INTERACTIONS BETWEEN THE ANTERIOR ABDOMINAL WALL MUSCULATURE OF ATHLETES

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The location of a muscle's origin and insertion, joint structure and the joint actions of the surrounding musculature are important factors to consider when evaluating the role of a muscle in human movement. An equally important concept is that the contraction of a muscle produces an equal force at both ends of the muscle. However, the previous statement is true only in cases where the muscle in question does not have an anatomical landmark between its ends which might be capable of transmitting forces to objects external to that muscle.

The anterior abdominal wall is comprised of a complex network of muscles. Within this network lie three pairs of flat muscles: external obliques (EO), internal obliques (IO), and transversus abdomini (TA); and one pair of vertically oriented strap muscles, recti abdominis (RA). The bony origins, insertions and actions of these muscles have been detailed in numerous works (12,24). RA is a strap-like muscle which longitudinally traverses the anterior abdominal wall (Figure 1).

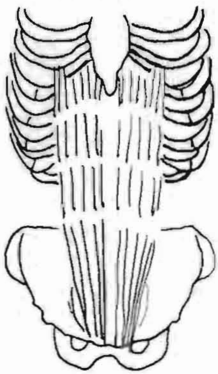

Figure 1. Rectus Abdominis

External oblique is a broad flat muscle which tends to traverse downward and medially as it crosses the abdomen. IO is a broad flat muscle which lies between EO and TA. The muscle fibers of IO traverse superiomedially across the anterior abdominal wall (Figure 2). TA traverses the anterior abdominal wall in a horizontal configuration. The pair of rectus muscles are encased in the rectus sheath which is formed by the aponeurotic tissues of EO, IO, and TA. Three tendinous intersections divide RA into four segments each of which are separately innervated. These tendinous intersections are located at the level of the umbilicus, the xiphoid process, and midway between these two points. Each of these tendinous intersections adhers to the anterior surface of the rectus sheath (7,8,9,10,15). Thus, each of the four segments of RA is capable of contracting independently from the rest while the forces which are generated by such a contraction may be transmitted to the adjacent segments of RA or may be applied to EO and IO through the rectus sheath. This arrangement would allow for the forces generated by each of the anterior abdominal wall muscles to interact on the tendinous intersections which traverse RA.

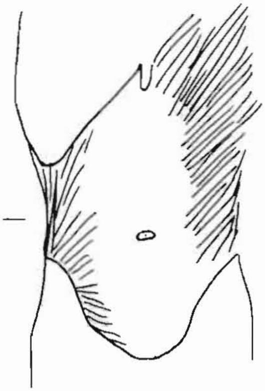

Figure 2. Oblique Muscles

Electromyographic evidence that RA acts segmentally can be found in the literature (5,6,7,11,13,14,21,23). However, the results of these studies vary greatly as to which segments of RA are active during selected activities. Evidence that the oblique muscles act segmentally is not as prominent (2,3,16). Attempts at modeling the muscles of the anterior abdominal wall have produced poor correlative results between EMG activity and internal forces when only the bony origins and insertions of the muscles were taken into account (17,18,19). In general, the muscles of the anterior abdominal wall tend to act in a complex manner (4,22).

The complexity of the muscular arrangement about the three tendinous intersections commonly found in RA precludes the validation of a model containing all the possible interactive capabilities of these muscles. However, the anatomy of this region does provide an oportunity to evaluate the muscular interactions about the level of the umbilicus. The interactions between the abdominal muscles may take several forms when EO, IO, the segments of RA above the tendinous intersection at the level of the umbilicus (URA), and the segment of RA below the umbilical level (LRA) are allowed to act simultaneously on the tendinous intersection at the level of the umbilicus. As an example, let EO, IO, URA, and LRA all be active such that the sum of the forces acting longitudinally on the tendinous intersection located at the level of the umbilicus equals zero. An increase in the force generated by URA would result in a net force acting on the tendinous intersection equal to the increase in URA and directed towards the sternum. This net force would tend to displace the tendinous intersection towards the sternum which would result in the elongation of LRA and IO. Several mechanisms could be used to negate the positive net force form URA. These mechnaisms include: an equal and opposite increase in LRA forces, an increase in the force produced by IO, a decrease in the force produced by EO, and combinations of each individual mechanism. The mechanism by which these muscles act may also be influenced by the orientation of each muscle as controlled by body position and the required magnitude and direction of resultant forces to either maintain a position or perform a controlled movement. The purpose of this investigation was to uncover evidence of independent segmental activity in RA, and to attempt to reveal the nature of segmental activity through the use of an interactive analysis of the muscles in question.

METHODS

Instrumentation

The central apparatus consisted of a 230 by 61 cm padded plinthe (Figure 3). The plinthe was designed to hold the subject in a supine position while they performed isometric trunk flexion tasks. The subject's lower extremities were secured to the plinthe using an ankle strap and two thigh (leg) straps. The hip joints were positioned with 20 degrees of hip flexion through the use of a posterior thigh pad. A position adjustable load cell and chain unit was used to record the level of force perpendicular to the sternum, produced by the subject. The signal derived from the load cell was scaled and displayed on an oscilloscope in view of the subject. This feedback device enabled the subject to accurately achieve and maintain a target level of force on the load cell unit. The load cell was attached to a chest harness which was comprised of a chest strap and a rigid back brace. The chest harness and load cell configuration together held the subject in the test position while simultaneously measuring the level of effort (force) the subject produced. On the posterior aspect of the chest harness was positioned a 1000 ohm precision pendulum potentiometer. This instrument provided a means of quantifying the degrees of trunk flexion relative to horizontal where the supine position was zero degrees of trunk flexion. Unilateral recording of electromyographic activity of the muscles located on the subject's left abdominal region was performed. The EMG activity emitted from the sections of RA above the level of the umbilicus (URA), below the level of the umbilicus (LRA), EO, and IO was monitored using paired silver-silver chloride surface electrodes.

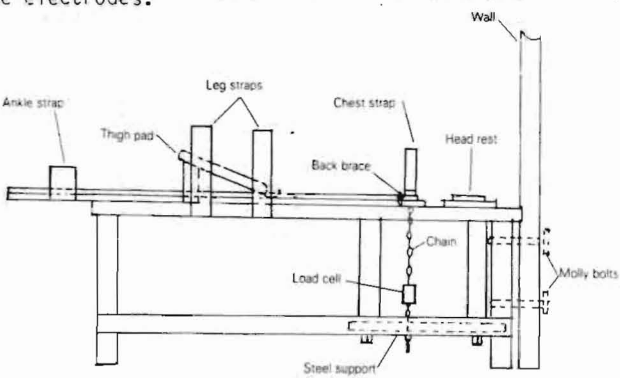

Figure 3. Test Apparatus

The effective diameter of each electrode was 11mm. A 16 mm diameter ground electrode was positioned over the inferior aspect of the subject's sternum. Electrolyte jelly and double sided adhesive collars were used to couple the electrodes to the surface of the skin. Impedence levels between each pair of electrodes was measured and accepted when below 3000 ohms. The EMG signals were electronically rectified, averaged, and amplified prior to sampling by a computer.

The electrodes monitoring URA activity were centered over the two segments of RA immediatey superior to the tendinous intersection at the level of the umbilicus. The LRA electrode pair had an interelectrode pair distance of 3 cm and was centered over the area bound by the tendinous intersection at the level of the umbilicus and the pubic crest. The EO pair was centered over the area bound by the anterior most origin of serratus anterior, on the seventh or eigth rib, and the linea semilunaris. The IO electrode pair was positioned 1 cm inferior to the line of Muskelecke and centered over the area bound by the iliac crest and the linea semilunaris

A PDP 11/34 minicomputer was used to sample and process the load cell, trunk flexion position potentiometer, and the EMG signals. The computer was equiped with a 12 bit sixteen channel analog to digital convertor having 4096 resolution on a zero to ten volt scale. Software was constructed that would calibrate each measurement device as well as sample and analyze the raw data. A sampling rate of 500 hz was used to collect trial data. Means, standard deviations, and ranges for each of the input signals were computed over each test trial.

The three dimensional position of each muscle segment in relation to the tendinous intersection at the level of the umbilicus was determined through the use of anthropometric measurements and still photography. The anthropometric measurements determined the lateral distance of the bony origin of each oblique muscle from the midline of the left RA. Photographic data were used to determine muscle lengths and the anterior-posterior and superior-inferior displacements of each of the muscles bony origin with respect to the tendinous intersection at the level of the umbilicus.

Subjects

Twelve well conditioned male volunteers ages 20 to 30 years participated in this study. Each subject was chosen on the basis of a pretest which included measurements on abdominal strength, trunk flexibility, abdominal skinfold, and the number and positions of tendinous intersections crossing RA. Subjects were barred from this study in cases where their medical history was contraindicative, abdominal skinfold was in excess of 2.5 cm, abdominal musculature contained anomalies, level of abdominal muscle strength prevented them from performing the trunk flexion task, or trunk flexion range of motion was less than 40 degrees. Trunk flexion range of motion defined as the degree changes measured from the pendulum potentiometer and the subject moved form the supine position to a trunk flexed position immediately prior to the occurence of hip joint flexion.

Procedures

Trunk flexion task

The experimental task involved performing isometric contractions of the anterior abdominal wall musculature. Each subject performed the experimental task during two similar test sessions. During the first test session, subjects performed three maximum isometric contractions in each of the two test positions, supine and 30 degrees of trunk flexion. The mean force produced in each test position served as guidelines for the performance of maximal and submaximal EMG test session trials. EMG test sessions were performed no sooner than 72 hours after the completion of the pretest.

Subjects were positioned on and secured to the test apparatus in a supine position. A water soluable skin marker was used to mark the tendinous intersection at the level of the umbilicus, the origin of EO at the level of the umbilicus, the origin of EO at the seventh or eighth rib, the anterior superior iliac spine, and the most cranial origin of RA. The supine position was maintained by preventing the subject from flexing beyond the ready position. The ready position consisted of placing the hands behind the head, fingers interlocked, elbows pointing anteriorly, full flexion of the cervical intervertebral joints, and posterior tilting of the pelvis. The flexed position was achieved by preventing the subject form flexing beyond 30 degrees of trunk flexion. This was accomplished by adjusting the position of the load cell and chest harness chain such that together they provided a perpendicular resistance force at the chest harness when the subject reached 30 degrees trunk flexion.

All test trials began with the subject positioned in the ready position. The EMG test trials were performed in much the same manner as the pretest trial. However, the pretest was limited to three trials at maximum effort per position. During the EMG test session subjects produced one isometric contraction at 0, 25, 50, and 75 percent of the pretest maximum force accompanied by three trials at 100 percent of the pretest maximum level. Subjects were asked to assume the ready position, flatten their lower back, exhale, and flex their trunk forward. When resistance provided by the load cell prevented the subject from continuing the movement, the subject increased the level of contraction until the level of force displayed by the feedback oscilloscope reached the predetermined target level set on channel two of that oscilloscope. Once the subject had reached the desired level of force, the computer was instructed to begin sampling. The computer sampled each instrument at a sampling rate of 500 hz for one second. During this time, one still photograph was taken of the subject. At the end of the sampling interval the computer produced a tone which was the subjects signal to relax.

Data Reduction

EMG data

Reduction of the mean electromyographic (MEMG) data was done in order to normalize the data from each muscle to a standardized value. The data acquired from each of the two test positions was treated separately during the normalization and evaluation process. The standardized values used to normalize the MEMG data were calculated from the three maximum effort trials. While the MEMG data from each level of effort were treated separately, the corresponding data from the three maximum effort trials were averaged. This process resulted in one average maximum effort trial for each of the two test positions. The average maximum MEMG value for each muscle was used to normalize (NEMG) each of the MEMG values for that muscle. The resulting NEMG values were expressed as percentages of the subject's average maximum value and subsequently used in the following evaluations.

Photographic data

The photographic slides taken during the EMG test sessions and the anthropometric data measured during the pretest were used to calculate geometrical factors used during the interactive analysis. Of particular importance were the lengths of each muscle segment and the angles formed between the oblique muscles and RA. The lengths of URA and LRA were calculated directly from each slide and converted to real lengths. The lengths and lateral offset angles of EO and IO were trigonometrically determined utilizing photographic and anthropometric data.

Interactive analysis

The hypothesis that the lateral abdominal musculature, acting through the rectus sheath, was capable of transmitting forces to RA via the tendinous intersection at the level of the umbilicus was evaluated using NEMG data. In order to do this, it was assumed that the NEMG was representative of relative muscular forces. Under the imposed test conditions this could be considered a valid assumption (1,17,18,19,20).

The NEMG differences in activity between the segments of RA were quantified by means of a root mean squared (RMS) technique. The 100 percent level of effort data were not used in the calculation of the RMS values. One noninteractive RMS error score was calculated for each test position and subject. The noninteractive RMS scores were derived from the differences between URA and LRA. In order to determine if the oblique muscle activity was capable of negating the segmental activity in RA, interactive RMS scores were calculated which included the percent of EO and IO NEMG values that acted in parallel to URA and LRA. Since the percent of actual force an oblique muscle could transfer across the tendinous intersection could not be directly measured, an optimization process was utilized to determine the relative magnitude of force transmission. The solution of the optimzation process was the percent of each oblique muscle activity which minimized the interactive RMS error for a given position.

Statistical analysis

The statistical test used to determine significance between the interactive and noninteractive RMS values for each of the two test positions was a one-tailed paired t-test ($p = .05$).

Results

Geometrical findings

The supine position mean lengths of each muscle are listed in Table 1. EO was consistently the longest muscle while IO was the shortest muscle. Muscles URA and LRA had similar lengths in the supine test position. However, across levels of effort, URA and EO decreased in length as much as 14 percent while the lengths of LRA and IO remained relatively constant.

TABLE 1
SUPINE POSITION MUSCLE LENGTHS†

Muscle	Percent Effort 100*	75*	50*	25*	0*
URA	15.2	14.9	16.4	16.8	17.6
SD#	1.3	1.2	1.2	1.5	1.4
LRA	16.7	16.9	16.9	16.8	16.8
SD#	2.0	2.0	1.9	1.9	1.9
EO	20.9	21.4	21.8	22.1	22.7
SD#	1.5	1.6	1.4	1.7	1.6
IO	12.2	12.3	12.3	12.3	12.3
SD#	.9	.8	.8	.8	.9

†in centimeters
*percent of pretest maximum effort
#standard deviation

The flexed position muscle lengths are presented in table 2. In the flexed position, changes in muscle lengths across levels of effort were minimal. A comparison of segment lengths based on zero effort trial of each test position reveals a 21 and 12 percent average decrease in the lengths of URA and EO. In contrast, muscles LRA and IO remained virtually the same length in the flexed position as in the zero effort supine position trials.

TABLE 2
FLEXED POSITION MUSCLE LENGTHS†

Muscle	Percent Effort 100*	75*	50*	25*	0*
URA	13.7	13.7	13.7	13.9	14.2
SD#	1.4	1.3	1.4	1.3	1.1
LRA	16.7	16.6	16.6	16.7	16.8
SD#	2.1	2.0	1.9	1.9	2.0
EO	19.9	19.8	19.8	20.0	20.2
SD#	1.5	1.4	1.6	1.5	1.4
IO	12.4	12.4	12.4	12.4	12.5
SD#	.88	.84	.79	.78	.83

†in centimeters
*percent of pretest maximum effort
#standard deviation

Electromyographic findings

The pooled means of the NEMG data recorded in the supine test position may be found in table 3. During the zero percent effort trial NEMG levels were trace in the majority of subjects and intermittently absent in each of the muscles studied. Oblique muscle activity began to rise above trace levels during the 50 percent effort trials. The standard deviations for the mean NEMG values ranged from 25 percent of the mean NEMG values to values greater than the mean recorded level.

TABLE 3
SUPINE POSITION NORMALIZED EMG†

Muscle	Percent Effort 100*	75*	60*	25*	0*
URA	100.	56.3	31.5	15.5	5.4
SD#	0.	14.4	11.3	8.9	4.7
Range	--	23-77	7-45	2-30	0-15
LRA	100.	49.9	33.6	14.8	6.4
SD#	0.	17.2	17.7	10.9	7.1
Range	--	20-76	9-60	.3-37	0-25
EO	100.	29.0	17.5	10.9	6.2
SD#	0.	26.4	22.2	14.1	9.4
Range	--	3-95	0-67	0-39	0-33
IO	100.	35.1	14.1	7.6	6.0
SD#	0.	29.2	12.5	6.3	5.7
Range	--	7-105	1-38	0-21	0-20

†as a percent maximum
*percent pretest maximum
#standard deviation

The flexed position mean NEMG values are presented in table 4. Each of the muscles was active from the zero percent to the 100 percent effort trial. Standard deviation values were on the order of 10 percent to 80 percent of the mean signal values. The range of individual subject NEMG values were one fifth to over two times the mean NEMG values.

TABLE 4
FLEXED POSITION NORMALIZED EMG†

Muscle	Percent Effort 100*	75*	50*	25*	0*
URA	100.	93.6	76.2	67.7	58.2
SD#	0.	11.35	15.7	13.5	19.6
Range	--	27-105	54-104	48-90	27-97
LRA	100.	97.8	82.1	64.8	61.4
SD#	0.	11.25	18.1	20.8	26.1
Range	--	80-114	46-126	14.97	14-130
EO	100.	82.4	65.0	47.3	36.9
SD#	0	34.6	33.6	28.5	29.4
Range	--	31-154	26-129	8-84	4-81
IO	100.	87.7	67.3	42.1	32.9
SD#	0.	28.0	39.7	20.5	22.6
Range	--	25-136	11-133	7-75	4-78

†as a percent of maximum
*percent pretest maximum
#standard deviation

Interactive analysis

The interactive and noninteractive analysis were used to calculate RMS values for forces about the tendinous intersection at the level of the umbilicus. Descriptive Statistics for the RMS values are located in table 5. The supine position noninteractive mean RMS error was 10.88 (SD=5.50) percent while the mean interactive RMS error for the same postition was 7.53 (SD=3.39) percent. The results of the one tailed t test between the supine position RMS values indicated that the interactive analysis produced a significantly lower (t=3.48, df=11, p _.01) RMS value than the noninteractive analysis. The flexed position mean noninteractive RMS value was 17.00 (SD=8.23) percent and the mean interactive RMS error was 11.71 (SD=7.35) percent. As in the supine position analysis, the flexed position interactive analysis produced a significantly lower (t=4.99, df-11, p .01) RMS value.

TABLE 5
RMS* ERROR STATISTICS

	Supine Position		Flexed Position	
	Noninteractive	Interactive	Noninteractive	Interactive
Mean	10.88	7.53	17.00	11.71
SD#	5.50	3.39	8.23	7.35
Range	1.66,21.41	1.18,12.49	6.06,34.86	4.96,28.45

*root mean squared
#standard deviation

Discussion

The fact that the lengths of URA and EO alone decreased as a result of an increase in effort in the supine position or as a result of flexing from the supine position to the flexed position indicates that the abdominal region is in fact divided into individual functional regions. These findings did not suggest that either the upper or lower section of RA created more force than its counterpart. The fact that each of these segments is capable of shortening independently from the other does suggest that either a mechanism external to RA, such as the oblique muscles acting that a very precisely regulated internal mechanism may control each segment of RA.

The electromyographic results of this investigation are typical of the results from investigations that quantitatively evaluated the effects of various loads (efforts) on the trunk musculature (1,17,18,19,20). When investigation phenomena of this type, it is not unusual for unique recruitment patterns to be displayed by a majority of the subjects tested. The arrangement of the anterior abdominal wall musculature is complex and it is not uncommon to find motor patterns that vary from person to person and from time to time in any one person (19).

Trace levels of NEMG activity were recorded from the abdominal muscles while the subjects maintained the supine position zero percent effort trial. In contrast, the mean of all NEMG values recorded in the flexed zero percent effort trial was approximately 50 percent of the mean NEMG activity recorded during the flexed position maximum effort trials. This finding in conjunction with the fact that the mean flexed position maximum recorded force was approximately half the magnitude of the mean supine position maximum recorded force indicated that the effort required to maintain the 30 degree trunk flexion position was approximately half of the subjects total trunk flexion strength. Since the resistance created by the trunk, head, arms, and load cell system was not quantified, this observation could not be verified.

The noninteractive analysis RMS results indicated that differences in NEMG levels did exist between the segments of RA. These differences were approximately one-quarter the magnitude of mean RA NEMG activity. However, neither of the segments of RA were clearly dominant in either of the test positions. In fact, the magnitude and direction of the differences between segments of RA varied from subject to subject and from trial to trial within one subject. Some of the subjects produced NEMG levels indicating that one level of RA was electromyographically dominant. However, an equal number of subjects demonstrated patterns which altered the segment of RA which produced the greater NEMG levels. These results suggest that proprioceptive influences and not functional neuromuscular patterns, play a major role in the recruitment patterns of the muscles of the anterior abdominal wall.

The use of the interactive analysis significantly reduced the RMS values from the levels that were calculated using the noninteractive analysis. This indicated that an interactive model of the anterior abdominal wall musculature best describes the functional roles of the muscles in this region. The interactive model reduced the RMS values an average of 31 percent in both the supine and the flexed position. The fact that the RMS values were not completely eliminated by the interactive analysis was not a surprise. It is important to remember that RA was divided into only two segments and the subsequent EMG data indicated the pooled activities of the segments superior to the tendinous intersection. A model based on one tendinous intersection, when in reality three exist, might not be expected to reduce the RMS values beyond 33 percent.

The interactive analysis did not reduce the RMS values equally for each subject. This does not imply that the capability for the oblique muscles to act on the tendinous intersection was not present. It does, however, suggest that this capability was not utilized or that its utilization was more complex than the methodologies of this investigation could discern. Subjects who utilized both oblique muscles to interact with the segments of RA may be in control of more complex mechanisms than those whose muscles did not interact. This suggests that greater efficiency of movement could be achieved by people who utilize the interactive mechanism.

The results of this investigation suggest that strength and motor training of the abdominal musculature should employ techniques which utilize all of the muscles in this region. If training techniques are limited to specific regions, benefits to performance derived from the interactive capabilities of these muscles may not be achieved. Furthermore, athletes who report isolated areas of fatigue within the anterior abdominal wall may require several different training techniques to effectively condition all of the muscles within this region.

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