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Transmission of Muscularly Generated Force and Stiffness Between Layers of the Rat Abdominal Wall

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Study Design. *In situ* testing of the rat abdominal wall.

Objective. To test the ability of muscularly generated force and stiffness to be transmitted between the layers of the abdominal wall.

Summary of Background Data. The abdominal wall is comprised of 3 obliquely oriented sheet-like muscles bound together through a connective tissue network. This anatomic arrangement would seem ideal to facilitate myofascial force transmission, which if present would indicate shear connections between the muscle layers that could have important mechanical consequences.

Methods. In 10 Sprague-Dawley rats, the 3 layers of the abdominal wall were isolated together and attached to a servomotor force/displacement system. The abdominal wall was stimulated via electrodes over the surface of the transverse abdominis, and measures of force and stiffness were obtained. The aponeurosis attaching the transverse abdominis to the rectus sheath was then cut and the wall was restimulated and the same measures were again obtained.

Results. Active force and stiffness were both reduced in the cut aponeurosis state. These drops were much lower (10.6% and 10.7%, respectively) than would be expected if the transverse abdominis were completely removed. Furthermore, a control group (5 rats), in which the aponeurosis was not cut, but a similar amount of time to that necessary to perform the aponeurosis surgery was allowed to elapse, showed reductions in active force and stiffness (7.9 and 8.2, respectively) nearing that seen in the cut state. This indicates that at least a portion of this drop was due to the passage of time in the compromised surgical state.

Conclusion. It was concluded that the majority of the force and stiffness generated by the transverse abdominis was transferred through the connective tissue network adhering to the internal oblique muscle. This indicates the presence of strong shear connections between the muscular layers, which suggests a composite stiffening function of the architectural design.

Key words: connective tissue, spine, myofascial force transmission, abdominal muscle, oblique, composite. **Spine 2009;34:E70–E75**

The abdominal wall musculature is highly unique in its architectural arrangement. It is composed of 3 sheet-like muscle layers, transverse abdominis (TrA), internal oblique (IO), and external oblique (EO) that are tightly bound together by a connective tissue network that exists between each consecutive layer. The abdominal wall muscles have a number of important mechanical roles, ranging from the generation of twist, lateral bend and flexion moments and motions,[1] maintenance and control of a stable spinal column[2,3] and intra-abdominal pressure,[4] and assistance with respiration.[5] The diversity and highly demanding nature of these roles has inevitably produced an anatomic/geometrical arrangement of the muscles and connective tissues that are most suitable to meeting these demands. However, very little is known about the exact mechanisms by which the anatomic structures suit and optimize the function of the abdominal muscles. Thus, the purpose of this study was to examine a specific mechanical function, the ability to directly transmit force and stiffness between the muscle layers, related to the composite nature of the abdominal wall. If present, the composite effect of the binding of adjacent muscular layers will enhance the efficiency of force and stiffness transfer relating to the stiffening and stabilizing of the spinal column.

Recent work has demonstrated that muscles linked through their bellies to connective tissue networks adjoining adjacent muscles should not be considered completely independent generators of force and stiffness.[6] The position and length of each muscle affect the output of the other muscles through what has been termed myofascial force transmission. Briefly, the force generated by sarcomeres in a given muscle need not be transferred entirely to the tendinous collagen fibers with which they are in series. Some of the force can be transmitted from sarcomere to sarcomere in parallel, and subsequently, through a shear linkage mechanism, outwards through fascial or connective tissue attachments between muscles.

The tightly bound layered formation of the abdominal wall musculature would seem to be an ideal anatomic scenario for myofascial force transmission. Demonstrating that direct force transmission is possible through the connective tissue networks between the muscle layers would provide a proof of principle for important shear connections binding the muscles to one another. Such shear connections can establish an array of important mechanical roles that can significantly affect the function and ability of the muscles to perform their needed roles. This is specifically important to the abdominal wall muscles, as enhancement in function to meet the vast mechanical demands can be achieved via shear connections through potential avenues such as the regulation of muscle lengths around optimal, the strengthening and tough-

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ening of the wall as a composite structure, and the direct transmission of force and stiffness in the case of potential neural deficits in a particular muscle layer. Thus, the current study was designed to test the ability of the force generated by the TrA muscle to be transferred, in the absence of its normal avenue of transmission, through its connective tissue attachments to the IO muscle, ultimately reaching its originally intended location on the rectus sheath.

Materials and Methods

All procedures were approved by the University Office of Animal Research Ethics. Fifteen male Sprague-Dawley rats (mean/SD mass 501.5/38.2 g; age 29.5/1.8 weeks) were used in this study. Ten rats served as part of the experimental group and the remaining 5 served as controls. Rats were initially anesthetized using 5% isoflurane gas, which was then reduced to a maintenance level for the remainder of the experiment. The rats were placed on a heated water pad (39°C) for all surgical and experimental procedures. Skin was removed from the abdomen and a cranial (just below the sternum) to caudal (inguinal level) incision was made just lateral to the right of the linea alba. Two transverse cuts were then made, the first caudal to the ribcage, the second cranial to the inguinal region. This isolated a region of the left side of the abdominal wall muscle and aponeurosis spanning the linea alba to the approximate beginning of the thoracolumbar fascia. The average (standard deviation) cranial to caudal width of the isolated wall was 26.5 (3.3) mm. The muscle wall remained attached dorsally to a portion of its blood and nervous supply. Throughout all procedures, the muscle unit was consistently wetted with an isotonic saline solution to prevent drying. Light wooden rods were glued to both the superficial and deep sides of the wall along the linea alba, and a 24-gauge copper wire was sutured just medial to the rods through the abdominal aponeurosis/rectus abdominis complex and attached, in line with the TrA fibers, to a servomotor force/displacement system (S300; Cambridge Technologies) (Figure 1). The spinal column was immobilized by inserting a pin, secured from above, into an intervertebral disc at a spinal level corresponding to the middle of the isolated muscle wall.

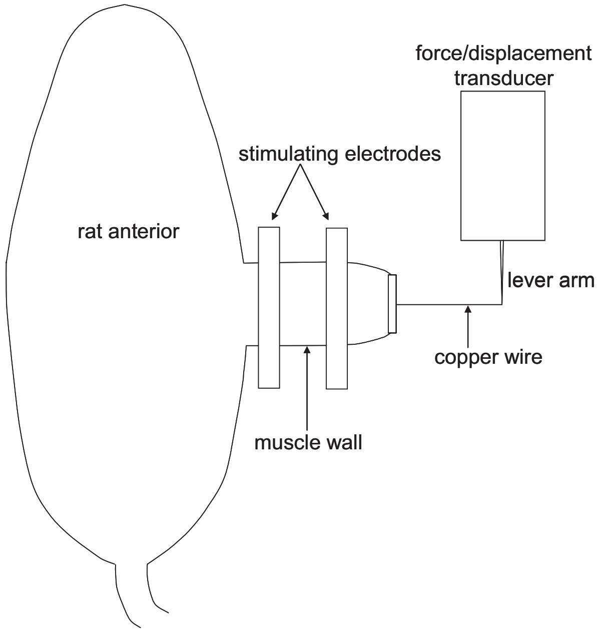

Figure 1. Picture of the experimental set-up.

The muscle wall was placed at its optimal length for active force production, and all tests were performed at this length. Two platinum plate electrodes were used to stimulate the abdominal wall. These plates were placed across the line of fibers of the transverse abdominis muscle, at an average (SD) distance of 27.5 (5.0) mm apart from one another. Electrode conductivity gel (Conmed, Utica, NY) was used to increase the conductance of the stimulus. A constant voltage stimulus ranging between 20 and 40 V, depending on the specimen (S48; Grass Medical Instruments, Quincy, MA) was used for all tests; voltages higher than this were found to occasionally saturate the range of our force transducer. Initial tests (400 milliseconds duration pulse trains; 100 Hz stimulation) were conducted to precondition the muscle and to ensure that electrodes had settled into a consistent location on the muscle. Once a consistent force reading was obtained, the experimental testing was begun. The experimental protocol consisted of a 100Hz (0.1 ms/pulse) pulse train stimulation for 800 milliseconds with a quick length change (muscle shortened by 0.35 mm) applied 400 milliseconds into the train. Force and position were digitally recorded at 1000 Hz.

Force was measured over a 100-milliseconds period at the plateau of the initial force recording, and the active contribution was obtained by subtracting this value from the initial passive force before the onset of stimulus. Stiffness was measured as the change in force over the change in position (g/mm) resulting from the quick release. One to 2 minutes rest was given between all trials to allow for recovery.

In the 10 experimental rats, the TrA was then cut along its aponeurosis (posterior aponeurosis of the abdominal wall; Figure 2) so that it no longer attached in series to the force/displacement transducer. The aforementioned force and stiffness tests were repeated in this new "cut" state. In the remaining 5 rats, an amount of time approximately equal to the amount of time required to perform the cutting of the aponeurosis (average of 3 minutes) was allowed to elapse and the force and stiffness tests were repeated. In these 5 rats, the aponeurosis was never cut. This control group served to test the hypothesis that an elapse of time, in the compromised surgical state, caused a decrease in the force and stiffness generating capabilities of the abdominal wall muscle group.

Finally, in 11 of the rats, the thickness of each of the abdominal wall muscles was measured, and in 7 of these rats, the fiber angle of the IO and EO muscles, with respect to the fiber line of action of the TrA, was measured.

A 1-way repeated measures ANOVA was conducted to test for differences between the intact and cut aponeurosis states for each of abdominal wall passive force, active force, and stiffness ($\alpha = 0.05$).

Results

Muscle Measurements

The TrA, IO, and EO were measured to make up an average (SD) of 30 (4.0), 39 (3.1) and 31 (3.6) percent of the total thickness of the abdominal wall, respectively. The EO fibers were measured to act at an average (SD) angle of 46° (3.7) from the line of pull of the TrA fibers, in an inferior-medial orientation, whereas the IO fibers were measured to act at an average (SD) angle of 50°

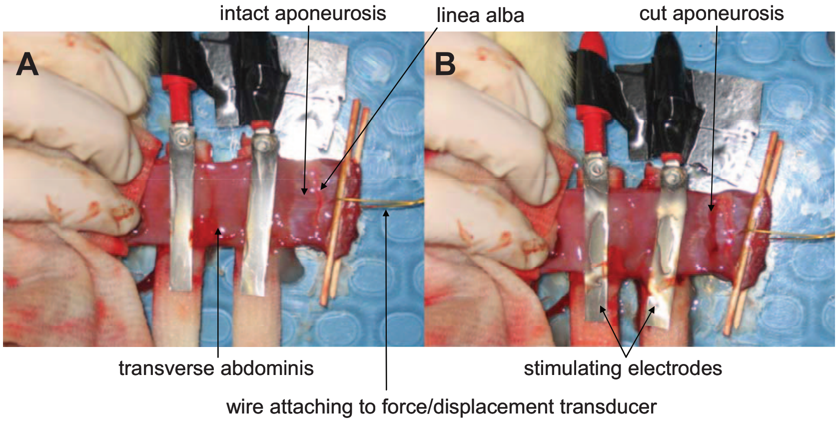

Figure 2. Picture of the abdominal wall in the intact state (**A**) and with the TrA aponeurosis cut (**B**). Note that both the IO and EO muscles are intact and attached beneath to the TrA muscle.

(3.0) from the line of pull of the TrA fibers, in a superior-medial orientation.

As the fibers of the EO and IO would transmit a proportion of their active force equal to the cosine of their angle of pull, it was estimated that the force transducer would record approximately 69% and 64% of the force of these muscles, respectively. Considering these proportions in the total force recorded at the transducer, the TrA should produce approximately 39% of the total active force recorded in the current experiment. Thus, if the force from the TrA was completely eliminated by the cutting of the aponeurosis, a force drop of 39% would be expected.

The Effect of Cutting the Aponeurosis

There was no significant difference in the passive abdominal wall force between the intact and cut aponeurosis conditions ($P = 0.6195$; mean/SD (g) = 15.2/11.8 intact; 13.4/10.9 cut). Thus, there was no statistically significant change in the passive state of the abdominal wall, most likely indicating that no significant length change occurred as a result of the cutting of the aponeurosis.

The active force produced by the abdominal wall did not change in a statistically significant manner ($P = 0.0998$), although there was a definite trend of a reduced active force production when the aponeurosis was cut (mean/SD (g) = 235.7/46.2 intact; 210.8/47.4 cut) (Figure 3). This amounted to a drop in active force of 10.6%.

The stiffness of the abdominal wall significantly reduced ($P = 0.0346$) as a result of the cutting of the posterior aponeurosis (mean/SD (g/mm) = 104.3/16.1 intact; 93.1/16.2 cut) (Figure 4). This amounted to a drop of 10.7%.

The Effect of Time

Five rats served as controls to determine if the reductions in active force and stiffness were influenced by the amount of elapsed time between the measurements pre and post the cutting of the aponeurosis. The average amount of time that was required to cut the aponeurosis and begin retesting was approximately 3 minutes, thus this amount of time was allowed to elapse in the control group whereas the aponeurosis remained intact. Percent

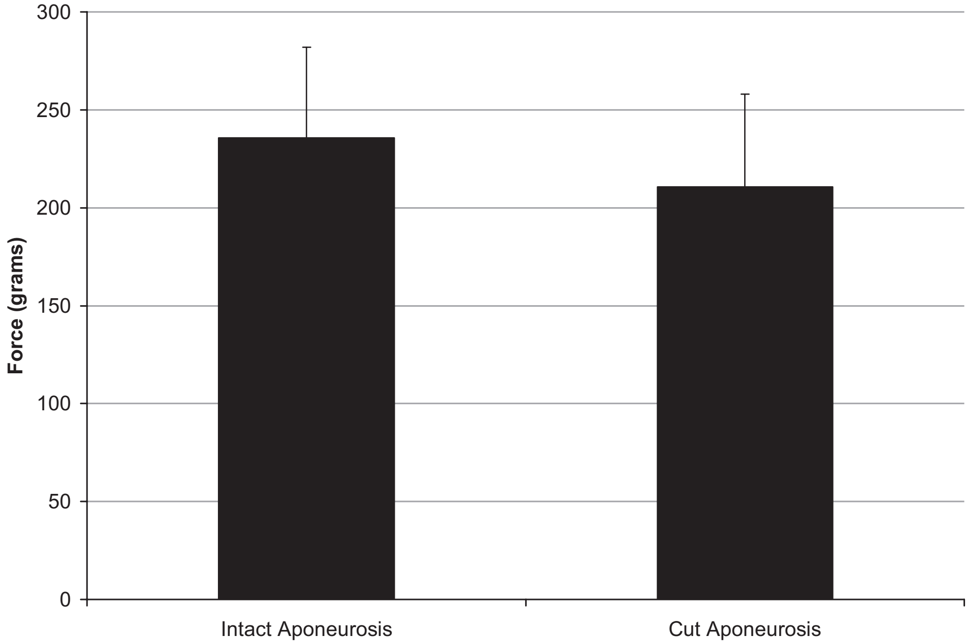

Figure 3. Average active force generated by the abdominal wall in the intact and cut aponeurosis states. Standard deviation bars are shown.

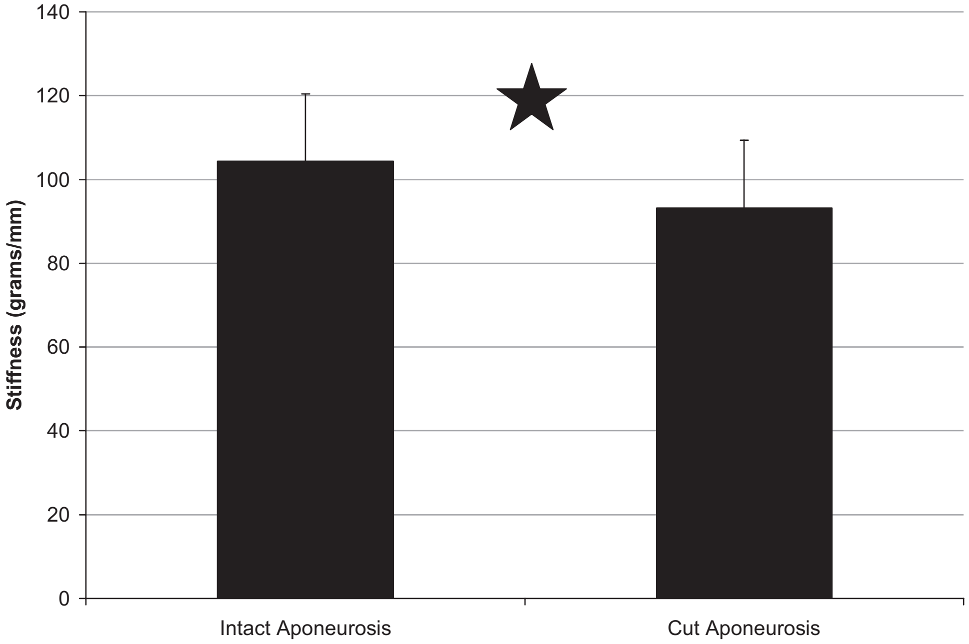

Figure 4. Average abdominal wall stiffness in the intact and cut aponeurosis states. The star indicates a statistically significant difference between the 2 states ($P < 0.0346$). Standard deviation bars are shown.

drops of 7.9 and 8.2 were found for active force and stiffness, respectively. These reductions are below, but approaching, the reductions determined for the cut aponeurosis state (Figure 5), thus indicating that at least a portion of the drop in these parameters was a result of the passage of time in a compromised muscular state.

■ Discussion

Cutting of the posterior aponeurosis of the abdominal wall, thereby eliminating the direct path of force transmission of the TrA muscle, did not reduce the force and stiffness production of the abdominal wall to a level that would be expected had the TrA been completely eliminated. Thus, force and stiffness generated by the active contraction of this muscle was transmitted in another manner, most likely through the connective tissue attachments binding it to the IO muscle, and still resulted in a highly significant portion of its force and stiffness reaching its originally intended point of application.

It was estimated, based on measurements of the sizes and orientations of the 3 abdominal wall muscles, that the TrA should be responsible for producing approximately 39% of the active force and stiffness recorded horizontally (in line with the TrA fibers) at the linea alba. The average percent drops in these 2 variables measured in the current study when the TrA aponeurosis was cut were 10.6 and 10.7, respectively, or approximately 27% of the reduction that would be expected had the TrA been

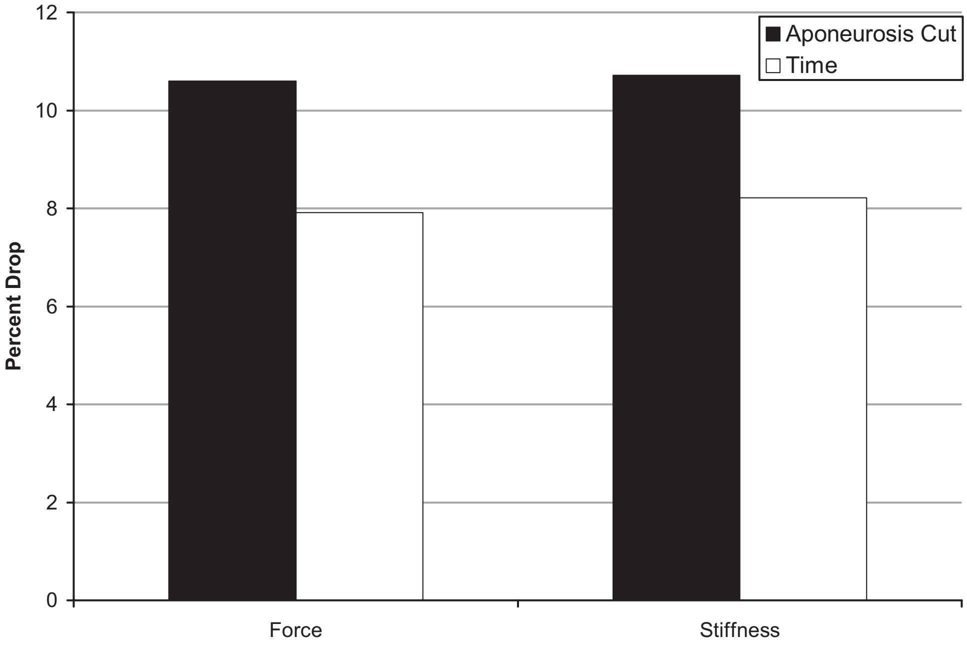

Figure 5. Percent drops, relative to the initial state, in each of abdominal wall active force and stiffness in the cut aponeurosis and time elapsed conditions.

completely eliminated. Therefore, in a best case experimental scenario, where the only variable affecting the force and stiffness recorded was the status of the aponeurosis, 73% of the force and stiffness generated by the TrA was transferred through alternate means to the linea alba.

Because of the highly invasive nature of the surgery required to isolate a portion of the abdominal wall, it was suspected that the blood supply to the muscle group may have been disrupted to the point that the function of the muscles may have degraded over time. Indeed, in the control group comprised of 5 rats, an elapsed amount of time approximately equal to the time required to perform the cutting of the aponeurosis, resulted in a reduction in both active force and stiffness, despite the aponeurosis remaining intact (Figure 5). This further strengthens the argument that the force and stiffness actively generated by the contraction of the TrA were transferred through alternate connective tissue attachments in the situation in which the aponeurosis was cut. Considering that the passage of time may have had a significant influence on force and stiffness generation, it appears possible that nearly the complete force and stiffness production reached its intended destination through alternate transfer means.

Numerous research studies have in recent years demonstrated the ability for muscle force to be transferred through nontendinous means.[6–8] Connective tissue networks are able to transmit force in a fairly efficient manner, highlighted when the normal route of transmission is disrupted, and the force maintains a substantial proportion of its original output.[9,10] The unique anatomic design of the abdominal wall seems especially capable of this type of force transfer. The 3 sheet-like abdominal wall muscles (TrA, IO, EO) are tightly bound to one another through complex connective tissue attachments. The current study has demonstrated that these connective tissues seem capable of transferring at least the vast majority (73%) of the force and stiffness generated by a single muscle in the situation where the traditionally held "normal" route of transmission has been removed. It would normally be expected for some force generating capability to be lost due to the cutting of the aponeurosis, as the muscle to which it was attached would shorten, thereby inhibiting its force producing ability, until a point is reached at which the shear strain of the interconnective tissues has reached a level of sufficient stiffness to allow the requisite force transmission. That the force drop measured in the current study is, at most, relatively low suggests an inherently high shear modulus between the muscle layers. It is not possible from the current study to determine the degree to which, if at all, this intermuscle connective tissue transmission route is used in the healthy or undamaged state; however, it can be stated that the force produced by the muscles will be transferred in the majority through the stiffest path. The suspected high shear modulus may suggest that force would be readily transferred between the muscle layers during *in vivo* situations. However, future work will need to isolate the stiffness of the connective tissues intervening the musculature and comprising the aponeuroses to definitively ascertain the most likely routes of force transmission.

The importance of this work lies in the establishment of the probable functional necessity of the anatomic arrangement of the abdominal wall musculature. The abdominal muscles, and their connective tissue networks, produce, respond to, and are acted on by a variety of complex forces and demands. The improper functioning of the abdominal muscles, in particular, has been shown to be highly linked to low back pain and injury.[11,12] The connective tissue attachments binding the muscles to one another may promote a more synergistic and unified mechanical function, thereby enhancing the stabilizing and stiffening effect of the muscle group while still enabling the generation of multifaceted movement patterns. Recent work has documented that individual abdominal wall muscles and regions within muscles can be neurally activated in a relatively independent manner.[13–15] Mechanical links between the muscles may allow for this independent neural activation to enable complex function while still ensuring that force and stiffness generated by these muscles is well distributed around the torso. Further, neural deficits in a single or small group of muscles, although clearly detrimental, may be somewhat protected against by the ability of the activation of the other muscles to transfer their capabilities to produce similar mechanical effects.

Because of the constraints of the testing system, submaximal stimuli were used to activate the abdominal wall. This level of activation was most likely beneficial to test the hypotheses posed in the current study. Meijer *et al*[16] recently demonstrated that transmission of muscle force through nontendinous connective tissues was more relevant and important to the *in vivo* situation at lower levels of force generation. Further, these lower levels of activation are much more representative of the levels that would be seen in the human abdominals during every day tasks.[17,18] Indeed, maximal abdominal activation levels are rarely accomplished, even during near maximal torque generation situations,[1,19] and levels of approximately 1 quarter of maximal are considered very difficult to achieve during isometric contractions that are generally associated with a stabilizing function.[20,21] Finally, the rat model seems justifiable for the purposes of the *in situ* work performed in the current study, given that previous work has established precise similarities to humans in terms of morphology and architecture of the muscles, intervening connective tissues, and aponeuroses.[22,23] Therefore, it is likely that the mechanical effects of the muscular and connective tissue structures presented here for the rat will be similar for the human abdominal wall.

From the results of the current study, it can be concluded that the vast majority of the force and stiffness generated by the abdominal wall muscles, particularly the TrA tested here, can be transferred around the abdomen through the linea alba, even when the normal route of transmission (aponeurosis) is eliminated. The most likely alternative path of transmission is through the connective tissue network that intervenes the 3 muscular layers. This may enlighten the ability of these muscles to work in a mechanically synergistic fashion, thought to be necessary to effectively stabilize the spinal column, through the linking of force and stiffness during contraction. Thus, the muscles of the abdominal wall should not be considered as totally independent from one another in terms of their mechanical function. Their activation and corresponding force and stiffness output will highly influence each of the other muscle layers, making the intact wall a synergistically functioning muscle unit. In this way, it seems that the abdominal wall functions as a composite laminate structure; this architecture results in substantial multidirectional stiffness where the activation of each muscle layer augments the total stiffness. This stiffening function will directly protect against unstable behavior of the spinal column, and rehabilitate the unstable spine related to low back pain and injury.

■ Key Points

- The ability of muscularly generated force and stiffness to be transferred between layers of the abdominal wall was investigated.
- Force and stiffness generated by the abdominal wall were reduced when the transverse abdominis aponeurosis was disrupted.
- These reductions (approximately 10.6%) were less than would be expected had the transverse abdominis been completely eliminated (approximately 39%).
- It was concluded that the majority of force and stiffness was transferred through the connective tissue attachments that bind the muscle layers together.
- This suggests a stiffening composite laminate function of the abdominal wall architecture.

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