

Structure and Function of the Abdominal Muscles in Primigravid Subjects During Pregnancy and the Immediate Postbirth Period

Background and Purpose. The purpose of this study was to investigate the abdominal muscle structural adaptations and functional capabilities during pregnancy and the postbirth period. **Subjects.** Six primigravid subjects, aged 28 to 33 years, participated in nine test sessions from 14 weeks of gestation to 8 weeks postbirth. **Methods.** At each test session, three-dimensional photography of abdominal skin markers was used to determine the gross morphology of a representative abdominal muscle, the rectus abdominis muscle. The functional capability of the abdominal muscle group was assessed on the ability of the muscle group to stabilize the pelvis against resistance. **Results.** Increases were found in rectus abdominis muscle separation width, length, and angles of insertion as pregnancy progressed. Reversal in rectus abdominis muscle separation was found by 4 weeks postbirth. The ability to stabilize the pelvis against resistance was shown to be decreased as pregnancy progressed and remained compromised postbirth. Decrements in abdominal muscle function paralleled in time the structural adaptations, as pregnancy progressed. Continued functional deficits were found in parallel with incomplete resolution of structural adaptations postbirth. **Conclusion and Discussion.** Abdominal muscle function is affected by structural adaptations that occur during pregnancy. Because our results showed that the ability to stabilize the pelvis against resistance is decreased during pregnancy and at least 8 weeks postbirth, abdominal muscle exercises should be chosen with care. [Gilleard WL, Brown JMM. Structure and function of the abdominal muscles in primigravid subjects during pregnancy and the immediate postbirth period. *Phys Ther.* 1996;76:750–762.]

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The anterior abdominal wall consists primarily of four paired muscles, with fibers directed vertically, horizontally, and obliquely.¹ The muscles have skeletal attachments on the thoracic cage and pelvis and via broad aponeuroses to both the thoracolumbar fascia and the rectus sheath.¹ As pregnancy progresses, the weight and dimensions of the uterus and its contents increase, influencing maternal trunk musculoskeletal morphology. The maternal inferior thoracic diameter is increased,^{2,3} thus altering the spatial relationship between the superior and inferior abdominal muscle attachments. In addition, anterior and lateral dimensions of the abdomen during pregnancy⁴ increase the distance between muscle attachments, producing increases in muscle lengths.⁵ Increasing anterior abdominal dimensions may alter the angle of abdominal muscle attachment in the sagittal plane. In some women, the rectus abdominis muscles move laterally during pregnancy and may remain separated in the immediate postbirth period.⁶⁻⁸ This alteration in the abdominal muscles' medial aponeurotic attachment also may influence the angle of bony attachments, made by the muscles, in the coronal plane. Alterations in the spatial relationship of muscle attachment and the muscles' angle of insertion may alter the muscles' line of action and therefore their ability to produce torque.⁹

The functional roles of the abdominal muscles during pregnancy appear to be similar to those in the nonpreg-

nant state¹⁰ and include trunk movement, pelvic stabilization, and restraint of the abdominal contents.¹ Many women continue, or even begin, abdominal exercise programs during their pregnancies. In addition, mothers often are encouraged to resume abdominal exercises shortly after delivery.¹¹ Abdominal muscle exercise prescriptions are a key component of prenatal and postnatal physical therapy programs. The ability to perform these functional roles and exercise programs during pregnancy and the immediate postbirth period has been questioned, however, due to musculoskeletal structural adaptations occurring in the trunk.¹⁰

Fast et al⁵ reported that abdominal muscles during the third trimester of pregnancy were weakened relative to the abdominal muscles of nonpregnant control subjects. Other researchers, assessing abdominal muscle strength at 6 and 12 weeks postbirth, have reported no differences between women postpartum and nulliparous control subjects,^{8,12} despite evidence of incomplete musculoskeletal readaptation in the postbirth period.^{6,8} It is therefore possible that some level of musculoskeletal structural changes may occur without affecting the muscle function.

Knowledge of the abdominal muscles' morphological adaptations and their functional abilities as well as of the relationship between muscle structural changes and functional ability is essential for the continued develop-

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Table 1.
Subject Profile Data^a

Subject No.	Age (y)	Length of Gestation (wk)	Neonatal Weight (kg)	Average No. of Exercise Sessions								
				Gestational Week						Postbirth Week		
				14	18	22	26	30	34	38	4	8
1	28	36	2.20	3+	3+	3+	3+	2	*	*	0	0
2	28	36	2.59		3+	2	2	3+	3+	*	3+	3+
3	28	40	2.66	2	3+	1	1	2	1	*	0	0
4	33	40	2.68	3+	3+	3+	3+	3+	2	1	0	1
5	28	42	3.34			3+	3+	3+	3+	3+	1	1
6	30	40	3.31	3+	3+	3+	3+	3+	3+	3+	3+	3+

^a 3+ denotes three or more exercise sessions per week. Asterisk (*) denotes data missing due to withdrawal on medical grounds or preterm delivery.

Table 2.
Mean (\pm SD) of Absolute and Normalized Rectus Abdominis Muscle Medial Edge Length^a

Gestational Week	Absolute (cm)	Na	Normalized (%)	Nb
14	33.9 \pm 0.1	2	100 \pm 0.0	2
18	32.8 \pm 1.3	4	100 \pm 0.001	4
22	34.7 \pm 0.7	3	106 \pm 0.051	3
26	37.0 \pm 2.0	6	109 \pm 0.057	5
30	37.2 \pm 2.7	5	112 \pm 0.070	4
34	37.7 \pm 2.1	5	114 \pm 0.049	4
38	38.4 \pm 2.7	3	115 \pm 0.027	2

^a Na=number of subjects in absolute length calculations; Nb=number of subjects in normalized length calculations. Note: One subject was excluded from the normalized length calculations, as she had visible changes in abdominal shape at her first test session at 22 weeks.

ment of prenatal and postnatal physical therapy programs. There is, however, a paucity of literature describing abdominal muscle structure and function investigated longitudinally during pregnancy and the immediate postbirth period.

The objectives of this study were to investigate longitudinally the structural and functional adaptations of abdominal muscles during pregnancy and the immediate postbirth period. We assumed that the adaptations of one muscle did not occur in isolation from other muscles. The gross morphology of the abdominal muscle group is very complex, with multiple muscle attachments and varying muscle fiber orientations. Therefore, to simplify the study, a representative muscle was chosen. The first aim of our study was to investigate structural changes in a representative abdominal muscle, the rectus abdominis muscle. The variables measured were the separation width, the muscle length, and the angle of insertion at both the superior and inferior attachments. The second aim of this study was twofold: to examine the functional abilities of the abdominal muscles during pregnancy and into the postpartum period and to determine the temporal relationship between abdominal

muscle function and the musculoskeletal adaptations to pregnancy.

Method

Subjects

Six primigravid subjects, aged 28 to 33 years, each with a single fetus, volunteered for the study. A detailed subject profile is presented in Table 1. Length of gestation ranged from 36 to 42 weeks, and neonate weight ranged from 2.20 to 3.34 kg. Subjects were tested every 4 weeks from their initial test session, which occurred at week 14, 18, or 22 of gestation, to 8 weeks postbirth. Due to medical conditions and preterm deliveries, three subjects temporarily withdrew from the study (one subject by week 34 and two more subjects by week 38). Photographic failures also resulted in some missing data. The number of subjects at each test session during pregnancy (Na) is summarized in Table 2. All subjects participated in postbirth test sessions. Subjects with a history of low back injury or recent abdominal surgery and those who exhibited excessive subcutaneous abdominal adipose tissue were excluded from the study. All subjects and their supervising physician gave informed consent prior to participation in the study.

As exercise is believed to minimize the effects of pregnancy on abdominal muscle structure and function,¹³ the exercise history of each subject was noted at each test session. The average number and type of aerobic exercise sessions in which the subject had participated in the previous 4 weeks were recorded. An exercise session was included if its duration was 30 minutes or greater.

Rectus Abdominis Muscle Model

The rectus abdominis muscle was chosen as the representative abdominal muscle. The rectus abdominis muscle is a superficial abdominal muscle that may be palpated without difficulty during pregnancy.^{6,7} The gross structure of the muscle may be inferred from labels outlined cutaneously on lean subjects. To obtain an

exact model of the gross structure of the rectus abdominis muscle would be very complex and time-consuming, as the surface of the human body is highly irregular and complex. In addition, the abdomen of a pregnant woman is continually changing shape to and beyond term. A detailed representation of the muscle's form would involve a large number of measurement points.¹⁴ Therefore, a simple three-dimensional, two-view model (Fig. 1) was developed based on nine label points chosen from a review of the literature.^{1,5-7} These labels were marked with ink on the skin of the supine subjects. The labels included the superior and inferior attachment points of the rectus abdominis muscle and the most anterior point of the abdomen (vertex). We also used the positions of the medial edges of the right and left rectus abdominis muscles at the umbilicus and 4.5 cm above and below the umbilicus.

To locate the positions for the labels, the medial edges of the right and left rectus abdominis muscles were palpated at the umbilicus and 4.5 cm above and below the umbilicus, with the subject positioned supine with the head raised to facilitate muscle palpation. The medial edges of the left and right rectus abdominis muscles were marked where the separation between the muscle bellies was 1.0 cm or greater for sites above and below the umbilicus, or 1.5 cm or greater if located at the umbilicus. With the subject relaxed, the medial edges of the superior and inferior attachment points of the right rectus abdominis muscle were palpated and marked. For the muscle's lower attachment, the pubic hair was gelled smooth and the muscle attachment point was then marked on adhered tape, as shown in Figure 2. As the study continued, we decided that the lower muscle attachment point was adequately marked by adhering the marking tape to firmly fitted underwear. The most anterior point of the abdomen in the sagittal plane (vertex) also was visually determined and marked when no separation of the rectus abdominis muscle bellies, as defined earlier, occurred.

The direct linear transformation (DLT) method for three-dimensional photography, with a modified Marzan and Karara¹⁵ method of analysis for static photographs, was then used to establish the three-dimensional position in space of the subject's labels. The DLT method allows a three-dimensional model to be established using two nonparallel nonmetric cameras,¹⁵ with a level of accuracy within those considered acceptable for traditional two-dimensional techniques.^{15,16}

For the DLT method, it is necessary to define the three-dimensional space within which measurements will be taken.¹⁵ This definition was provided by a reference structure, as shown in Figure 2, constructed from 4-mm-diameter steel rods. Rigidity was ensured by diag-

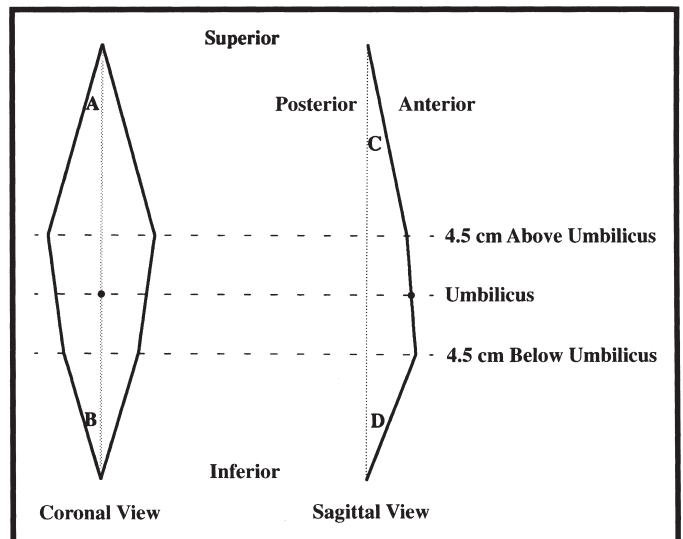


Figure 1. Model of rectus abdominis muscle structure. Solid lines represent the medial rectus abdominis muscle edge; dotted line indicates the normal position of the linea alba. A, B, C, and D represent angles of attachment.

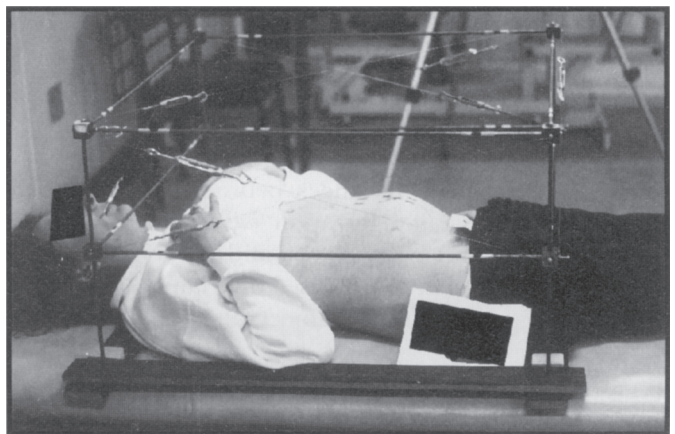


Figure 2. Reference structure and subject.

onal wire braces held taut by turn clasps. Sixteen control points were marked on the steel rods, and their x, y, and z placements from a selected origin were measured. It was critical to the DLT method that the cameras not be moved once the control points had been photographed. To avoid this possibility, and to avoid errors attributable to inaccurate placement of reference structure and subject photographs in the digitizing system, the reference structure was constructed to be placed around the subject's trunk (Fig. 2). The four legs of the reference structure were stabilized in two wooden braces placed beneath the supine subject's cervical spine and thighs (Fig. 2). Each photograph, therefore, contained both the reference structure containing the control points and the labeled subject. The dimensions of the reference structure were such that the three-dimensional

space defined by this reference structure was adequate in size for all the subjects.

Two tripod-mounted 35-mm SLR cameras fitted with 50-mm lenses were positioned to the right and left of the supine subject, with all subject labels and reference control points being visible in each camera's field of view. Simultaneous photographs were then taken. The control points and subject labels were digitized twice (Sonic Digitizer GP-8[†]) from each photograph, and stored on a personal computer. The DLT computer program,¹⁷ using the previously measured x, y, and z placements from the origin of the control points and digitized data from the control points and subject labels, gave the three-dimensional spatial coordinates (x, y, and z) for each of the subject labels.

The gross structural model for the rectus abdominis muscle, as shown in Figure 1, was then constructed as follows. The distance (*r*) between any two adjacent subject labels (label 1 located in space at coordinates *x*₁, *y*₁, and *z*₁ and label 2 located at coordinates *x*₂, *y*₂, and *z*₂) was calculated using the following equation:

$$(1) \quad r^2 = x^2 + y^2 + z^2$$

where *x* = *x*₂ - *x*₁, *y* = *y*₂ - *y*₁, and *z* = *z*₂ - *z*₁.¹⁸

The averages of the distances between subject labels resulting from each digitization were recorded. The angles of attachment A, B, C, and D (Fig. 1) were calculated using equation 2, based on triangles with sides formed by the appropriate subject labels:

$$(2) \quad \cos\Theta = (a^2 + b^2 - c^2)/(2ab)$$

where Θ is the angle of intersection between two sides, *a* and *b*, of a triangle with side lengths *a*, *b*, and *c*.¹⁹ For example, angle C was formed by subject labels located 4.5 cm above the umbilicus and at the superior attachment and inferior attachment points, and angle D was formed by subject labels located 4.5 cm below the umbilicus and at the superior attachment and inferior attachment points.

The reliability of the DLT procedure was examined over four test sessions for four subjects. At each subject's test session, the lengths between two pairs of control points were reconstructed using DLT software. Because the test frame being measured did not vary, variance-based reliability indexes were not appropriate. We therefore used a count-based technique to obtain an agreement index over repeated measurements.²⁰

The gross structural model was used to establish the following measures for each subject: (1) the length of the medial edge of the right rectus abdominis muscle, (2) the length of the medial edge of rectus abdominis muscle at each test session normalized as a percentage of rectus abdominis muscle length at the first test session, (3) the width of the rectus abdominis muscle separation at the umbilicus and 4.5 cm above and below the umbilicus, and (4) the superior and inferior angles of attachment of the rectus abdominis muscle in the coronal and sagittal planes.

At each test session, the functional capabilities of the abdominal muscle were assessed by two methods similar to those that have been used previously for gravid subjects and for subjects postpartum.^{5,8,12} First, each subject was asked to perform a supine trunk flexion (curl-up with knees flexed and feet flat) to a maximum trunk angle of 45 degrees to the horizontal, as visually determined by the examiner. The subject performed the movement in a slow, controlled manner while directed by verbal instructions from the examiner. The subject's performance was rated based on her ability to raise her trunk, using the following ordinal scale:

1. Grade 1—unable to attempt the movement.
2. Grade 2—very difficult. The subject was able to raise her head from the plinth but was not able to raise her trunk.
3. Grade 3—difficult. The subject was able to raise her head and scapulae partially clear of the plinth.
4. Grade 4—moderate success. The subject was able to partially perform the exercise, but the curl-up was to less than the 45-degree trunk angle from the horizontal, as determined by the examiner's visual assessment.
5. Grade 5—successful completion.

Second, an abdominal muscle test (AMT) based on the ability of the abdominal muscles to isometrically maintain a posterior pelvic tilt at progressively increasing levels of difficulty, was performed. A validation study of the AMT has been presented elsewhere.²¹ Briefly, the AMT procedures were as follows. A lightly inflated child's-size sphygmomanometer cuff was placed horizontally under the subject's lumbar spine. The cuff was connected to an electronic sphygmomanometer, the output of which was amplified to enable monitoring on an oscilloscope. A baseline pressure reading was obtained for a maximum posterior pelvic tilt while the subject was positioned supine with knees flexed, hips

[†]Science Accessories Corporation. Supplied by Haveland Cytonics Pty Ltd, PO Box 332, Glenwaverly, Victoria, Australia 3150.

flexed to 90 degrees, and buttocks remaining on the surface of the plinth.

The supine subject then proceeded through the AMT test levels in ascending order of difficulty. The AMT initial test positions were (1) level 1—knees flexed to 90 degrees with the feet flat on the plinth, (2) level 2—hips flexed to 90 degrees and one thigh supported by the subject's hands, (3) levels 3 and 4—hips flexed to 90 degrees and unsupported. For standardization in retesting, the distance between the ischial tuberosities and the heel was recorded in the level 1 test position. In the level 1 to level 3 test positions (Fig. 3), the subject rotated the pelvis posteriorly, flattened the lumbar curvature, extended the right knee, and lowered the lower limb, as far as possible, to the horizontal. This procedure was then repeated with the left lower limb. At level 4, the subject again flexed the lumbar spine and, while holding the posterior pelvic tilt, simultaneously extended both knees and lowered the lower limbs to the horizontal (Fig. 3). The AMT result was the level at which the subject was able to maintain the pressure reading to within 10 mm Hg of the previously established baseline reading during the test. The last successfully completed test position was considered to be the level of ability of the abdominal muscles.

Data Analysis

Changes over time for each of the nine rectus abdominis muscle structural variables investigated were analyzed by an analysis of variance (ANOVA).²² Scheffé *post hoc* tests were used to show where differences, if any, occurred. Significance was established at $P < .05$. The muscle test grades are ordinal data,²³ which would indicate the use of nonparametric statistics in further statistical analysis. Low subject numbers and missing data due to subject withdrawal on medical advice or preterm delivery, however, precluded the use of nonparametric statistical methods. The presented results and discussion of muscle test results, therefore, are based on qualitative descriptions.

Results

The reliability of the DLT procedure was assessed for four subjects over four test sessions, a total of 16 occasions. The percentage of close agreement for the reconstruction of a 500-mm length, where close agreement was defined as ± 2 mm, was 70%, with 4 mm being the largest difference. The ANOVA and Scheffé *post hoc* test results for the nine structural variables are presented in Tables 3 and 4.

The means and standard deviations for length of the medial edge of the right rectus abdominis muscle (absolute and normalized values) and the number of subjects used in each calculation are given in Table 2. One

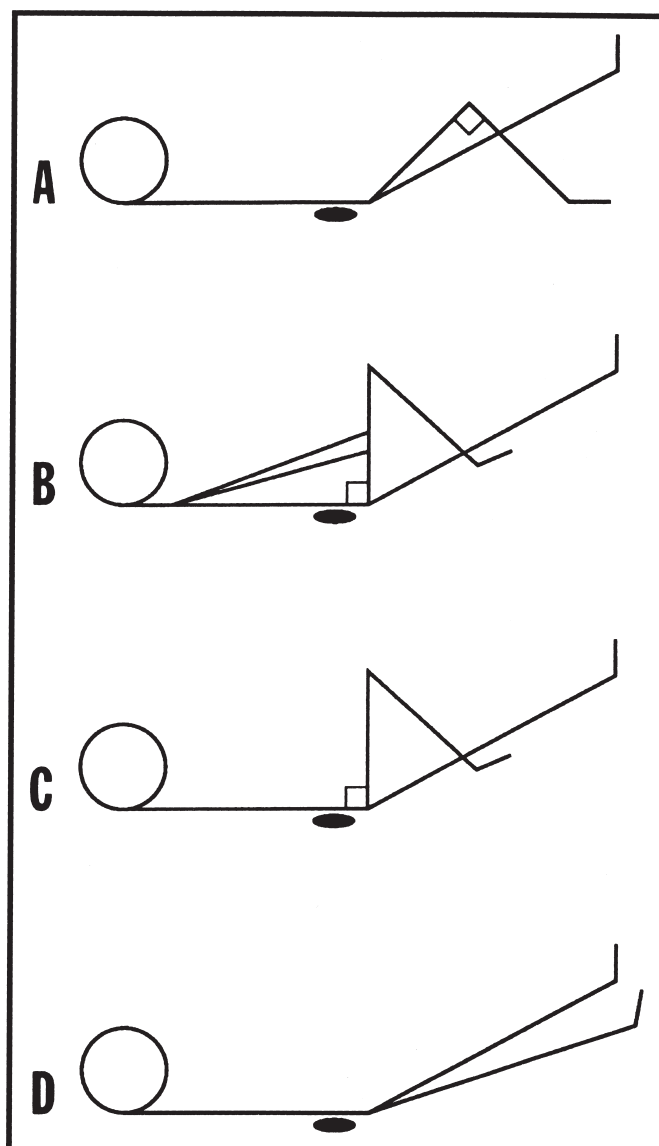


Figure 3. Abdominal muscle test (AMT) levels of difficulty: (A) level 1—crouching, knee flexed to 90°; (B) level 2—90° of hip flexion, thigh supported by hands; (C) level 3—90° of hip flexion, thigh unsupported; (D) level 4—90° of hip flexion, lower both limbs. Darkened circle represents child's sphygmomanometer cuff.

subject exhibited visible changes in abdominal shape at her first test session at 22 weeks of gestation and was therefore excluded from the rectus abdominis muscle normalized length calculations. There was an increase ($P < .05$) in absolute and normalized rectus abdominis muscle lengths between 18 and 38 weeks of gestation. The length of the rectus abdominis muscle was not recorded postbirth, as we believed that superficial skin labels may not accurately reflect muscle length. This opinion is based on possible length discrepancies, which are not detectable by palpation, between skin and muscular length adaptations when the underlying stretch from the uterus is removed.

Table 3.

Analysis-of-Variance Results and Scheffé Post Hoc Values

Variable No. and Name	Analysis-of-Variance Overall F ($F_{Critical}$)	Scheffé Value
1 Absolute length (cm)	$F_{6,21}=3.67$ (2.57)	4.61
2 Normalized length (%)	$F_{6,17}=4.72$ (2.70)	14
3 Rectus abdominis muscle pair separation 4.5 cm above umbilicus (mm)	$F_{8,41}=19.63$ (2.18)	26.07
4 Rectus abdominis muscle pair separation at umbilicus (mm)	$F_{8,41}=21.09$ (2.18)	18.4
5 Rectus abdominis muscle pair separation 4.5 cm below umbilicus (mm)	$F_{8,41}=11.16$ (2.18)	19.48
6 Sagittal-plane angle of insertion, superior ($^{\circ}$)	$F_{6,21}=12.00$ (2.57)	8.27
7 Sagittal-plane angle of insertion, inferior ($^{\circ}$)	$F_{6,21}=14.50$ (2.57)	10.46
8 Coronal-plane angle of insertion, superior ($^{\circ}$)	$F_{6,30}=18.40$ (2.42)	4.98
9 Coronal-plane angle of insertion, inferior ($^{\circ}$)	$F_{6,29}=12.59$ (2.43)	4.73

Table 4.Variables Showing Significant Scheffé Post Hoc Comparisons ($P<.05$)^a

Week	Gestational Week							Postbirth Week	
	14	18	22	26	30	34	38	4	8
Gestation									
14	7	3,4,5,6,7,8,9	3,4,5,6,7,8,9	2,3,4,5,6,7,8,9	...	...
18	7	3,4,5,6,7,8,9	1,3,4,5,6,7,8,9	1,2,3,4,5,6,7,8,9	...	...
22	3,8	3,4,5,8,9	3,4,5,6,7,8,9	...	...
26	3,8	3,4,6,7,8,9	...	...
30	6,9	...	...
34	3,4,5	3,4,5
38	3,4,5	3,4,5
Postbirth									
4
8

^a Ellipsis (...) indicates no significant difference.

Rectus abdominis muscle-pair separation widths above, at, and below the umbilicus, with the means highlighted, are shown in Figure 4. Increases ($P<.05$) in separation widths above, at, and below the umbilicus were seen between gestational weeks 18 and 30. Increases in separation widths above and at the umbilicus also were seen between gestational weeks 26 and 38. At 38 weeks of gestation, the mean rectus abdominis muscle separation width was 62 mm above the umbilicus, 47 mm at the umbilicus, and 32 mm below the umbilicus. The rectus abdominis muscle separation widths at all sites showed narrowing between 38 weeks of gestation and 4 weeks postbirth, to between week 22 and week 26 levels.

The calculated means and standard deviations of the rectus abdominis muscle angles of insertion in the sagittal and coronal planes (angles A, B, C, and D as shown in Fig. 1) are presented in Table 5. All angles of insertion showed increases ($P<.05$) between gestational weeks 18 and 30 and between gestational weeks 26 and 38. We were unable to calculate postbirth rectus abdominis muscle angles because data on muscle length were not available.

Table 1 shows the number of aerobic exercise sessions per week over the study period. During pregnancy, five subjects were consistent exercisers. They typically exercised three times or more per week. For most subjects, the number of aerobic exercise sessions per week was substantially reduced postbirth. Only two subjects (subjects 2 and 6) exercised three or more times per week postbirth. The types of exercise sessions recorded included brisk walking, cycling, wind surfing, aerobic classes, circuit training, weights, and swimming. Some abdominal muscle exercise would be expected to occur either indirectly as a result of essential postural control or directly due to specific exercises during all of these types of exercise sessions.

Table 6 shows the results of grading of curl-up performance for each subject. All subjects were able to complete a curl-up at their initial test session. By 26 weeks of gestation, all subjects showed a decreased ability to perform a curl-up, and the performance continued to decrease as pregnancy progressed for five subjects. At 8 weeks postbirth, the ability to perform a curl-up

increased to grade 4 (moderate success) or 5 (successful completion) for five subjects.

As shown in Table 7, the AMT results for each subject at the first test session ranged between levels 2 and 4. Half of the subjects had decreased ability to stabilize the pelvis against resistance by week 26 of gestation (Tab. 7). At 30 weeks of gestation, the AMT results ranged from level 1 to level 3. Between 30 and 38 weeks of gestation, the ability to stabilize the pelvis against resistance was found to diminish in all subjects tested. At 4 weeks postbirth, five subjects achieved level 1, and, at 8 weeks postbirth, only one subject had increased her result to the level of her first test session.

Discussion

The results of this study are based on a pool of six primigravid subjects who were conscientious aerobic exercisers throughout their pregnancies, although postbirth they reduced the number of exercise sessions per week. Four babies were delivered at term, between 38 to 42 weeks of gestation.²⁴ We believe that due to the small number of subjects and their exercise histories, the application of the results of this study to the general maternal population should be done with care until larger subject samples are studied.

The first aim of the study was to investigate changes in the morphology of a representative abdominal muscle (rectus abdominis) during pregnancy and the immediate postbirth period. The reliability of the DLT procedure, which was used to establish the three-dimensional position in space of the subjects' labels, was found to be high, with 70% close agreement. Unfortunately, as the maternal abdomen is continually changing shape due to fetal movements, the reliability of the morphological variables assessed in this study would be expected to be low. Despite this variability, the magnitudes of the observed changes in structure were sufficiently large (Tab. 3) to be distinguished from other methodological sources of variability such as small inaccuracies in location of subject labels.

As pregnancy progresses, the rectus abdominis muscle tends to curve around the abdominal protuberance rather than maintain its normally vertical orientation. The gross structural model used in this study simplified this curve to three straight lines. Equating curve length to the displacement between the two endpoints will underestimate the curve length. The simplified model, therefore, would have led to an underestimation of the rectus abdominis muscle medial edge lengths and angles of insertion. As the radius of the curve in this case is relatively large, we believe that this inaccuracy would have been small and therefore the effect on the structural measurements would be minimal.

Table 5.

Mean (\pm SD) of Rectus Abdominis Muscle Angle of Insertion

Gestational Week	Insertion Angle ($^{\circ}$)			
	Sagittal Plane		Coronal Plane	
	Superior	Inferior	Superior	Inferior
14	5 \pm 1	7 \pm 1	0 \pm 0	0 \pm 0
18	5 \pm 2	7 \pm 3	0 \pm 0	0 \pm 0
22	10 \pm 1	16 \pm 2	1 \pm 2	1 \pm 2
26	12 \pm 3	20 \pm 5	4 \pm 3	4 \pm 2
30	14 \pm 4	23 \pm 6	7 \pm 3	5 \pm 3
34	18 \pm 5	26 \pm 6	9 \pm 3	6 \pm 3
38	24 \pm 6	33 \pm 2	10 \pm 3	10 \pm 4

Table 6.

Curl-up Performance Grading^a

Subject No.	Gestational Week							Postbirth Week	
	14	18	22	26	30	34	38	4	8
1	5	5	5	4	4	*	*	4	5
2		5	4	4	4	3	*	4	4
3	5	5	4	4	3	3	*	3	4
4			5	4	3	3	3	3	3
5	5	5	5	4	3	3	3	4	4
6	5	5	5	4	4	2	2	3	4

^aNumbers 1 to 5 represent an ordinal scale. 1 represents inability to perform the task, and 5 represents a successful completion. Asterisk (*) indicates data missing due to withdrawal on medical advice or preterm delivery.

Table 7.

Abdominal Muscle Test Results^a

Subject No.	Gestational Week							Postbirth Week	
	14	18	22	26	30	34	38	4	8
1	3	3	3	3	3	*	*	1	1
2		3	3	3	3	3	*	2	3
3	2	2	1	1	1	1	*	1	1
4			3	3	3	3	2	1	1
5	2	3	3	2	2	1	1	1	1
6	4	3	3	3	2	3	2	1	2

^aLevels of difficulty range from 1 to 4, with level 4 being the most difficult. Asterisk (*) indicates data missing due to withdrawal on medical advice or preterm delivery.

The mean length (\pm SD) of the medial edge of the right rectus abdominis muscle at 14 weeks of gestation (when there was no external evidence of pregnancy) was 33.9 \pm 0.1 cm. This result was similar to previously reported linea alba lengths in nonpregnant subjects.^{5,25} The mean length of the medial edge of the right rectus abdominis muscle increased to 38.4 \pm 2.7 cm in the supine subjects at 38 weeks of gestation. An increase in

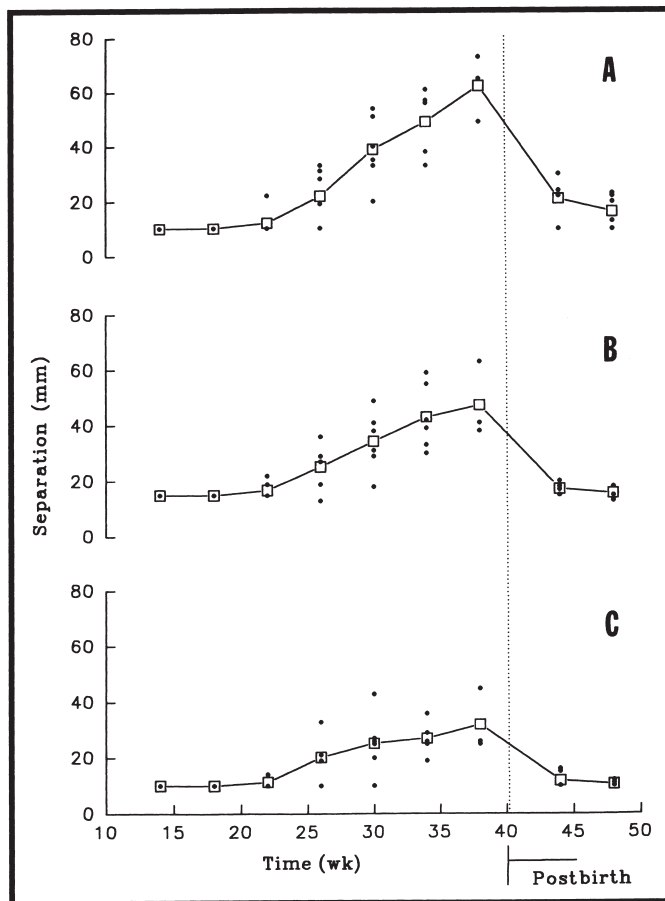


Figure 4. Scatterplot of rectus abdominis muscle separation width: (A) above umbilicus, (B) at umbilicus, (C) below umbilicus. □=mean.

length also was found by Fast et al,⁵ who reported an abdominal muscle length of 43.0 ± 4.03 cm for subjects with a mean gestation of 38 weeks in comparison with 31.85 ± 2.79 cm for nonpregnant subjects. Fast et al⁵ assumed the midsagittal abdominal length to be equal to abdominal muscle length, with no allowance for abdominal muscle separation during pregnancy, which permits the muscles to traverse around rather than over the abdominal protuberance. This assumption may account for the larger values they reported.

In our study, there was a maximum mean normalized length for the rectus abdominis muscle of 115% at 38 weeks of gestation. This length included intertendinous connections and attachments. The effect of pregnancy, however, on skeletal muscle connective tissue in humans is currently unclear. We assume that the increase in rectus abdominis muscle length is a reflection of the muscle fiber length increase. The rectus abdominis muscle is anecdotally described as being overstretched and thinned during pregnancy.^{13,26-28} From muscle length-tension relationships, it is known that an overstretched muscle fiber is unable to produce normal amounts of tension.²⁹ In pregnancy, however, the

increase in abdominal muscle length occurs over a period of approximately 22 weeks and therefore the stretch is applied over time. Longitudinal studies on animals have shown that adult skeletal muscle fibers add sarcomeres to their length when stretched over time periods such as 3 weeks.³⁰ The maximum active tension is increased relative to controls, and this maximum tension is developed at the new length.³⁰ Similar studies have not been done on human skeletal muscle. Human calf muscles stretched by serial casts applied for 7 days, however, show increases in length.³¹ The rectus abdominis muscle of humans, therefore, may increase in length and maintain maximum active tension in response to the long-term stretch of pregnancy. The 115% increase in rectus abdominis muscle length in our study is unlikely to greatly reduce the ability to produce tension within the muscle. Thus, any detected functional deficits of the abdominal muscles during pregnancy may result from other factors such as altered line of action rather than from overstretching and thinning.

We were unable to measure the length of the rectus abdominis muscle in our subjects postbirth. At childbirth, when the stretch from the uterus is removed, there would be a sudden effective increase in total muscle length. This sudden increase in effective length would affect the muscle's ability to produce tension. It is currently unknown whether and over what time period the total muscle length adapts to a nonpregnant length.

The rectus abdominis muscle pair is separated by the linea alba, which is arranged in two distinct parts.²⁵ The triangular upper part is 0.6 to 0.8 cm wide at the sternum and 1.5 to 2.5 cm wide at the umbilicus and extends 1 to 3 cm below the umbilicus.²⁵ The lower 13-cm section is a linear raphe, slightly wider at its attachment to the pubis.²⁵ During pregnancy, the rectus abdominis muscles separate and the width of the linea alba is increased.^{6,7} Criteria that have been used previously to indicate a significant rectus abdominis muscle separation width have included greater than 2 cm³² or 4 cm.³³ It is unknown, however, what separation width is functionally significant.¹⁰ Therefore, for our study, rectus abdominis muscle separation was defined as a width greater than 1.5 cm at the umbilicus and greater than 1 cm at sites 4.5 cm above and below the umbilicus. The minimum of 1 cm was chosen because we believed that, for distances less than 1 cm, palpation was unable to differentiate between a depression between the two muscle bellies and a muscle separation.

For all subjects, separation of the rectus abdominis muscles was not evident at week 14 of gestation. In all subjects, an increase in separation width was seen above the umbilicus at gestational week 30, at the umbilicus by gestational week 26, and below the umbilicus by gesta-

tional week 34. At 4 weeks postbirth, four of the six subjects had rectus abdominis muscle separation above the umbilicus, five subjects had muscle separation at the umbilicus, and three subjects had muscle separation below the umbilicus. The absence of rectus abdominis muscle separation in the first trimester, in conjunction with an increased incidence as the pregnancy progressed, and a reduced incidence postbirth also were found by Boissonnault and Blaschak.⁶ Spence⁸ reported that rectus abdominis muscle separation occurred in 50% of her subjects at 6 weeks postbirth, although the measurement site was not noted.

All subjects in our study showed rectus abdominis muscle separation below the umbilicus at 38 weeks of gestation. In an earlier study, Boissonnault and Blaschak⁶ found that only 11% of their subjects had rectus abdominis muscle separation below the umbilicus in their third trimester. The authors noted, however, that a higher incidence would have been found if the diastasis criteria had approached the normal linea alba width at this point rather than the 2-cm criterion suggested by Noble.³²

Kapandji³⁴ described the rectus abdominis muscle as a powerful trunk flexor muscle operating by a lever system through the lumbosacral and thoracolumbar joints. The rectus abdominis muscle's normal line of action is aligned vertically from the costal margin to the pubis.^{9,34} Our results, however, show that by 30 weeks of gestation, the angle of insertion in the coronal and sagittal planes for rectus abdominis muscle had altered such that the muscle's line of action was deviated laterally and anteriorly, as shown in Figure 5. A simplified force diagram for the rectus abdominis muscle at 30 weeks of gestation in the sagittal plane at the thoracolumbar and lumbosacral joints is shown in Figure 6. This diagram shows that the moment arm length, and therefore torque production of the rectus abdominis muscle about these joints in this plane, may be reduced at 30 weeks of gestation. The ability of the rectus abdominis muscle to flex the trunk is therefore possibly diminished. Whether the minimum change in angles of insertion at which reduced torque production of the rectus abdominis muscle will have a demonstrable affect on the muscle's functional capacity is unknown.

As we assumed that the adaptations of this representative abdominal muscle did not occur in isolation, we believe the ability to generate torque may be compromised across the entire muscle group. Hence, the second aim of this study was to examine the functional ability of the abdominal muscles, and the temporal relationship between functional ability and muscle adaptations, during pregnancy and into the postpartum period. Because there were few subjects in this study, which precluded

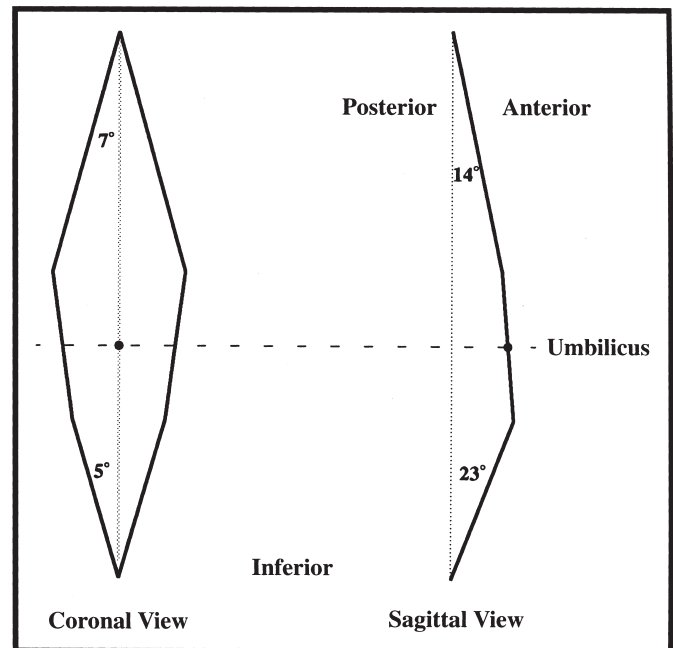


Figure 5. Right rectus abdominis muscle angles of insertion at 30 weeks of gestation.

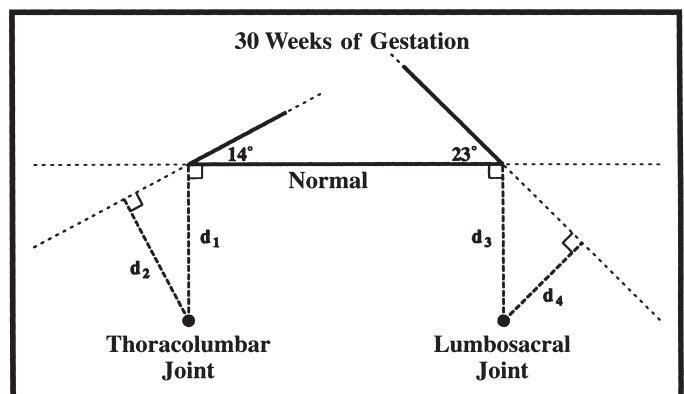


Figure 6. Normal and gestational week-30 lines of action for rectus abdominis muscle in the sagittal plane about the thoracolumbar and lumbosacral joints. Light dashed lines=line of action, heavy dashed lines=moment arm, and solid lines=muscle.

the use of some statistical methods, we view this part of the study as a pilot investigation of abdominal muscle function during pregnancy and the postpartum period on a longitudinal basis.

By 26 weeks of gestation, the ability to perform a curl-up type of abdominal exercise had diminished for all subjects. This decline continued to 38 weeks of gestation, at which time no subjects were successful in completing a curl-up. Fast et al⁵ found that 22 out of 164 subjects at a mean of 38 weeks of gestation could successfully complete a hook-lying sit-up to a visually determined 40-degree angle from the horizontal. The higher percentage of successful subjects in the study by Fast et al⁵ may

be due to the use of a less extensive curl-up movement than that used in our study.

We found the performance of curl-ups was improved postbirth. Five of the six subjects were successful or moderately successful in performance of a curl-up at 8 weeks postbirth. This postbirth improvement supports the previous results of Spence,⁸ who found that 80% of her subjects could complete a similar curl-up exercise at 6 weeks postbirth.

A comparison of the results for the two AMTs used in this study show that the AMT and curl-up results concur for test sessions during the pregnancy; however, these results are conflicting for the postbirth period. These apparent conflicts in AMT results also have been noted by Kendall and McCreary³⁵ for nonpregnant subjects. The AMT results showed that the ability to stabilize the pelvis against resistance while positioned supine generally remained compromised postbirth. In contrast, the abdominal muscles' supine trunk flexion ability increased postbirth. The use of a curl-up as a functional test for the abdominal muscles during pregnancy, however, is questionable. During pregnancy, the uterus presents a physical obstruction to the close approximation of the thorax and pelvis, which is necessary to complete a curl-up. The ability to perform the curl-up may be more related to the presence of this physical obstruction rather than to the functional ability of the muscles. In addition, supine trunk flexion may be assisted by the hip flexors.^{35,36} Thus, the performance of a curl-up in the postbirth period may not solely be a test of the abdominal muscles' capabilities. In contrast, the AMT is performed primarily by the abdominal muscles.³⁵ Potential assistance by the hip extensors acting to rotate the pelvis posteriorly is comprised due to the lack of a fixed distal attachment on the rotating limb. Therefore, we conclude that the AMT results of our study are more indicative of the true functional capabilities of the abdominal muscles during pregnancy and the immediate postbirth period.

At the first AMT test session, all subjects achieved a level 2 or greater result, and one subject achieved a level 4 result. This proportion of maternal subjects achieving a level 4 result was similar to the proportion of nonpregnant subjects who achieved a level 4 result in a previous AMT validation study.²¹ The proportion of subjects achieving a level 2 or higher result, however, was greater in our maternal group of subjects than in the nonpregnant subjects in the validation study. Despite regular aerobic exercise, as pregnancy progressed the functional capabilities of the abdominal muscles generally decreased. Postbirth, the subjects' ability to stabilize the pelvis generally remained low in comparison with early pregnancy results. This result suggests that despite fre-

quent aerobic exercise during pregnancy, the functional ability of the abdominal muscles is compromised by pregnancy.

The AMT results of subjects 2 and 6 were improved postbirth (Tab. 7), and this finding may be interpreted as a consequence of their exercise levels during this period. As it is unknown whether subjects 2 and 6 included a specific abdominal exercise component in their exercise program, and AMT results in the nonpregnant population are not related to the amount of aerobic exercise,²¹ this interpretation is not necessarily valid. Further investigation is necessary to establish the relationship between levels of specific abdominal exercise and AMT results. Jackson and Kleinig,¹² using an AMT similar to that of our study, reported that there was no difference in muscle functional abilities between postnatal subjects who attended prenatal exercise classes with a specific abdominal exercise component and nulliparous control subjects who had a similar frequency, but not type, of exercise. Unfortunately, Jackson and Kleinig¹² did not report data to enable comparison of the abdominal muscle functional ability of their postnatal subjects with that of the subjects in our study. Therefore, whether specific abdominal exercises have beneficial effects on abdominal musculature functional capabilities during pregnancy and postbirth remains unknown.

The temporal relationships between the gross structural adaptations of a representative abdominal muscle (rectus abdominis) and the functional abilities of the abdominal muscles are interesting. Changes in rectus abdominis muscle separation, and consequently in angles of insertion, were seen by 30 weeks of gestation. At 30 weeks of gestation, when the mean rectus abdominis muscle separation at the umbilicus was 3.4 cm, 50% of our primigravid subjects had a reduced ability to stabilize the pelvis against resistance in comparison with their initial test results. Further structural changes were seen as pregnancy progressed to 38 weeks of gestation. An additional reduction in functional ability also was seen within 30 to 38 weeks of gestation. Thus, the gross structural alterations (including angles of insertion and consequently muscle lines of action) seen in a representative abdominal muscle during pregnancy, which may result in reduced torque production, were paralleled in time by reducing abdominal muscle functional capabilities.

Postbirth, the separation of the rectus abdominis muscles returned to gestational week 22 to 26 levels. Although we were unable to measure muscle length postbirth, the sudden effective increase in muscle length due to the removal of uterine stretch at birth may affect the muscles' ability to produce tension. Thus, the

abdominal muscles may remain disadvantaged biomechanically. The ability to stabilize the pelvis against resistance also remained low at 8 weeks postbirth. Thus, incomplete resolution of structural adaptations postbirth also was paralleled by functional deficits into the eighth week postbirth.

The posterior pelvic tilt movement has been recommended as an abdominal muscle exercise during pregnancy.^{26,37} The results of our study indicate a decreased ability to perform this movement against resistance as pregnancy progresses. In a standing position, where there is increased resistance to posterior rotation of the pelvis due to the increasing weight of the gravid uterus, the ability of the abdominal muscles to perform the posterior pelvic tilt movement as pregnancy progresses is therefore uncertain. Further study is warranted to examine the ability of a pregnant woman to perform the posterior pelvic tilt movement while standing and the level of muscle tension generated by such a movement.

Strengthening of the abdominal muscles during pregnancy is advocated to improve muscle performance during labor,²⁶ to correct poor posture,^{13,26,32,37,38} and to prevent rectus abdominis muscle separation.¹³ Abdominal muscle exercise is encouraged postbirth to rehabilitate the effects of pregnancy on the maternal trunk.^{38,39} Many abdominal exercises require the generation of a large amount of torque. The results of our study indicate that the ability of the abdominal muscles to generate torque is reduced to at least 8 weeks postbirth and when rectus abdominis muscle separation is greater than approximately 3.5 cm at the umbilicus during pregnancy. Therefore, exercises that require high levels of torque production may be unsuitable. In addition, correct performance of many abdominal exercises requires stabilization of the pelvis to reduce the potential for low back injury.³² As the ability to stabilize the pelvis against resistance was reduced in the third trimester of pregnancy and postbirth, caution must be used when performing abdominal exercises at these times. When an abdominal exercise is difficult to perform, as was seen for the curl-up in late pregnancy, correct performance techniques also may not be followed by the subject. Close supervision of the maternal subject during the performance of abdominal exercises, therefore, is warranted to minimize the potential for low back injury.

Summary

The results of this study have shown that for primigravid subjects who were generally conscientious aerobic exercisers during their pregnancies, there were changes in the gross morphology of a representative abdominal muscle (rectus abdominis) by week 30 of gestation. These morphological changes continued as pregnancy progressed. The change in muscle length during preg-

nancy, although statistically significant, may not necessarily reduce the tension produced by the muscle. The torque production and therefore the functional capacity to produce movement, however, may be reduced due to the change in the muscle's line of action.

The ability of the abdominal muscles to stabilize the pelvis against resistance was shown to be compromised by the third trimester of pregnancy, and for the majority of subjects remained so to at least 8 weeks postbirth. As pregnancy progressed, the functional changes paralleled in time the structural changes seen in the representative muscle. Continued functional deficits were observed postbirth, again in parallel with incomplete resolution of structural adaptations. The structural changes and decreased functional abilities occurred despite the continued participation in aerobic programs in which some abdominal muscle exercise would be expected to occur. The effect of specific abdominal exercise on abdominal muscle structure and function during pregnancy, however, remains unknown.

To gain a more complete representation of the morphological changes to the abdominal muscles and their functional capabilities during pregnancy and the immediate postbirth period and of the effect of specific abdominal muscle exercise at this time, we conclude that further information is needed. Investigation of abdominal muscle cross-sectional area, the effect of pregnancy on abdominal skeletal muscle connective tissue, and abdominal muscle morphological changes and functional capabilities in nonexercising subjects is warranted.

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