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ORIGINAL ARTICLE

An ultrasound investigation into the morphology of the human abdominal wall uncovers complex deformation patterns during contraction

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Abstract The abdominal wall components, specifically muscle and connective tissue, must meet and accommodate a wide range of force demands for torso movement, spine stabilization, and respiration. It has a composite laminate nature that may lend itself to facilitating the required tissue responses. The purpose of this exploratory study was to examine the deformations of the abdominal wall connective tissues, with a special focus on both the internal oblique aponeurosis and the tendinous intersections of the rectus abdominis, using ultrasound imaging, during relatively simple contractions of the abdominal musculature. There were two main findings of this study: (1) deformations occurred in nearly 50% of contractions that would be characterized by a simultaneous expansion in multiple planes; (2) the laterally generated forces of the oblique and transverse muscles transfer a great deal of force across the rectus abdominis muscle and sheath, leading to a lateral movement of the rectus muscle during abdominal contraction.

Keywords Abdominal muscles · Connective tissue · Biomechanics · Spine · Oblique · Poisson's ratio

Introduction

Very little research has been dedicated to the examination of the morphology of the abdominal muscles and connective tissues during contraction, and even less on the means of force sharing among these components. The muscles within the abdominal wall, the internal oblique (IO), external oblique (EO), and transverse abdominis (TrA), along with the rectus abdominis (RA) are responsible for producing movements of the torso (McGill 1991), ensuring a stable spinal column (Granata and Marras 2000), regulating intra-abdominal pressure (Cholewicki et al. 2002), and assisting with respiration (Campbell and Green 1953). Many of these abdominal demands occur simultaneously, thus producing an array of forces (eg. muscle shortening and thickening forces, intra-abdominal forces, and muscle and connective tissue contact forces) within and upon the abdominal wall. A lack of knowledge concerning the mechanisms integrating the muscles with the various tissues encompassing and investing the abdominal wall motivated this investigation.

Properly coordinated abdominal muscle contraction provides a stiffening effect that protects the spine from instability related injury. The coordination and timing of abdominal muscle contraction has been studied a great deal in relation to low back pain and injury, but with little explanation as to the mechanical interaction of the muscle layers, and how this interaction may modify the stiffening and stabilizing effects. Knowledge of the in vivo mechanical interaction of these muscles with respect to force and stiffness transfer through the intervening connective tissues and ultimately to the skeletal structure is lacking. This knowledge is of fundamental importance to the understanding of how the coordination of abdominal muscle contraction ultimately contributes to the stiffening of the spine and torso.

A limited number of biomechanical studies have evaluated the abdominal wall. Nilsson (1982a, b), Rath et al. (1997), Junge et al. (2001) and Hwang et al. (2005a), all performed fine investigations into the mechanical properties of abdominal wall structures, but all did so with

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harvested dead tissues, which limits the applicability of the results to live contracting muscle. Brown and McGill (2008a) demonstrated the presence of a mechanical transfer of actively generated muscle force and stiffness through the connective tissues between the layers of the abdominal wall in anaesthetized rats, but similarly, deformations of connective tissues in the in vivo human may differ from those in a controlled rat model, and thus need to be further investigated.

Ultrasound imaging enables views of contracting muscle and connective tissues, and has recently begun to be utilized to study the mechanical properties of tendon (e.g. Bojsen-Moller et al. 2005; Ishikawa et al. 2005; Maganaris and Paul 2002), as well as the contraction of the abdominal muscles (e.g. Hides et al. 2006, 2003; Misuri et al. 1997). The majority of work on the abdominal muscles using ultrasound imaging has focused on thickness changes during contraction, but has not examined the complex deformation interactions of the connective tissues investing the musculature.

Connective tissues serve a complex and demanding role within the abdominal wall. Unlike the majority of muscles found in the human body, the abdominal wall muscles do not necessarily transmit force through tendinous attachments directly to bone. Many of the fibres of the EO, IO and TrA terminate into anterior aponeuroses that attach into and make up the sheath surrounding the RA, continuing to the midline region of the linea alba and even crossing over the midline to fuse into the contra-lateral rectus sheath (Rizk 1980). Connective tissues in the human body are arranged in a variety of manners and compositions, necessary to meet the demands placed upon the tissue. In general, these tissues can be thought as a matrix of protein fibres, primarily collagen, at varying degrees of parallel or random arrangement, encompassed within a gel-like ground substance. The assortment of compositions of these structures in different connective tissues allows for many unique properties that have been recorded in tissues such as skin (Lees et al. 1991), artery (L'Italien et al. 1994) and diaphragm central tendon (Hwang et al. 2005b), suitable to the demands placed on these tissues. With the range of demands placed on the abdominal wall muscles and tissues, it is reasonable to expect quite distinctive deformations during contraction.

The purpose of this exploratory study was to document the deformations of the abdominal wall muscles and connective tissues, with a specific focus on the aponeurosis of the internal oblique muscle and the tendinous intersections (referred to from now on as tendon) of the rectus abdominis muscle during relatively simple abdominal contractions. Ultrasound imaging was utilized to record and view the contractions, and electromyography (EMG) based modeling was employed to estimate the forces exerted by the muscles during contraction.

Materials and methods

Participants

Eight healthy males (average/standard deviation: age = 25.1/3.2 years; height = 1.78/0.06 m; mass = 75.5/4.6 kg) volunteered from the University population. None had a history of any chronic or acute episodes of back pain or abdominal pathology/injury. The protocol was approved by the University Office of Research Ethics and consent was obtained from each participant.

Data collection

Surface electrodes were placed along the line of fibres of seven muscles on the right side of the body: rectus abdominis (RA); external oblique (EO); internal oblique (IO); latissimus dorsi (LD); and the erector spinae at vertebral levels of T9, L3 and L5 (ES-T9, ES-L3, ES-L5, respectively). Signals were amplified (1,000–5,000 times; ±2.5 V; AMT-8, Bortec, Calgary, Canada; bandwidth 10–1,000 Hz, CMRR = 115 db at 60 Hz, input impedance = 10 GΩ) and digitally recorded (2,048 Hz). EMG signals were then rectified, low-pass filtered (Butterworth 2.5 Hz), and normalized to the maximum signal obtained during standardized maximum voluntary contractions (MVCs; Brown et al. 2008b; Vera-Garcia et al. 2006). An EMG biofeedback (MyoTrac, Thought Technology Ltd., Montreal, Canada) electrode was also secured over the right EO muscle, to allow participants to visually monitor the activation level of this muscle during contraction.

Three-dimensional lumbar spine angles, using an electromagnetic tracking system (Isotrak, Polhemus, Colchester, VT, USA) with the source secured over the sacrum and the sensor over T12, were monitored to ensure minimal movement during contractions.

Ultrasound images were obtained in B-Mode (MicroMaxx, Sonosite Inc., Bothell, WA) with a 38-mm linear transducer (6–13 MHz).

Procedures

Participants performed a series of static abdominal brace contractions in a modified sit-kneel position, designed to keep the spine in a neutral posture (Fig. 1). Target contraction levels were set to 25, 50 and 100% of the maximum activation capability of the right EO in the testing position. Two trials of each activation level were performed in randomly assigned order. To view the aponeurosis of the IO muscle, ultrasound images were taken with the probe at the level of the umbilicus on the left side of the body, with the lateral position adjusted to ensure a view of the aponeurosis between the medial edge of the IO

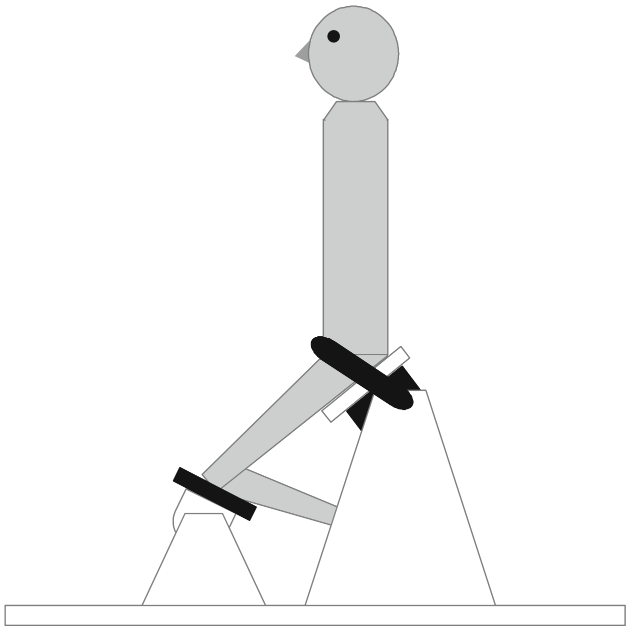

Fig. 1 Participant posture in which ultrasound images were obtained

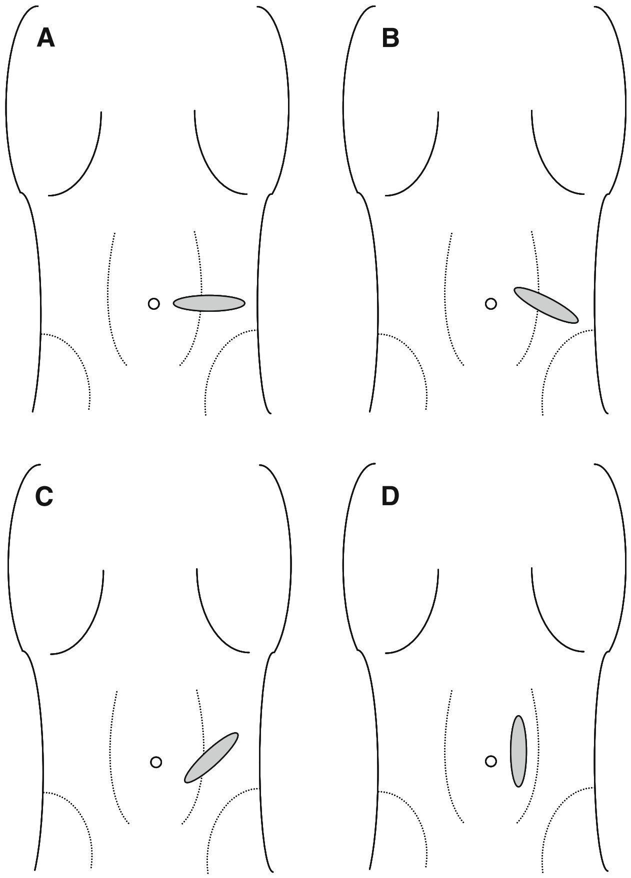

Fig. 2 Locations of the three probe orientations to view the IO aponeurosis: (**a**) horizontal along the transverse plane; (**b**) oriented 35° inferior-laterally (along the approximate line of the IO fibres); (**c**) oriented 60° superior-laterally (along the approximate line of the EO fibres). (**d**) Location of the probe to view the RA tendinous intersection

muscle and the lateral edge of the RA muscle (Fig. 2a). The standard orientation of the probe was horizontal along the transverse plane of the torso. Ultrasound images provide a two-dimensional representation of a three-dimensional structure, and thus out of plane deformations cannot be accounted for in a single image. Therefore, to provide a view of additional planes (and thus deformations) within the abdominal wall, a sub-set of four participants was selected and another series of the identical contractions were performed with the probe at two additional orientations: (1) angled 35° inferior-laterally (along the approximate line of the IO fibres, (Urquhart et al. 2005); (2) angled 60° superior-laterally (along the approximate line of the EO fibres, (Urquhart et al. 2005) (Fig. 2b, c). The mid point of the probe was positioned in the same location for each of the three orientations. For the RA tendon, the ultrasound probe was positioned over the intersection lying most closely superior to the umbilicus, oriented in the inferior-superior direction along the anterior of the RA muscle, and positioned approximately mid-way between the linea alba and linea semilunaris (Fig. 2d). For every ultrasound image, care was taken to secure the probe perpendicularly to the body at all times and to maintain the same position of the probe throughout and between each contraction. This was accomplished through the matching of probe location and orientation physically to marks placed on skin, and also by visually ensuring that the borders of the connective tissues of interest maintained a consistent starting position with respect to the outer edges of the ultrasound image. Two still ultrasound images were captured on a video cassette for each trial, the first when the muscles were relaxed and the second when the target activation level had been reached at a steady state.

Each participant also performed two ramped torso contractions producing a net flexor muscle moment. Participants were seated, and secured around the hips. A trunk harness was fit snuggly over the shoulders and attached through a cable in-series with a force transducer to an immovable anchor point, designed to prevent any torso movement. Participants used their torso to slowly pull against the anchor point, ramping the moment from zero up to maximum and back down to zero.

Ultrasound image analysis

All measurements were made visually off-line from stored video images. For the IO aponeurosis images trials, the length and thickness of the aponeurosis were measured in both the relaxed and contracted image (Fig. 3). Specifically, the IO aponeuorsis was digitized at the inner edge of

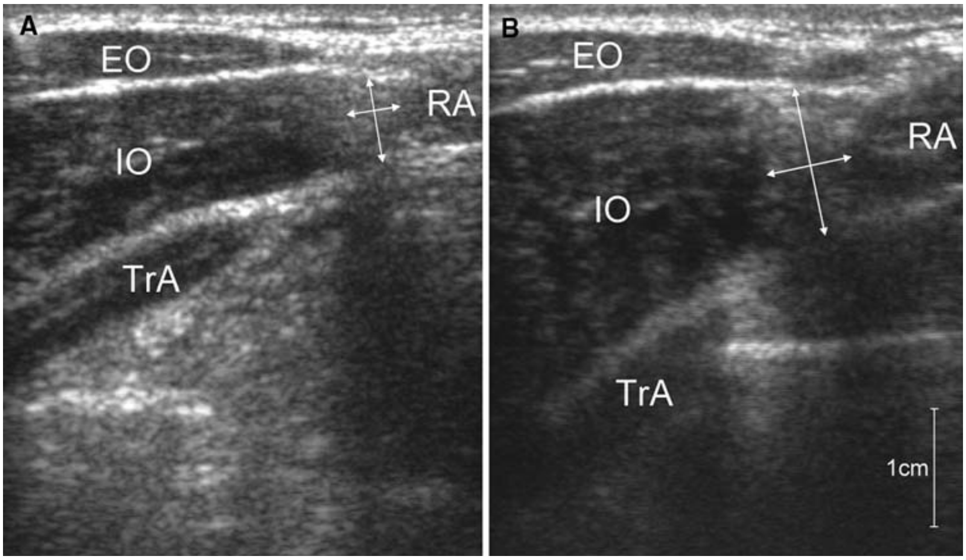

Fig. 3 Example of an ultrasound image, taken transverse (horizontal orientation) through the abdomen, of the IO aponeurosis captured at relaxation (**a**) and 100% of maximum contraction (**b**). The more vertically oriented *arrows* indicate the measure of aponeurosis thickness; the more horizontally oriented arrows indicate the measure of aponeurosis length

both its deep and superficial fascial borders, mid-way between its medial and lateral edges; a straight line was drawn between the two points as a measure of the aponeurosis thickness. The length of the aponeurosis was measured by digitizing a point on both its medial and lateral borders, mid-way between its superficial and deep edges; a straight line was drawn between the two points as a measure of the aponeurosis length. Measures were also made of the RA tendinous intersection in the relaxed and contracted states (Fig. 4). In this case a point was digitized on inner edge of both the superficial and deep fascial borders, mid-way between its superior and inferior edges; a straight line was drawn between the two points as a measure of the tendon thickeness. Tendon length was measured by drawing a straight line connecting a digitized point on each of the superior and inferior borders, mid-way between its superficial and deep edges. The changes in length and thickness of each of the IO aponeurosis and RA tendinous intersection were recorded as both an absolute magnitude (in mm), as well as a percent change from the resting measure. The lateral most position of the RA muscle was also measured from the IO aponeurosis trials, to assess any lateral movement of this muscle during contraction.

Reliability

To assess the intra-rater reliability in determining the change in aponeurosis/tendon length and thickness from rest to contraction, off-line measures were repeated (on a day separated by 1 week) on thirty randomly chosen trials (selected across all participants and conditions) and each of

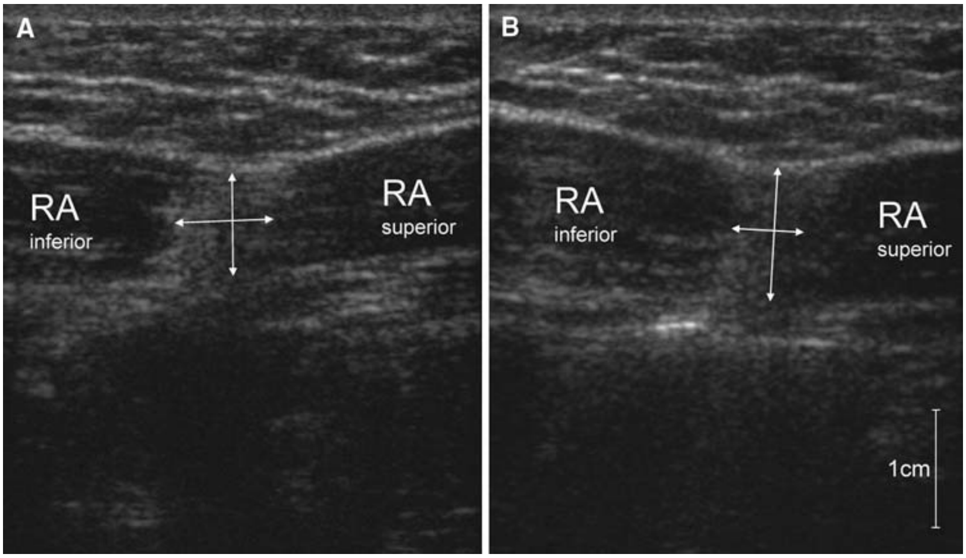

Fig. 4 Example of an ultrasound image, taken sagittally (inferior–superior orientation) through the abdomen, of the RA tendinous intersection captured at relaxation (**a**) and 50% of maximum contraction (**b**). The portion of the image above the RA is subcutaneous tissue and skin, while below the RA is visceral content. The more vertically oriented *arrows* indicate the measure of tendon thickness; the more horizontally oriented *arrows* indicate the measure of tendon length

a Pearson correlation and a paired t-test were computed to test the relationship and mean difference, respectively, between the days.

Muscle force estimates

The forces produced by the RA, EO, IO, and TrA muscles were estimated using the following equation (McGill and Norman 1986; Marras and Sommerich 1991):

$$F_{\mathrm{m}} = \mathrm{NEMG}_{\mathrm{m}} \times \mathrm{PCSA}_{\mathrm{m}} \times \sigma_{\mathrm{m}} \times l_{\mathrm{m}} \times G$$

where F_{m} = force in muscle m (N)

$\mathrm{NEMG}_{\mathrm{m}}$	normalized EMG signal for muscle m (% MVC)
$\mathrm{PCSA}_{\mathrm{m}}$	physiological cross-sectional area of muscle m (cm^2)
σ_{m}	maximum stress generated by the muscle m (set at 35 $\mathrm{N/cm}^2$)
l_{m}	length coefficient of the muscle m (unitless)
G	participant specific gain factor (unitless)

Anatomical data was obtained from Cholewicki and McGill (1996). The participant specific gain factor was determined from the ramped force contraction trials. In these trials the moment generated by the abdominal muscles was calculated (as the sum, across all abdominal muscles, of the product of the individual muscle moment arms and estimated forces) and compared to the estimated net resistive moment (measured externally as the sum of the moment produced by the upper body weight and the moment measured as the product of the force in the force transducer and the moment arm to the L4/L5 joint, and combined with the moment produced by the trunk extensor muscles). A gain factor was obtained as the value that produced the least-squares best fit between the abdominal muscle and resistive moments.

The increase in force generated by each of the muscles, with respect to the relaxed state, was recorded for each ultrasound trial. Finally, activation recorded by the IO electrode site was used to estimate the force produced by the TrA muscle. McGill et al. (1996) demonstrated a moderately good relationship between the activations of these two muscles, such that this produced an estimate at the force generated by the TrA.

Statistics

Two-way Repeated Measures ANOVAs were utilized to assess the effect of contraction level and probe orientation on the absolute and relative length and thickness changes of the IO aponeurosis. One-way Repeated Measures ANOVAs were performed to assess the effect of contraction level on the absolute and relative length and thickness change of the RA tendon, the lateral movement of the RA muscle, and the estimated force produced by each of the RA, EO, IO and TrA muscles.

A Tukey HSD test was performed to examine post-hoc differences where appropriate. The alpha level was set at 0.05 for all analyses.

Results

All eight participants followed the classical basic anatomical form of the abdominal wall (Monkhouse and Khalique 1986); external oblique aponeurosis anterior to rectus, internal oblique aponeurosis splitting anterior and posterior to rectus, and transverse abdominis posterior to rectus.

Muscle force production

There was a significant effect of the level of abdominal contraction on the estimated muscle force produced by each of the abdominal muscle groups ($p < 0.0001$ for RA, EO, IO, TrA) (Fig. 5). Specifically, each of the EO, IO and TrA increased their force output for each successive increase in contraction level; for the RA the force output for the 25 and 50% contraction levels were not significantly different from each other, but were from the 100% contraction level.

Reliability of ultrasound image digitization

A high correlation ($r = 0.89$) was found between the measures made on the two separate days, while the paired

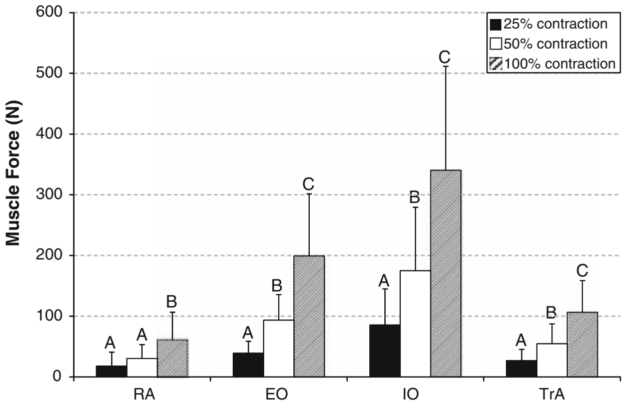

Fig. 5 Averages and standard deviations, taken across all trials and participants, of the estimated increase in force, with respect to the relaxed state, generated by each of the RA, EO, IO and TrA muscles during abdominal contractions. Different letters indicate contraction levels which are significantly different from one another within a given muscle

t-test showed no significant difference ($p = 0.609$) between days.

RA tendon and muscle

During contraction the RA transverse tendon lengthened (along the longitudinal axis of the RA) in 26 of the 48 trials examined. The level of abdominal brace did not affect the absolute or relative magnitude of RA tendon length change ($p = 0.1395$ absolute; $p = 0.2768$ relative), and no apparent trends existed. The tendon appeared to thicken (depth-wise) in 47 of 48 trials. This again was not statistically affected by the level of abdominal brace (absolute $p = 0.3678$; relative $p = 0.2967$) although there was a trend of increasing thickness change with brace level (1.5 mm or 18.3% increase at 25% contraction; 1.6 mm or 19.6% increase at 50% contraction; 1.9 mm or 23.9% increase at 100% contraction). The one trial in which the tendon thinned it also lengthened. Therefore, in 25 of the 48 trials, the RA tendon lengthened and thickened simultaneously. It is also worthy of note that, based on the deformations of the RA tendon, it would appear that the RA muscle, upon contraction, tended to thicken depth-wise more than it shortened.

Across all probe orientations, the lateral border of the RA muscle was pulled more laterally upon contraction in 64 of 94 trials (68%). This was not affected by contraction level ($p = 0.6519$) but was by the orientation of the ultrasound probe ($p = 0.0496$), with the horizontal orientation displaying a greater movement as compared to each of the 35 and 60° orientations. The ratio of summed oblique muscle (EO, IO, TrA) force to RA muscle force was used to assess a relationship with the lateral displacement of the RA muscle, with an exponential R^2 fit of 0.54 (Fig. 6). A lower ratio was found to be related to a medial displacement of the RA, whereas a higher ratio was related to a lateral displacement of the muscle. It is important to note that, due to Poisson's effect, the longitudinal contraction of the RA also results in stress/force and strain/deformation in the axes perpendicular to the direction of the fibres. The current findings indicate that the laterally produced forces of the oblique muscles dominate over the normal Poisson's effect produced by RA contraction, causing the RA to be pulled more laterally with higher oblique forces.

Oblique aponeurosis

The aponeurosis of the IO lengthened (in the medio-lateral direction) upon contraction in 77 of the 94 trials examined. The level of abdominal contraction did not significantly affect the magnitude of length change of the IO aponeurosis ($p = 0.3645$ absolute; $p = 0.1620$ relative). Probe orientation did have an effect on the absolute magnitude of length change ($p = 0.0428$) with the 35 and 60° views being significantly different from each other (mean/S.D. 35° 0.9/1.6 mm; horizontal 1.6/1.7 mm; 60° 3.2/5.5 mm). When normalizing to rest length, probe orientation was no longer significant ($p = 0.0792$) but showed the same trend as the absolute measure.

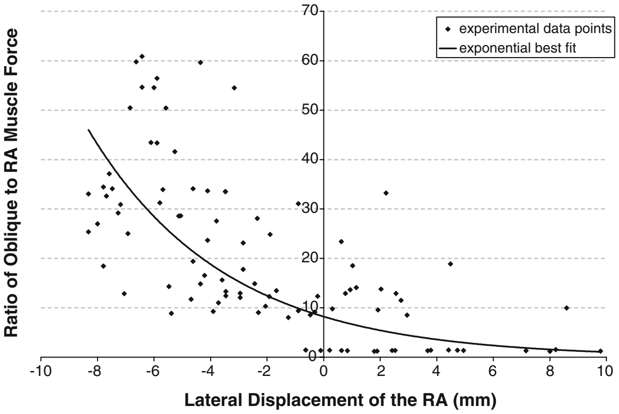

Fig. 6 Relationship between the ratio of summed oblique (IO, EO, TrA) muscle force to RA muscle force and the lateral displacement (mm) of the RA abdominis muscle. The exponential best fit produced an $R^2 = 0.54$. A negative lateral displacement indicates lateral movement whereas a positive lateral displacement indicates medial movement

The IO aponeurosis became thicker depth-wise in 51 of the 94 trials examined. In this case neither the level of abdominal contraction ($p = 0.9213$ absolute; $p = 0.9539$ relative) nor probe orientation ($p = 0.1750$ absolute; $p = 0.9646$ relative) significantly affected the magnitude of thickness change. In 38 of the 94 trials the IO aponeurosis appeared to lengthen and become thicker. In 5 of the 94 trials the IO aponeurosis appeared to shorten and become thinner. Comparing probe orientations for the subset of four participants shows potential differences in the number of trials in which the aponeurosis simultaneously lengthened and thickened or shortened and thinned (10 of 24 trials horizontal orientation (8 lengthened and thickened; 2 shortened and thinned); 5 of 24 35° orientation (4 lengthened and thickened; 1 shortened and thinned); 10 of 24 60° orientation (8 lengthened and thickened; 2 shortened and thinned).

Discussion

This study was designed as exploratory in nature in order to provide insight into the interactions between muscle and connective tissue in the abdominal wall during relatively simple contractions. The neural control of the abdominal muscles has garnered a great deal of attention and claims have been made as to the importance of these muscles in the stabilizing of the spine, yet little attention has been paid to the actual mechanical workings of these muscles. The primary finding of this study is that the connective tissues supporting the various attachments to the muscles of the anterior abdominal wall take on a complex arrangement that allow them to deform in complex manners, notably simultaneous expansion or contraction along multiple axes, to conform to the different forces acting throughout the system. Further, the laterally produced forces of the oblique and transverse muscles appear to dominate the medial contraction effect of the longitudinally produced force of the RA muscle, such that the connective tissues intervening these muscles (specifically the transverse RA tendons and linea alba) must function to accommodate such force distribution.

The major complexity uncovered in the current investigation was that in approximately half of the recorded abdominal contractions, both the tendinous intersection of the RA and the IO aponeurosis deformed in a manner that has the appearance of a negative Poisson's ratio. The sagittal view of the RA tendon showed it simultaneously lengthening longitudinally and thickening depth-wise in approximately 52% of the trials. Likewise, the transverse view of the IO aponeurosis displayed it simultaneously either lengthening and thickening or shortening and thinning in approximately 46% of trials. Two general explanations can be posed for this phenomenon. The first is simply a function of the methodology. The ultrasound image is a two-dimensional representation of a three-dimensional structure. Therefore it is possible that out of plane deformation was occurring that negates the apparent volume expansion of the tissue. An attempt was made to account for this possibility by imaging the IO aponeurosis at three different orientations, two of which were nearly orthogonal to each other (35° superior-medial and 60° infero-medial). The apparent negative Poisson's ratio was documented at all three views within a given participant, albeit in fewer instances when the probe was oriented along the direction of the IO fibres. Further, for this possibility to hold true, the RA tendon would have to shorten along approximate medio-lateral direction, which seems unlikely considering the large forces exerted laterally upon it by the oblique musculature. Thus, the finding most likely cannot be completely explained by this methodological limitation.

A second explanation relates to the composite laminate nature of the abdominal wall. Composite laminate structures can display negative Poisson's ratios (Tsai and Hahn 1980), the more anisotropic the plies, the more readily (Yeh et al. 1999) negative Poisson's ratios are observed. The abdominal wall is composed of three sheet-like muscles and their corresponding aponeuroses overlying each other, each with what has been anecdotally described as loose connective tissue intervening (Bendavid and Howarth 2000). Also, other authors have noted that each aponeurosis is made up of two layers (Askar 1977; Rizk 1980); the IO in particular separates into an anterior and posterior portion to encompass the rectus sheath. Further, Axer et al. (2001) described an intermingling of oblique fibres throughout neighboring layers of the aponeuroses and hypothesized that the mesh-work nature of the collagen fibres of the rectus sheath and linea alba allow for unique deformations, or adaptability, to the different demands of the tissue. The abdominal wall produces and resists forces in a number of competing directions; stress along the direction of the fibres in each of the angle-plied muscle layers; the hydrostatic force created within the abdomen and acting outwardly on the wall of the musculature, the force of which is related to the level of muscular contraction. Also, stress is exerted along the plane of thickening at the muscle-aponeurosis junction. The abdominal wall muscles have been shown repeatedly with ultrasound to thicken depth-wise during contraction (Hides et al. 2006, 2003; Misuri et al. 1997). It was noted here that the muscles, in particular the IO, did not show a great deal of tapering at the muscle-aponeurosis junction; both the RA and IO muscles demonstrated thickening right up to the aponeurosis border. It would thus be beneficial for the aponeurosis to deform (thicken) along with the muscle to avoid potentially detrimental stress concentrations from developing at the muscle-aponeurosis junction. Perhaps the layered nature of the abdominal wall and aponeurotic or fascial structures allows for such expanding deformations by accommodating a slight separating between the layers in response to the diverse forces acting on the various tissues, while still providing the shear connections that allow for the binding and toughening of tissues.

Connective tissues, while not having the capability of actively contracting, do possess the potential for passive contraction dependent upon the stiffness of the tissue at a given time. Connective tissues resisting a force at a given length will effectively contract as the stiffness within the tissue increases. This increase in stiffness may effectively occur due to a rearrangement of fibres as the tissue deforms in response to other applied forces. Alternatively, tissue with an apparent pre-stress to give the fibres an initial orientation prior to contraction may relax during contraction as the fibres rearrange to resist other forces. Challenged breathing recruits the abdominal muscles, and deformation of the connective tissues probably occurs cyclically during respiration, both due to muscular contraction and also simply due to changes in the IAP and the distention of the abdomen (Campbell and Green 1953). In the current study, participants were told not to alter their breathing during contractions; however, it is possible that in some instances a slightly exaggerated inspiration may have occurred prior to the target contraction which may have pre-stressed the tissue prior to contraction. This may explain the connective tissue structures seemingly contracting (becoming shorter) during a portion of trials.

The lateral border of the RA moved laterally during contraction in approximately 68% of trials. The documented lateralization of the muscle could be movement of the whole RA muscle by stretching of the linea alba, or alternatively transverse stretching the RA (by separating parallel fibres). The tendinous intersections are thought to function, at least in part, to provide transverse strength to the RA by giving it anchor points along its length (McGill 2002). For this to function as hypothesized, the transverse stiffness of the tendinous region must be greater than the muscle region, which has been shown to be true for the diaphragm muscle (Hwang et al. 2005b). The lateral movement of the RA muscle should be dictated by the competing forces generated by the RA muscle, which will stiffen its fibres both along and transverse to its fibre direction, and the forces generated in the abdominal wall muscles (EO, IO, TrA), which will act to pull the RA muscle transversely across its fibres. An interesting relationship was found to partially support this idea, where the amount of lateral movement of the RA was exponentially related ($R^2 = 0.54$) to the ratio of oblique muscle to RA muscle force (Fig. 6).

The magnitude of abdominal contraction did not affect the deformation of any of the connective tissue structures examined. In other words, the deformations could not be statistically separated for any of the abdominal contraction levels. This is despite the fact that the estimated magnitude of force generated by the abdominal muscles was significantly different between the contraction levels. This again points to connective tissues being a highly non-linear network, with great deformations occurring at low contraction levels, most likely as fibres rearrange in response to the applied forces, and then leveling off with higher levels of contraction as the fibres have reached their most organized arrangement. This effective toe region of lower stiffness followed by a more linear region of high stiffness has been reported and reviewed at length for connective tissue (Jeronimidis and Vincent 1984; Viidik 1973).

Orientation of the ultrasound probe had a significant effect on the measure of the length change of the IO aponeurosis, as well as the lateral movement of the RA muscle during contraction. The smallest IO aponeurosis lengthening was recorded when the probe was oriented along the fibre direction of the IO muscle, which would most likely produce the most accurate measure of this variable. The largest lengthening was recorded when the probe was oriented 95° away from this orientation, along the line of the EO fibre direction. This may be partially explained by a difference in the rest length of the aponeurosis in the two orientations, as when the length changes were normalized as a percent of rest length, the measure was no longer statistically affected, although the same trend still existed and may have again reached statistical significance with a larger sample population. The lateral movement of the RA muscle could not be normalized to a rest position, as the entire muscle was not able to be captured completely in a single image. In this case, the largest movement of the RA was found with the probe oriented horizontally, statistically greater than either of the angled orientations. The horizontal position should capture the image nearly perpendicular to the fibre direction of the RA muscle, and thus may provide the most accurate measure of its lateral or transverse movement.

No forces were directly measured within the abdomen. Surface EMG was recorded and used to estimate the force generated by the individual muscles. This requires a number of assumptions, including the form of the relationship between EMG and muscle force (Brown and McGill 2008c), and the scaled magnitude of the relationship. Calibration trials were used here to attempt to generate inter-individual scaling to obtain the most accurate estimates of muscle force as possible. Still, assumptions were made as to the partitioning of muscle force based on assumed sizes and lengths of muscles relative to one another. Intra-abdominal pressure was not measured. Previous work has established a link between the activation of the abdominal musculature and intra-abdominal pressure (Cholewicki et al. 2002; Cresswell 1993), so that is can be safely assumed that internal abdominal pressure increased along with contraction levels; future work should however attempt to measure the IAP while imaging muscular contractions within the abdomen. Finally, limitations exist regarding the methods utilized to measure the deformations of the abdominal wall. A single examiner made all of the measurements, and thus the results and conclusions are based on the expertise and judgment of this one individual. This examiner performed all of the experimental protocols and ultrasound imaging, but was blinded to all of the image trials during the off-line analysis. Further, intra-rater reliability was shown to be quite high, meaning this examiner was very consistent is assessing the connective tissue deformations. Automated image detection techniques have been developed and tested for ultrasound imaging of the calf musculature (Loram et al. 2006). These automated methods decrease the likelihood of human induced measurement error, and improve the probability of reliable tracking of muscular and connective tissue features. However, they require specifically tracked features to remain present in each image assessed, which would be difficult to ensure due to the tissue depths and large muscular contractions explored in the current study.

Conclusions

This exploratory work has documented unique in-vivo deformations of the human abdominal wall connective tissues that cannot be explained by simple mechanical and tissue properties; a complex network of fibres and matrix interact to accommodate the deformations necessary for varying demands. In particular, the composite laminate nature of the connective tissues appears to allow for expansion and/or retraction in multiple planes simultaneously. In this way, the anatomical make-up of these tissues enables complex mechanical deformations to transfer the force and stiffness generated by the abdominal muscles around the torso and to the skeleton. In addition, the high laterally produced forces of the oblique and transverse muscles appear to dominate the medial contraction effect of the longitudinally produced force of the RA muscle, thereby creating lateral movement of the RA during abdominal contraction. Future work should be dedicated to testing the morphology and mechanics of the abdominal wall muscles and tissues during in vivo contraction, in order to better understand how these structures function to produce movements of the torso, stabilize the spine, and regulate intra-abdominal pressure and respiration under a wide array of demands.

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