, proximal lower limb structures, and the active and passive structures that either produce or restrict motion of the above structures (12,24). Many of the muscles that act as prime movers for the most proximal limb segments of the body attach to the core. More specifically, these prime movers include, for the upper limbs, the latissimus dorsi, pectoralis major, and for the lower limbs, iliopsoas, quadriceps and hamstrings. Additional stabilising muscles for the distal segments (the lower trapezius, hip rotators, and glutei) also have an attachment in the core (12). However, the core mostly consists of proximal stabilisers for the spine and pelvis involved in the kinetic chain during mobile action at distal segments of the body in activities such as throwing, kicking, or running (8,12,20). During these activities the core muscles will act to absorb ground-impact forces and reduce translation, compression, and shearing forces along the segments of the kinetic chain (9). Performing these types of movements can subject the body to sudden perturbations which may potentially move the centre of gravity outside the base of support. To avoid falling, postural adjustments, made to move the centre of gravity back within the base of support, require recruitment of the core muscles in order to stabilise the structures implicated in the change of position (12). Thus, having a properly functioning core will help athletes maintain postural stability and aid in the appropriate generation of force while subjected to perturbations.

The rectus abdominis (RA) is a long and flat muscle, considered a key component of the lumbopelvic-hip complex. It is divided into segments by one vertical and three horizontal tendinous inscriptions, the intersections of which create four bilateral sections. The RA originates from the pubic crest and symphysis, and inserts at the xiphoid process and costal cartilages of the 5th to 7th ribs, innervated by the intercostal nerves, specifically T6 and T7 – T12. This muscle acts to flex and twist the lumbar region of the vertebral column, to fix and depress the ribs, to stabilise the pelvis during mobile action, and finally to increase intra-abdominal pressure in tandem with other abdominal muscles (16).

Duchateau et al. (6) found through anatomical dissection that the segments of the RA are both innervated independently and share a common nerve branch. This finding suggested the possibility of independent recruitment of the segments of the RA. The topic of differential activation of the RA has been debated for over twenty years since Sarti et al. (21) found differences in upper and lower RA activation in subjects who performed various dynamic exercises with trunk and limb movement. While others have presented evidence of no differentiation in activation of RA segments (2,13), more recent evidence suggests differential recruitment may occur (7,15,23). Current conditioning guidelines for strengthening the RA are mostly based on differential activation depending on exercise. Individuals who perform various abdominal exercises report a subjective feeling of tension differences in the upper and lower RA depending on the exercise being performed. Understanding the activity of the RA is important to substantiate current conditioning guidelines aimed at increasing the effectiveness of the core.

Diagnostic ultrasonography is an imaging modality that has been used for more than 20 years (1,14,22). It has been referred to as a primarily qualitative form of analysis in past research (10). More specifically, this technique has been found to be particularly effective in identifying changes in muscle tissue, such as inflammation and fibrosis (1). However, recent research suggests that ultrasonography can quantify the differences between relaxed and contracted muscle tissue (1). In addition to measuring muscle thickness, this can be achieved by means of elastosonography which measures the stiffness change in the tissue, including muscle tissue, where a contracted muscle is stiffer than a relaxed muscle (5). Often when ultrasound data is explored quantitatively, the data is analysed in conjunction with image analysis software. A transducer frequency between 7 and 12 MHz (14) is thought to be most appropriate for muscle tissue but little research exists exploring the rectus abdominis (RA) muscle tissue via this medium (3,17). Coldron et al. (3) have successfully used ultrasonography to measure the thickness of the RA muscle belly when investigating diastasis in postnatal women. While not as detailed, compared to other imaging techniques, such as computerised tomography or magnetic resonance imaging, ultrasonography is considered to be relatively inexpensive and more portable (1). The evidence presented in previous literature concerning ultrasound and its relative ease of access suggests that it is a favourable method of muscle tissue analysis, and thus was the primary focus of this study.

The main objective of this study was to provide new information to contribute to resolving the conflict in literature regarding differentiation in activation of the segments of the rectus abdominis. We hypothesised that muscle shortening would occur in the segments of the rectus abdominis during exercises traditionally targeting those segments. More specifically, that muscle shortening would occur in the segments closest to the load being moved i.e., greater shortening of segment 1 relative to the other segments would occur during the crunch exercise, whereas segment 4 would see the greatest shortening during the leg raise exercise.

METHODS

Participants
This work adhered to the policies and guidelines for ethics in research detailed by Navalta et al. (18). This study was reviewed and approved by the University Ethics committee. Participants were recruited through class presentations to target individuals with low subcutaneous fat levels. There were a total of 15 participants (9 male and 6 female) that took part in the study, with a mean age of 20.67 ± 1.05 years. A within effects power analysis calculation with the "wp.kanova" function in R's Webpower package showed an effect size of 0.98 with three groups: exercise (3 levels), type of measure (4 levels), and abdominal section (4 levels); assuming a medium effect size (0.25). All participants were asked to complete both a consent form and a PAR-Q+ to screen for contraindications to exercise.

Protocol
A model RUS9000F diagnostic ultrasound machine manufactured by RisingMed Inc. with a 7.5 MHz transducer was used to record the contraction of each rectus abdominis segment on the left side for every exercise (Figure 1).

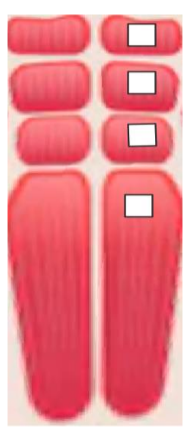

Figure 1. Schematic representation of the abdominal muscles. The white squares represent the ultrasound transducer placement.

The machine's B-mode was used to locate the measurement area for each segment, so that the edges of the muscle belly could be avoided as much as possible. Whereas B-mode provides a two dimensional image, in this study the data was recorded in M-mode utilizing a longitudinal scan method, because the objective was to see if the volume under observation changed during the contraction. Having a time varying image allowed us to measure not only muscle thickness variations during the trials but also the slope of that thickness change. Fifteen participants were asked to perform one repetition of each exercise for each of the four segments: a total of 12 repetitions were recorded for each participant. Each recording lasted 8 seconds providing a snapshot of the contraction. All the ultrasound images were imported into Image-J for further analysis where a calibration grid and pixel-mm ratio were applied to each image so that muscle thickness measurements could be made. A total of 14 coordinates were plotted on each image, which provided X and Y values necessary to calculate measures of interest (see Figure 2).

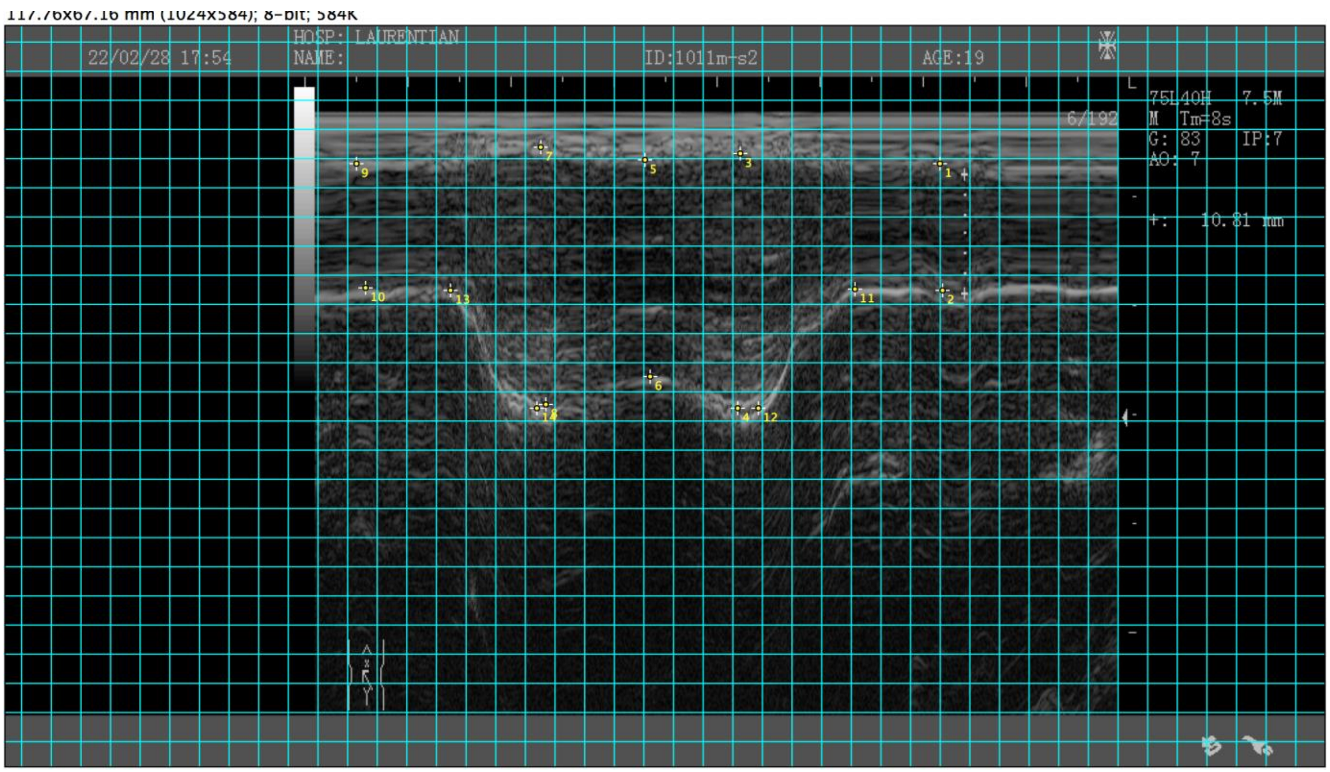

Figure 2. The image-J import of ultrasound images with the overlaid relevant coordinates plots of interest for the measurement of thickness change for one independent exercise. Time progresses along the x axis of the image. Differences between plots were used to calculate both the change and rate of change in thickness.

The measures created for each image were the thickness of the rectus abdominis at rest before (R1) and after the recorded contraction (R2), respectively. The C-measure was the thickness of the muscle tissue during the concentric portion of the contraction, whereas the E-measure was the thickness during the eccentric portion. The T-measure was the thickness of the muscle tissue at the top of the movement, which was measured in between the concentric and eccentric portions. Both S1 and S2 slope measures were created to find the rate of change of thickness for each recorded contraction. S1 was measured from the beginning of the contraction to the top of the concentric contraction, whereas S2 was measured from the top of the eccentric contraction to the end of the contraction. Each value was calculated using $\frac{\Delta Y}{\Delta X}$, where ΔY is the vertical distance and ΔX is the horizontal distance, both expressed in millimetres.

Statistical Analysis

Each of the measures (C, T, and E) were expressed as a percent difference from the thickness at rest before the contraction (R1), and the slope values were expressed as calculated. The percent difference values (DV1) and slope values (DV2) were normalised using a fractional ranking and an inverse function. Both dependent variables (thickness and slope) were tested in SPSS using a multivariate ANOVA consisting of three independent variables: (1) type of exercise, (2) type of measure, and (3) segment number. A Tukey test was performed to identify differences between pairs.

RESULTS

There was a significant interaction between segment number and type of exercise when testing for percent difference ($F_{6, 440} = 4.718$, $p < .01$, $\eta^2 = .065$). The percent difference data passed the Shapiro-Wilk test ($p > .05$) and was assumed to be normally distributed. However, homogeneity of variance was not met ($F_{(35, 405)} = 2.274$, $p < .01$). The mean thickness change for the crunch manoeuvre was greater than the leg raise by 36.39 ± 3.21 % ($p < .01$). The mean thickness during the sit-up manoeuvre was greater than the leg raise by 32.49 ± 3.04 %. Not all data was usable for the data analysis due to complications with the equipment and test protocol. A summary of the data from analysis of both DVs can be seen in Table 1. A plot of means (Figure 2), showed that the greatest percent difference in the crunch exercise occurred in segment 1, whereas the greatest percent difference in the leg raise exercise occurred in segment 4. The leg raise exercise showed an increase in percent difference from segment 1 to segment 4. The sit up data was much more variable than the other two exercises.

The slope data was assumed to be normally distributed (Shapiro-Wilk; $p > .05$) however, as with the percent difference data, homogeneity of variance was not met ($F_{(23, 211)} = 3.308$, $p < .01$). Both exercise types ($F_{(2, 234)} = 44.578$, $p < .01$) and segment number ($F_{(3, 234)} = 5.053$, $p < .01$) were significantly different from each other. The mean slope of the crunch manoeuvre was found to be significantly greater than the slope of the leg raise by 0.403 ± 0.048. The mean slope during the sit-up manoeuvre was also found to be significantly greater than the leg raise by 0.418 ± 0.048. Across all exercises, segments 2 and 4 had significantly greater slope values than segment 1 by 0.237 ± 0.059 and 0.197 ± 0.057, respectively. A plot of mean slope data (Figure 3) shows the leg raise exercise had the greatest slope values in segment 4, while the crunch exercise had the greatest slope values in segment 2. As with the difference seen in Figure 2, Figure 3 shows that the sit-up exercise had a trend of slope values that were different from the rest of the exercises. The sit-up exercise saw a close to linear increase in slope values from segment 1 to segment 4.

Table 1. Percent differences and slopes compared between exercises and between rectus abdominis segments.

	(I) Exercise	**(J) Exercise**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**
Percent Difference	Crunch	Leg raise	37.459*	3.217	.000
		Sit-up	5.200	3.193	.104
	Leg raise	Sit-up	-32.259*	3.054	.000
	(I) Segment	**(J) Segment**	[redacted]		
	1	2	-12.524*	3.699	.001
		3	-10.648*	3.689	.004
		4	-14.411*	3.778	.000
	2	3	1.876	3.504	.593
		4	-1.887	3.597	.600
	3	4	-3.763	3.587	.295
	(I) Exercise	**(J) Exercise**	**Mean Difference (I-J)**	**Std. Error**	**Sig.**
Slope	Crunch	Leg raise	-.4028*	.04840	.000
		Sit-up	-.0149	.04716	.946
	Leg raise	Sit-up	-.4177	.04797	.000
	(I) Segment	**(J) Segment**	[redacted]		
	1	2	-2.368*	.05894	.000
		3	-.1145	.05710	.189
		4	-.1973*	.05710	.004
	2	3	.1223	.05409	.111
		4	.0395	.05429	.886
	3	4	-.0828	.05228	.390

* = significant difference

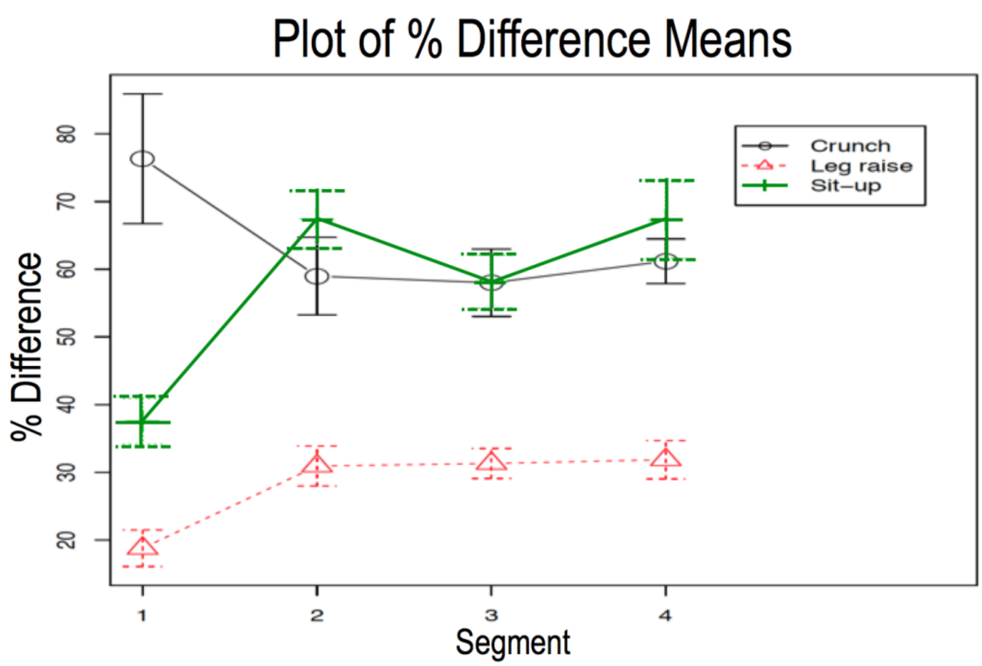

Figure 2. Change in thickness of each segment represented by a percent difference from resting thickness. Data shown as mean ± SEM for the exercises of interest and is representative of one independent experiment.

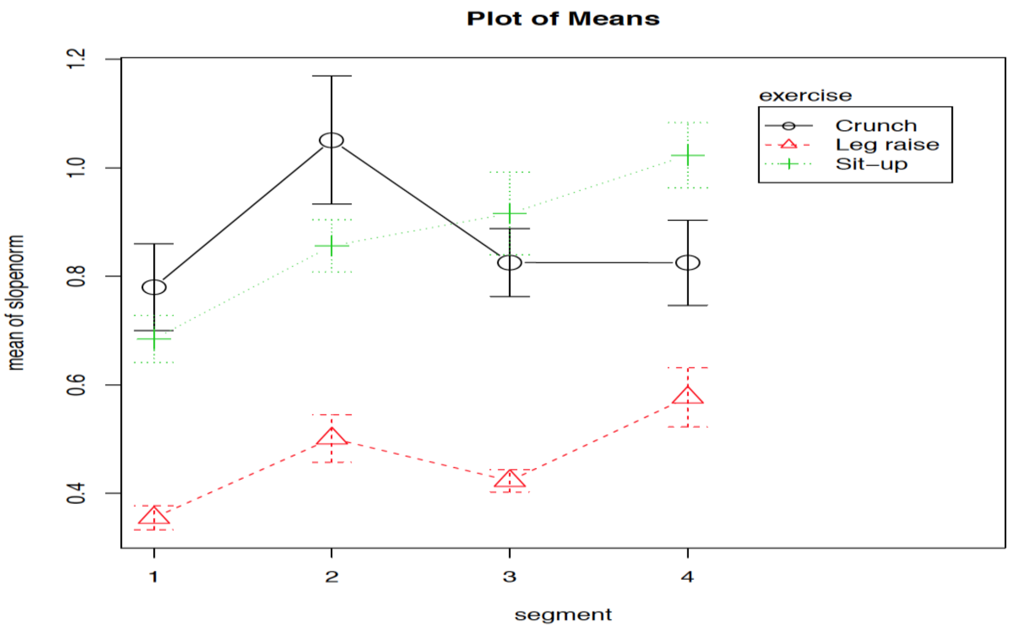

Figure 3. Slopes of the change in thickness for all recorded contractions. Recall slopes are between pre-contraction and concentric thickness and between eccentric thickness and post-contraction. Data shown as mean ± SEM for the exercises of interest and is representative of one independent experiment.

DISCUSSION

As hypothesized, the segments closest to the load being moved saw the greatest change in thickness. The results of this study suggest that differentiation in activation of the segments of the RA is possible, and the degree of differentiation depends on the exercise being performed. Specifically, segment 1 had the greatest change in thickness during the crunch exercise, whereas segment 4 had the greatest thickness change during the leg raise exercise. However, the slope values calculated were much more variable compared to the thickness change data. It is important to note that the slope values do not represent the absolute speed of contraction, but rather a rate of change in thickness that allows comparison between conditions. While the variability in the activation of rectus abdominis segments may be the product of an independent innervation (6,15) it is most likely task specific versus voluntary recruitment. Additionally, the linear trend of the slopes of the sit-up exercise suggests that the independent recruitment may also work in conjunction with the common nerve branch. In general, the varied change in thickness and the relative rate of this occurrence are consistent with a subjective feeling of greater tension in the upper RA sections during a crunch manoeuvre or lower RA sections during a leg raise exercise.

The results of this study substantiate previous evidence using electromyography (EMG) analysis suggesting that differential activation of the RA is possible (7,15,23). EMG has proven to be an effective standard of measuring muscle activity, but has its limitations. Although EMG can provide insight into the relative activation level of a contraction and the state of the muscle of interest, it fails to distinguish changes between areas of a single muscle either in terms of dimension or length change. Diagnostic ultrasound provides the possibility to visualise changes in muscle activation in different planes of motion (3,19). An example of this is the use of diagnostic ultrasound to measure muscle velocities during contractions (19). Interestingly, Kianbostanab et al. (11), found a strong correlation between EMG root-mean square (RMS) values and thickness change in skeletal muscle, suggesting that greater thickness change will occur with higher RMS values. However, this correlation seems to be weaker for flat muscles. The results of this study provide evidence to support that a correlation exists between EMG activity and thickness change in flat muscle. It would be most beneficial for future studies related to contraction and other changes in muscle tissue to use methods that include both an EMG and diagnostic ultrasound analysis. The pairing of both analysis types has the potential to provide a detailed observation in both muscle kinematics and kinetics.

One of the main limitations of this study was the exercise movements inducing some movement of the US probe facilitated by the gel used for signal conduction. Fortunately these images were easily identified as being unusable. Additionally, the specific location or area of measure sometimes was changed in order to record the clearest images but in every case the tendinous inscriptions of the RA were used to discern and limit an area of measurement for each segment. However, it was found that there was variability across participants in both subcutaneous fat levels and the location of the inscriptions. Due to this, the transducer was moved to provide an optimal view of the muscle tissue in a particular section of RA for the recording. Finally, the absolute speed of contraction is unobtainable through the methodology used. Although the slope values can provide a relative comparison in rate of change, finding the absolute speed of contraction in each segment may provide further insight into the independent control of the rectus abdominis.

Differential activation of the rectus abdominis (RA) is possible and may be dependent on the functional task at hand. Differences in muscle thickness and shortening may depend on body angle, the type of exercise performed and load placement. Anecdotal reports of conditioning programs that target the upper and lower sections of the RA are supported by these results, and the choice of exercise type may lead to improved performance of the RA. It would be most beneficial for future studies to pair electromyography with diagnostic ultrasound to provide a more detailed analysis of changes in the muscle tissue. Future studies would benefit from measuring velocities of the RA segment contractions using diagnostic ultrasound and other muscles in general.

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