ORIGINAL ARTICLE

Quantification of Lumbar Stability by Using 2 Different Abdominal Activation Strategies

Sylvain G. Grenier, PhD, Stuart M. McGill, PhD

ABSTRACT. Grenier SG, McGill SM. Quantification of lumbar stability by using 2 different abdominal activation strategies. Arch Phys Med Rehabil 2007;88:54-62.

Objective: To determine whether the abdominal hollowing technique is more effective for lumbar spine stabilization than a full abdominal muscle cocontraction.

Design: Within-subject, repeated-measures analysis of variance was used to examine the effect of combining each of 4 loading conditions with either the hollow or brace condition on the dependent variables of stability and compression. A simulation was also conducted to assess the outcome of a person activating just the transversus abdominis during the hollow.

Setting: Laboratory.

Participants: Eight healthy men (age range, 20−33y).

Interventions: Electromyography and spine kinematics were recorded during an abdominal brace and a hollow while supporting either a bilateral or asymmetric weight in the hands.

Main Outcome Measures: Spine stability index and lumbar compression were calculated.

Results: In the simulation "ideal case," the brace technique improved stability by 32%, with a 15% increase in lumbar compression. The transversus abdominis contributed .14% of stability to the brace pattern with a less than 0.1% decrease in compression.

Conclusions: Whatever the benefit underlying low-load transversus abdominis activation training, it is unlikely to be mechanical. There seems to be no mechanical rationale for using an abdominal hollow, or the transversus abdominis, to enhance stability. Bracing creates patterns that better enhance stability.

Key Words: Abdominal muscles; Back injuries; Low back pain; Motor skills; Rehabilitation; Spine.

WITH A GOAL TO DECREASE low back pain (LBP), stabilizing exercises, along with modifications of other daily activities, have been shown to be effective in randomized clinical trials.[1,2] However, the source of this effect is uncertain. This study assessed the influence of different abdominal activation strategies on mechanical stability in the lumbar spine. Lumbar spine stability is an important issue, especially given its potential link to mechanisms of injury and associated clinical efforts directed toward enhancing stability in patients.[3] The way in which patients activate their abdominal muscles is central to the stability theme. For example, findings that transversus abdominis is recruited later, in some LBP sufferers, have led to speculation that it is related to an unhealthy or unstable spine.[4] The strategy to recruit the transversus abdominis, through the abdominal hollowing technique, has been proposed as an effective way to increase stability.[5] Richardson et al[6] investigated the effect of bracing and hollowing on sacroiliac joint laxity in a nonfunctional task. They found that both improved stiffness but concluded that hollowing was better. However, the muscle resting levels differed between groups. Until now, most of the supporting evidence, for the transversus abdominis being an important contributor to stability, has been indirect and qualitative.

Motivation to focus on the transversus abdominis in the clinic has been provided by Hodges and Richardson[5] who documented delays of the transversus abdominis during rapid arm movements in some people who have a history of low back disorders, although this result has not been confirmed in recent reports.[7-9] It has also been suggested[9] that, although the direction of limb movement does not affect preactivation time, the magnitude of the arm movement perturbation does. Although this does not provide direct evidence linking the transversus abdominis to stability, it was suggested that this is evidence of motor control deficit in chronic back pain patients. Additional evidence of other types of motor control deficiencies in those with LBP include larger delays of onset in several torso muscles when the entire torso is moved quickly,[10] inhibition of knee extensors,[11] and perturbed gluteal patterns while walking and inability to simultaneously breathe heavily and maintain spine stability.[12]

It appears that the transversus abdominis may be activated independently of other abdominal muscles at very low levels of challenge (1%−2% of maximum voluntary contraction [MVC]).[6] But at higher levels of activation, when people perform tasks requiring spine stability, the transversus abdominis has also been shown to be a synergist of internal oblique.[13] Some clinical trials, testing the "stabilization exercise," have shown success in addressing LBP.[1,2] However, none of these studies have showed a direct link to the transversus abdominis and the mechanism for efficacy is not known. For example, Vezina and Hubley-Kozey[14] have measured abdominal wall activation levels during abdominal hollowing exercises and reported that none of their subjects were able to activate only the transversus abdominis. Furthermore, Davidson and Hubley-Kozey[15] showed that, as the demand of an exercise progression increased, the abdominal muscles converged, such that all muscles were activating to the same percentage of maximum at the highest exercise level. A recent study[16] suggests that hollowing and attempts to specifically activate the transversus abdominis reduced the efficacy of the exercise. One could argue that there is no quantitative evidence identifying the transversus abdominis as an important stabilizer, although our own clinical efficacy study[17] has shown that stabilization exercises are effective for patients with LBP.

From the Spine Biomechanics Laboratory, Department of Kinesiology, Faculty of Applied Health Sciences, University of Waterloo, ON, Canada.

Supported by the Natural Sciences and Engineering Research Council of Canada (grant no. RGPIN36516-98).

Reprint requests to Sylvain G. Grenier, PhD, Biomechanics, Ergonomics and Kinesiology Laboratory, School of Human Kinetics, Laurentian University, Sudbury, ON P3E 2C6, Canada, e-mail: *sgrenier@laurentian.ca*.

0003-9993/07/8801-10692$32.00/0
doi:10.1016/j.apmr.2006.10.014

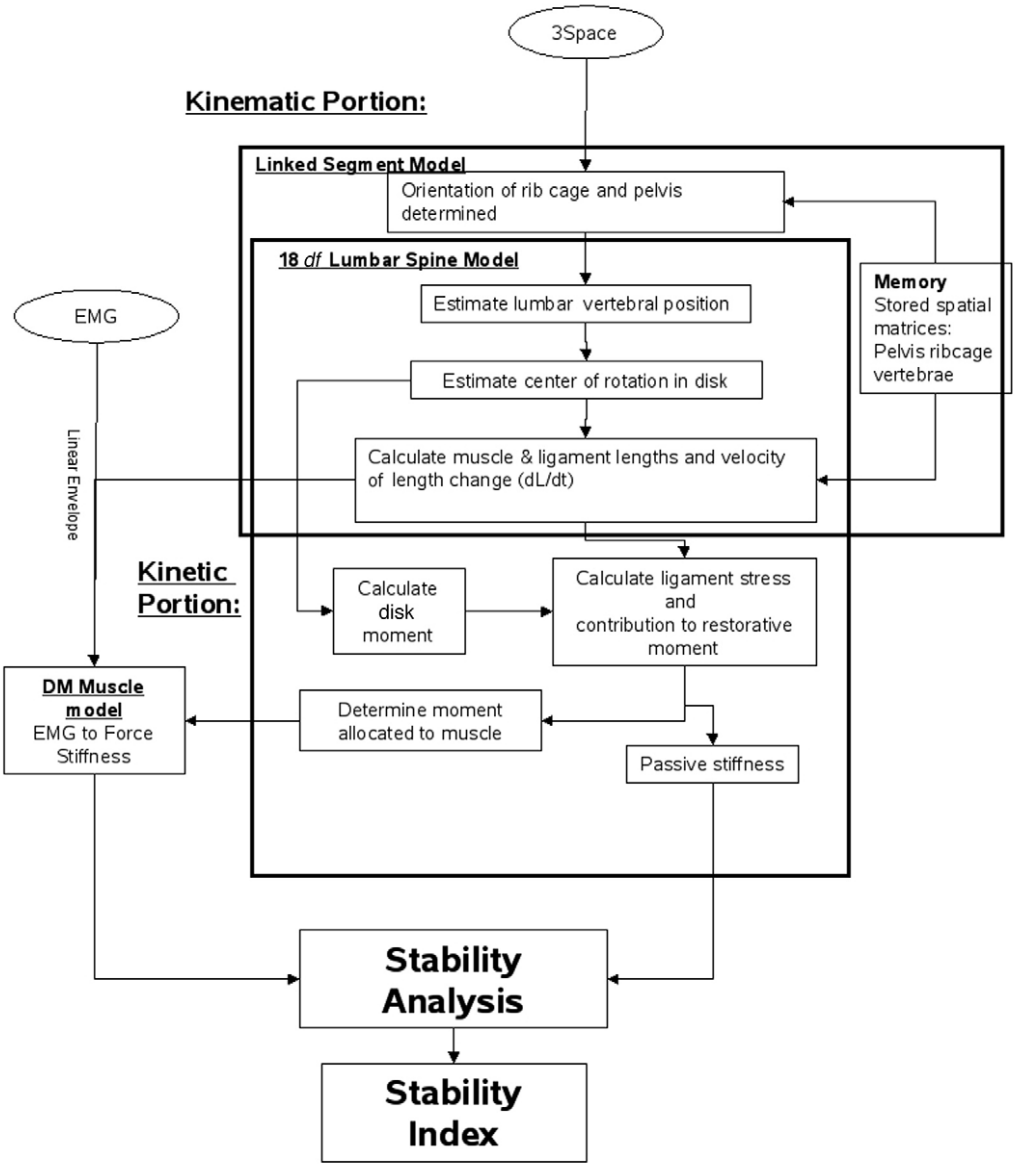

Fig 1. Stability analysis. This schematic depicts the process leading up to the calculation of stability. Abbreviations: DM, distribution moment; dL/dt, derivative of length with respect to time; EMG, electromyography.

Nevertheless, it is not possible to make legitimate claims as to the stabilizing role of any specific muscles, only that the general approach was effective.

Quantification of Stability

The definition of stability is a critical issue. Because clinicians generally do not have the technical capability to quantify stability, kinematic "indicators" of instability have evolved. In and of itself, this is not a problem, except that these indicators can be disguised with appropriate muscle recruitment. Stability, as assessed in this study, is defined as the ability of the spinal column to survive an applied perturbation (known as Euler column stability). If the work done (input energy or disturbance) is greater than the potential energy of the column (energy stored in disks, ligaments, muscles, tendons), equilibrium will not be regained. From a clinical perspective, there is a subtle, but important, difference between excessive motion and instability; excessive motion does not imply instability, only the potential for instability (for a detailed description, see Cholewicki and McGill[18]). The model used in this experiment, which quantifies stability in this mechanical sense, is fully described elsewhere,[19] although an overview is provided here (fig 1).

In the context of lumbar stability, the effect of the transversus abdominis on the spine is still inconclusive. Isolated contraction of the transversus abdominis beyond very low levels of activation has not been measured because all abdominal muscles become involved at more functional levels of activation (5%−20%).[15] An investigation of specific abdominal muscle activation strategies and individual muscles' role in that strategy should provide insight to the clinical decision-making process. The hollowing technique has been developed as a transversus abdominis motor pattern retraining technique by Jull and Richardson[20] to address the motor disturbances. It appears that others have assumed that it should be used as a technique to enhance spine stability. This article evaluates 2 abdominal activation strategies, hollowing and bracing, which are techniques used clinically to improve lumbar spine stability. Given the clinical issue stated previously and our previous work[21,22] examining the stabilizing role of many torso muscles, we were motivated to quantify the mechanical impact of the 2 strategies on lumbar stability. It was therefore hypothesized that the abdominal hollowing strategy would be inferior to that of a bracing strategy for enhancing stability. Spine stiffness is always stabilizing (summarized in McGill[23]). The question motivating this study therefore is as follows: is the isolated transversus abdominis recruitment associated with the abdominal hollowing technique a more effective stabilizer than a full abdominal girdle cocontraction?

METHODS

In the present study, the comprehensive lumbar spine model used to quantify stability[19] was enhanced to include a representation of transversus abdominis. Because pilot work showed that none of our subjects could perform an ideal "hollow"[6] (ie, activating only the transversus abdominis and internal oblique), simulations were also conducted to artificially activate the muscles in an "ideal" way. This was done, together with real, in vivo data collection, with the understanding that subjects may have had imperfect technique. In this way, we were able to evaluate "perfect hollowing" and bracing, as well as the imperfect clinical reality.

Data Collection

The study proceeded with 2 components in parallel. The first was the in vivo data collection, and the second was the simulation. During the in vivo task, torso muscle electromyographic activity and spine kinematics were recorded from each subject. These data were then input to the biomechanic model to determine spine stability. In the simulation, a single subject's data were modified to reflect the anatomic and electromyographic changes associated with an "ideal" hollow and brace. In this way, several combinations of muscle activation were tested to assess their effect on stability.

In vivo: subjects. Data were collected from 8 healthy (no back pain in the past year) men between the ages of 20 and 33. All subjects provided informed consent, and the study was approved by the university ethics committee. Subjects had a mean height ± standard deviation (SD) of 1.82±0.06m (range, 1.73−1.88m), a mean weight of 79.8±11.5kg (range, 60.5−93.6kg), and a mean age of 23.8±4.33 years (range, 20−33y). None had any experience with the transversus abdominis recruitment training.

In vivo: kinematics. Spine kinematics were recorded with a 3Space Isotrak unit,[a] which measured lumbar flexion and extension, lateral bend, and axial twist at a sample rate of 60Hz. The 3Space electromagnetic field source was strapped in place over the sacrum, and a sensor was worn over the T12 vertebrae, isolating lumbar motion. The 3Space unit returns Euler angles. These were adjusted for anatomic relevance to the spine's orthopedic axes. Flexion and extension corresponds to rotation about y, lateral bend to rotation about x, and twist to rotation about z.[24]

In vivo: electromyographic activity. Electromyographic signals were obtained by using Ag-Ag/Cl Meditrace surface electrodes,[b] in a bipolar configuration, spaced 25mm apart, in line with muscle fiber directions.[25] The signals were then amplified[c] (12-bit analog-to-digital conversion; sampling rate, 1024Hz; frequency response, 10−1000Hz; common mode rejection ratio, 115dB at 60Hz; input impedance, ≈10GΩ). As per the previously validated electrode positions,[19] 7 muscles on each side of the body were recorded for a total of 14 muscles, including the rectus abdominis (2cm lateral to the umbilicus), internal oblique (caudal to the anterior superior iliac spine and medial to the inguinal ligament), external oblique (15cm lateral to the umbilicus), latissimus dorsi over the muscle belly (15cm lateral to T9), thoracic erector spinae (5cm lateral to T9 over the muscle belly), lumbar erector spinae (3cm lateral to L3), and the multifidus (2cm lateral to L5, angled slightly with superior electrode more medial). The electromyographic signals were normalized to the amplitudes measured during the MVC procedure after rectification and low-pass filtering at 2.5Hz. In addition to preparing the electromyography for force estimation, this process also removed electrocardiographic interference.

MVCs, for normalization, were performed in 2 separate trials.[26] First, the abdominal flexors were contracted maximally in a seated position, leaning backward at 45°. Then, the extensors were contracted maximally in a Biering-Sorensen position.[27] In both cases, the experimenter provided sufficient resistance for a maximal isometric contraction. Once this was done, the hollowing and bracing strategies were explained and demonstrated.

In vivo: protocol. Subjects were asked to hollow their abdomen without sucking in their belly. They were told that they should be able to breathe normally. Assuming that the transversus abdominis was synergistic in its activation with the internal oblique,[13] the subjects practiced until they were able to easily achieve the required internal oblique activation target of 20% of MVC, as displayed on an oscilloscope. This compares with a range of approximately 12% of MVC of external oblique activation in hollowing and 32% of MVC of external oblique activation in bracing measured by Richardson et al.[6] A brace is different from the hollow in several ways; the brace involves activation of all abdominal muscles to a level that increases torso stiffness. This does not mean that no motion can occur, only that the motion is controlled. Furthermore, abdominal bracing causes the back extensors to become active, which further enhances spine stiffness. Initially, the electromyographic patterns were verified with oscilloscope, and observations of initial muscle contraction with ultrasound ensured that the activation patterns reproduced the technique reported in the literature.[6] The ultrasound probe was placed at the rectus border so that the 3 layers of the abdominal wall could be viewed. In the current study, there were considerable variations in the recruitment patterns used to achieve the hollowing. Hollowing trials were collected when subjects could show, on an oscilloscope, a decrease in external oblique and rectus abdominis activity, along with an increase in internal oblique activity, although this increase was often minimal. The testing was performed in an anatomically neutral standing posture, with a 10-kg load in either or both hands, depending on the condition. Over a period of 25 seconds, subjects were then asked to relax for 5 seconds, "hollow" the abdomen for 5 seconds, relax for 5, "brace" the abdomen for 5 seconds, and relax for the final 5 seconds. These trials were repeated, in random fashion, 3 times each with (1) no load in the hands (bilateral no lift), (2) with 10kg in each hand (bilateral lift), (3) 10kg in the right hand only, and finally with (4) 10kg in the left hand only. Different load conditions were used to target the effect of asymmetric activation, as well as to address the issue of increased intervertebral stiffness with higher compression loads. The kinematic and electromyographic data were then input to the custom stability model. Note that, for this part of the experiment, because transversus abdominis activity was not measured, it was assumed to be a synergist of the anterior and caudal portions of internal oblique. Thus, the internal oblique recording was used to drive the transversus abdominis in the model. Two studies have shown this to be a realistic assumption.[13,28]

Data-Collection Procedures

Quantification of stability. Spine stability was calculated by computing the potential energy of the spinal system. For the purpose of summing potential energy, the muscle and tendons were considered as linear springs, whereas the intervertebral disks were considered as torsional springs. The elastic potential energy was then summed in each rotational degree of freedom, and the work done by the external load was then subtracted from this. The second derivative of the potential energy matrix, if greater than or equal to 0, indicated a stable system.[19] This method of quantifying stability has been applied to mechanical structures and validated repeatedly in civil and mechanical engineering.[29] Its application to the osteoligamentous spine has also been validated.[30-32] Specific components of the model are described as follows.

Passive contribution to potential energy. The skeleton of the model consisted of 5 lumbar vertebrae between a rigid pelvis and sacrum and a rigid ribcage. The vertebrae were linked by torsional springs representing the vertebral disks, which generated passive stiffness and allowed rotation but no translation (about 3 orthogonal axes). Three-dimensional lumbar motion, measured with the 3Space Isotrak was proportionally distributed among all vertebrae.[33] The stiffnesses, including stiffness of the disks, ligaments, fascia, skin, and viscera,[34] were also distributed among the vertebrae.[19,33]

Active contribution of potential energy. In addition to the restorative moment of the passive tissues, the muscles also contributed a restorative moment to balance the external load (fig 2). The muscle force and stiffness estimates were obtained from a distribution-moment muscle model that used electromyographic and muscle length as input.[35] The muscle forces were then applied through 118 muscle fascicles to the skeletal components such that the moment they created balanced the moment generated by the external load. Stability calculations used all of these variables as input, together with the muscle stiffnesses calculated by the distribution-moment model.[36]

Modifications to the model. Anatomic improvements were made to better represent the application of transversus abdominis forces on the spine. Specifically, the fascial attachment of the transversus abdominis on the lumbar vertebrae was represented with 10 fascicles bilaterally on the 5 segments (2 originating on the posterior tip of the lumbar spinous processes and the other 2 originating on the transverse process of the lumbar vertebrae). To capture the line of action of the fascial attachments on the posterior spinal processes, the 10 fascicles converged on a point 60cm directly lateral of L5. This arrangement also closely approximated the experimental findings of Tesh et al[37] that the compression cosine of the lateral transversus abdominis force was 39% of its resultant magnitude. Because transversus abdominis activity was not measured, the stiffness of the transversus abdominis was calculated by using internal oblique activity magnitude because these have been shown to be synergistic. The length of the transversus abdominis fibers was calculated based on the real hoop-like architecture of the muscle. This architecture was intended to simply evaluate the effects of the muscles recognizing their attachment to the spine. There were no assumptions made regarding the role of intra-abdominal pressure to stiffen the abdominal wall.

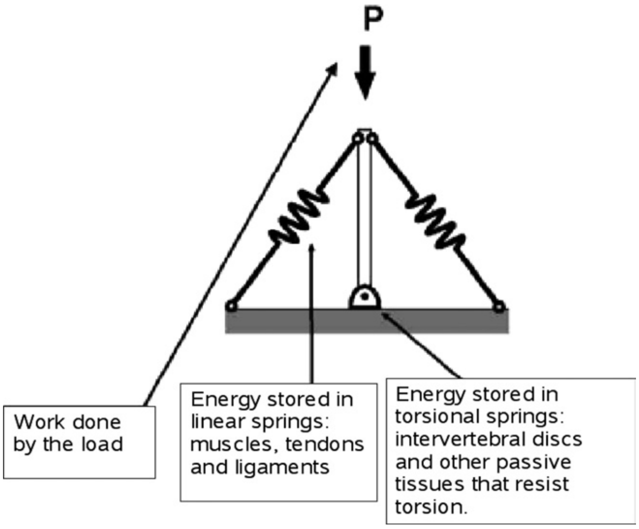

Fig 2. A schematic representation of a simplified spine motion segment to show the concept of linear (muscles, ligaments, tendons) and torsional (intervertebral disks) springs working to sustain an applied load.

Simulations. The objective of the simulation trials was to artificially adjust abdominal muscle activity levels to imitate "ideal" hollowing and bracing strategies because subjects could not completely isolate, or preferentially activate, any single abdominal muscle to the extent required.

A total of 1 each of 5 types of simulations was performed.

1. Simulation of the hollowing strategy: the transversus abdominis and internal oblique electromyographic signals were adjusted to an activity level at 20% of MVC, whereas the rectus abdominis and external oblique were adjusted to 2% of MVC. The activity levels in the back extensor muscles were simply those measured.
2. Simulation of the bracing strategy: all abdominal electromyographic signals were replaced by activity at 20% of MVC. The activity levels in the back extensor muscles were simply those measured.
3. Simulation of the bracing strategy: the stabilizing effect of the transversus abdominis was evaluated, and isolated, with a sensitivity test in which transversus abdominis activation was zeroed during a bracing simulation (bracing with no transversus abdominis).
4. Simulation of the bracing strategy: the procedure in simulation 3 was repeated by zeroing each abdominal muscle pair, similar to the muscle "knockout" approach of Cholewicki and VanVliet.[38]
   A. A right and left external oblique set to 0% of MVC.
   B. A right and left internal oblique set to 0% of MVC.
   C. A right and left rectus abdominis set to 0% of MVC.

In addition to these trials, across conditions, a sensitivity analysis was also conducted to assess the effect of the transversus abdominis alone on stability. First, only the transversus abdominis was set to 0% of MVC. This was compared with the condition in which all abdominal muscles were left untouched. Then, all abdominals except for the transversus abdominis were set to 0, whereas the transversus abdominis was set to 20% of MVC and then to 100% of MVC so that the transversus abdominis was the only active muscle. In addition to modifying the muscle activity of selected muscles in all simulations, the moment arm of rectus abdominis (and consequently the attachments of internal and external oblique) was shortened by 5cm, for the hollowing simulations, to mimic the "drawing in" of the abdomen (figs 3, 4). These artificially modified data were then input to the spine stability model as described earlier and in figure 1.

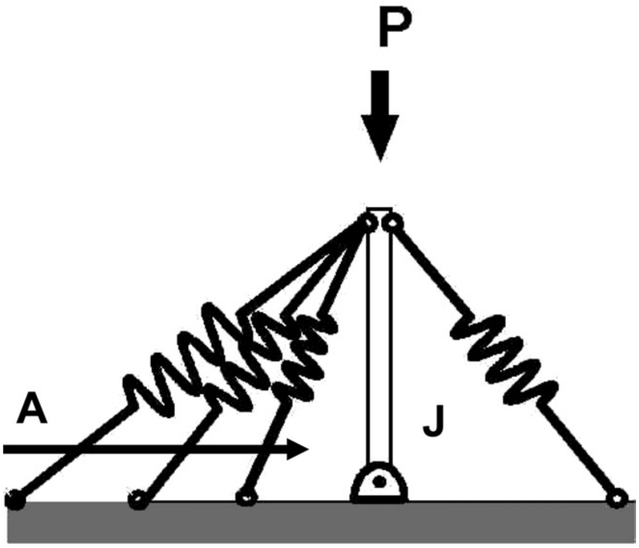

Fig 3. Because the moment is calculated as the product of force and perpendicular distance, moving the muscle attachment (A) closer to the joint (J) (as occurs during hollowing) shortens the moment arm of rectus abdominis. This has a large effect on the resulting potential energy, and, consequently, stability as well. Stability of a column with guy wires (or a spine with muscles) is a function of geometry (the location of the support attachments), stiffness, the "balance" in stiffness in all directions, and column imperfections, such as curvature. Hollowing reduces the potential energy and stability by narrowing the geometric base.

Statistical Analyses

The dependent variables from the in vivo trials were spine compression and the stability index, which is a general indicator of the stability of the equilibrium state of the spine.[19]

In vivo analysis. Using the R statistical package,[39,d] a within-subject, repeated-measures analysis of variance was performed to examine the effect of combining each of 4 loading conditions with the hollow or brace condition on the dependent variables of stability and compression. In this study then, the independent variable of "muscle activity pattern" had 2 conditions, hollowing and bracing, whereas the second independent variable of "load type" had 4 conditions: (1) load in both hands, (2) no load, (3) right-hand load, and (4) left-hand load. The Tukey post hoc honestly significant difference test was used to investigate differences.

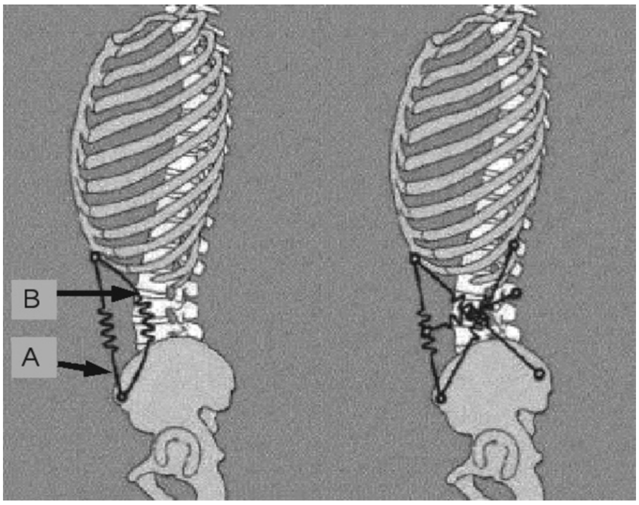

Fig 4. In the hollowing simulation, the moment arm of rectus abdominis was reduced by 5cm ("B" in left panel), when compared with the bracing condition (right panel), to account for the change in anatomic geometry. "A" defines the relaxed condition.

Table 1: Mean Stability and Compression Value From In Vivo Data Trials

Trial	Mean Stability Index (Nm/rad)	Mean Compression (N) at L4-5
Hollowing: no load	474.6±85.4	1866.5±451.4
Hollowing: 2-hand load	495.6±70.8	1929.2±360.0
Hollowing: left-hand load	517.7±55.8	2003.0±264.6
Hollowing: right-hand load	533.4±57.7	2041.7±286.6
Bracing: no load	511.3±39.5	1911.0±189.0
Bracing: 2-hand load	527.3±59.8	1989.1±247.9
Bracing: left-hand load	555.0±70.1	2060.4±223.1
Bracing: right-hand load	546.1±59.7	2008.6±266.1

NOTE. Values are mean ± SD. In the case of stability, there were differences between muscle activity patterns (bracing > hollowing, $P<.001$) and between the loading conditions ($P=.009$). The compression values had no differences, either between loads or between activation types.

Simulation analysis. Simulation trials were compared to the reference bracing trial, with the "muscle knockout" model, as well as with the simulated hollowing condition by using a paired t test. The change in (dependent) compression and stability index between bracing and hollowing trials was expressed as a percentage change.

$$\%\ \text{change} = \frac{\text{BRC} - \text{HLW}}{\text{BRC}} \times 100 \tag{1}$$

where BRC is bracing and HLW is hollowing.

RESULTS

Bracing stability was always greater than hollowing stability, and asymmetric loads always produced greater stability than symmetric loads. In in vivo trials, stability differed significantly for hollowing and bracing conditions (bracing > hollowing, $P=.001$) and between the loading conditions ($P=.009$) (table 1). Figure 5 shows a hollow-brace composite for 1 subject showing this difference. Compression values were not different, either between hollowing and bracing ($P=.54$) or between loading conditions ($P=.095$). One of the subject's results were excluded because the abdominal recruitment patterns were not consistent with what had been requested for the trials (ie, hollowing of the abdomen was not achieved with a 20% of MVC internal oblique activation). Post hoc testing revealed that spine stability, in the no-load condition, was less than both right- and left-side loads but not less than the bilateral load condition.

The simulation data supported the in vivo data, showing that the hollowing was not as effective as bracing for increasing stability in the lumbar spine. In fact, bracing improved stability over hollowing by 32%, with only a 15% increase in compression. Figure 6 shows the difference in stability, whereas figure 7 shows the difference in compression for 1 in vivo subject. In table 2, 1 subject's data were used for the simulation. The unmodified hollow data were compared, for that subject, with the brace data. The various simulations were also compared with the full brace trial. When removing only the transversus abdominis from the bracing pattern (see table 2, Simulation

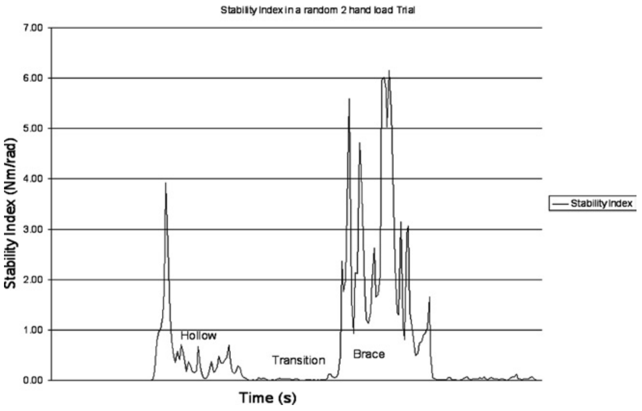

Fig 5. A composite of 2 trials of in vivo subject data (a 2-hand load trial chosen at random) shows that bracing had greater stability than an attempted hollowing. The ideal hollowing was not achieved. Ideal hollowing was tested in the simulations. Note the initial overactivation when trying to establish the hollow.

bracing: no transversus abdominis), stability decreased by .14% with a less than 0.1% decrease in compression. Furthermore, the importance of the transversus abdominis relative to other abdominal muscles in affecting stability was very small when assessed by a "muscle-knockout" approach[40] (P=.01) (fig 8).

DISCUSSION

Is the abdominal hollowing technique and its specific transversus abdominis recruitment pattern a more effective stabilizer than a full abdominal girdle cocontraction? These data suggest that it is not. The bracing strategy provided greater stability than hollowing in both the simulation and in vivo data. Furthermore, for our subjects, the ability to activate just the transversus abdominis at functional levels was extremely challenging, if not impossible, as evidenced by all other abdominals' electromyographic activity not being silent. This suggested that the attempt to hollow would, in effect, result in some degree of bracing. The simulations showed that the transversus abdominis had virtually no effect on stability. Although Hodges et al[41] have shown that the transversus abdominis does contribute stiffness to the spine in a porcine model, our sensitivity tests (see fig 8) show that its relative contribution is very small when compared with the other abdominal muscles. Assessment of this relative performance was absent from their experiment. Performing a hollowing pattern by using just the transversus abdominis greatly reduced stability, as opposed to all other abdominal muscles being active (fig 9). In addition, the compression-stability ratio favored bracing. The fact that the bracing strategy was more effective at stabilizing than the hollowing strategy should not be interpreted as evidence to diminish abdominal hollowing as a tool for training, or retraining the recruitment of the transversus abdominis from a motor control perspective, because this muscle does form a component of the abdominal girdle. However, many therapists and coaches, in our experience, recommend "drawing in" of the abdomen in an effort to increase stability. Based on our results, this appears to be misdirected. In fact, 2 studies have recently concluded that focusing on general activity[42] and nonspecific exercise[16] is more beneficial for both pain reduction and functionality.

Study Limitations

Several limitations should be addressed to guide interpretation of these results. The transversus abdominis in the model

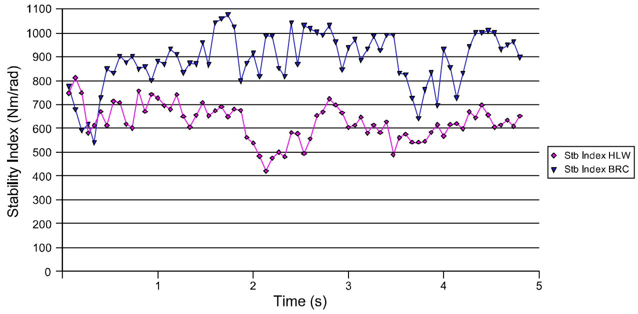

Fig 6. Lumbar stability increased by a significant margin (32%) under the simulated bracing condition. The hollow was conducted with 20% activation in both the lateral oblique and the transversus abdominis and 2% activation in both rectus abdominis and external oblique. This was considered feasible after observing our subjects. Most of the stability was obtained through the internal oblique. Abbreviations: BRC, bracing; HLW, hollowing; Stb, Stability.

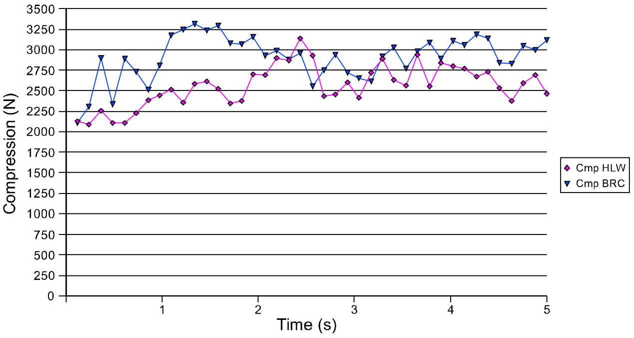

Fig 7. Although the external load component contributes to lumbar compression equally among conditions, compression due to muscle activation differed between the simulation bracing and hollowing condition by as much as 500N. Note that the hollowing here included both the internal oblique and transversus abdominis as in figure 6. Abbreviation: Cmp, compression.

Table 2: One Subject's Data Were Taken and Modified for the Simulation

Compared With Bracing	Stability % Change	Compression % Change
In vivo: no load hollowing	7.2	2.3
In vivo: 2-hand load hollowing	6.0	3.0
In vivo: left-hand load hollowing	6.7	2.8
In vivo: right-hand load hollowing	2.3	−1.7
Simulation hollowing	32.5	15.3
Simulation bracing: no TA	.14	.00
Simulation bracing: no EO	16.5	11.0
Simulation bracing: no IO	32.5	12.7
Simulation bracing: no RA	12.6	10.6

NOTE. The unmodified hollow data were compared, for that subject, to the brace data. The various simulations were also compared with the full brace trial. The percentage increase in stability of bracing over hollow is clear, especially for the ideal simulation of bracing. Each condition was compared with pure bracing trial. Note that in the subject data, compression increased under right-hand load hollowing conditions, although only by 1.7%.
Abbreviations: EO, external oblique; IO, internal oblique; RA, rectus abdominis; TA, transversus abdominis.

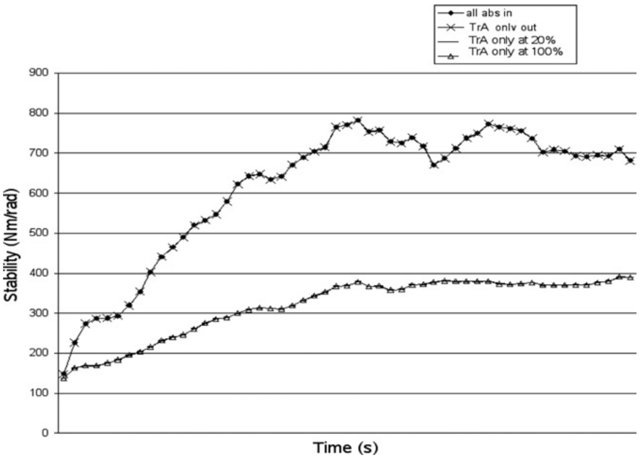

Fig 8. Stability index in simulation trial. A single, 2-hand load trial was processed, with 4 sensitivity tests, to isolate the role of different muscles. The bottom trace is actually 2 conditions using the transversus abdominis as the only active abdominal muscle (at 100% and 20% of MVC). Whether the transversus abdominis is active at 20% or 100% of MVC had little effect and those 2 plots are superimposed. The top trace is actually 2 conditions: (1) with all abdominal muscles active in a brace pattern (at whatever level the subject had activated them) and (2) with only the transversus abdominis removed. Only 1 line is visible because removing the transversus abdominis has almost no effect, and its plot overlays the full activation plot. The variability in the stability plot, including what stability is present, results from variable activity in the extensor (and other modeled) muscles. Abbreviations: abs, abdominals; TrA, transversus abdominis.

was driven by the internal oblique activation profile because it has been shown to share a synergistic activation for neutral static postures, such as those tested in this study.[13,43] The way in which the transversus abdominis was modeled was an attempt to capture its force, moment, and stabilizing effects on the spine. The architecture of the transversus abdominis suggests a limited capability to influence lumbar stability on its own. In contrast, the oblique vertical "wrap" of the internal oblique, for example, has a much higher potential to directly stabilize and compress the spinal column. Also, although a transversus abdominis muscle was modeled, the interaction between the transversus abdominis and intra-abdominal pressure was not accounted for. Intra-abdominal pressure is linked to abdominal wall activity, which stiffens and stabilizes the lumbar spine. However, at least 1 study[44] suggests that a hollowing strategy is unlikely to generate a greater intra-abdominal pressure than full bracing. This being the case, if pressure does affect stability, even more stability would result when bracing as compared with hollowing. The work of Tesh et al[45] contributed some insight as to the modeling of the transversus abdominis, its link with abdominal pressure, and resistance to lateral bending moments in full flexion. The force generated by our transversus abdominis equivalent was on the order of 50N for a 20% MVC. They also report that intra-abdominal pressure may contribute as much as 40% of the restorative moment in lateral bending. Our own work shows that intra-abdominal pressure contributes significant stiffness, especially in the neutral posture.[44] We speculate that there may be a binding of the abdominal muscle layers, when contracted together, that creates more stiffness than the sum of the parts. If this is the case, then the transversus abdominis would be an important member of the "abdominal team" but no more important than any of the other muscles.

In this study, the stability response was measured only with fully anticipated loads in isometric, neutral postures, for symmetric and asymmetric loads. It is possible that for a sudden load, the combination of a pressurization response and transversus abdominis activation might maintain sufficient stability until the remainder of the torso muscles are recruited. However, we remain skeptical of this possibility because the reported 30-ms delay for transversus abdominis onset is just a fraction of the 130-ms electromechanical delay inherent in the force production for trunk muscle.[46] In other words, a loss of stability is not likely to occur within the window between 30ms, the time at which the transversus abdominis turns on, and 130ms, the time at which it begins to produce force. It is therefore suggested that, although transversus abdominis onset delay[5] may be statistically significant, it is not mechanically significant. In any case, recent work done with cocontraction of the abdominals and its effect on stability, supports our findings.[47] A general cocontraction of the abdominal wall, balanced against antagonists and the load, is most effective in attaining and maintaining lumbar stability. There were considerable variations in the recruitment patterns, shown by subjects, used to achieve a hollowing. This is normal and is an advantage of our modeling approach, which is sensitive to the individual ways people activate muscle. The simulation was able to reproduce the ideal. Furthermore, this study was performed on young healthy males with no LBP. Injury, LBP, or population variability may result in different muscle recruitment patterns and stability profiles. Again, this possible weakness in the in vivo data was addressed via the simulations in which muscle activation was under complete control of the experimenters to elucidate the differences between ideal techniques and in vivo reality.

The simulations were important, for interpretation of this study, in 2 ways. First, the difficulty that participants had in achieving a hollowing recruitment pattern necessitated some

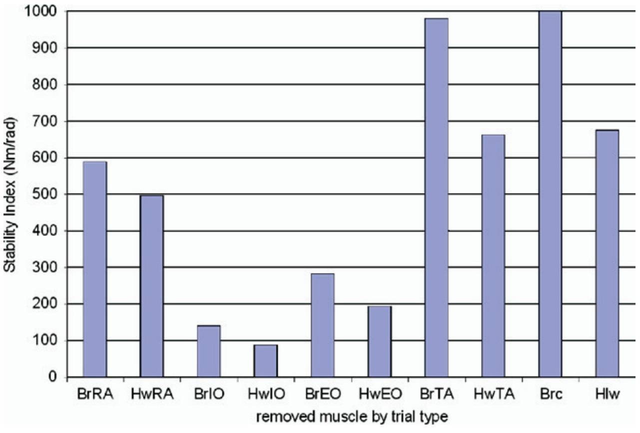

Fig 9. Stability index with abdominal muscles removed from simulation. This histogram shows the stability, for actual subjects, performing the brace and an attempted hollow (shown at the far right). Then, the right and left abdominal muscle pairs were removed from the analysis, each in turn, and the stability was recalculated. Although the removal of the transversus abdominis made little difference to stability, internal oblique was the most important in affecting stability, followed by external oblique and finally by rectus abdominis. Abbreviations: Brc, normal brace; BrEO, brace with external oblique; BrIO, brace with internal oblique; BrRA, brace with rectus abdominis; BrTA, brace with transversus abdominis; Hlw, normal hollow; HwEO, hollow with external oblique; HwIO, hollow with internal oblique; HwRA, hollow with rectus abdominis; HwTA, hollow with transversus abdominis.

way of testing the "ideal" hollowing pattern. Second, the simulations confirmed that, even if an ideal hollowing pattern was achieved, it would still fall short of the stability provided by bracing. This is the case regardless of the fact that in this study the transversus abdominis was not measured; the simulations assumed that it was optimally active. Recent work by Howarth et al[48] showed that the magnitude of the stability index is proportional to the level of risk of becoming unstable (of having the stability index go below 0). Nonetheless, it is still a relative measure so that it is not possible to compare the magnitude of the index between people. It should only be used comparatively within a subject, and even then, only within a testing session. For this reason, the participants acted as their own controls. Finally, this work examined Euler column stability; it is possible that the abdominal muscles work differently to buttress shear or pelvic instability. The mechanical effect on lumbar stability, of either the transversus abdominis or of hollowing, has not, to our knowledge, been reported in the literature before this. It must be clearly stated that this is a mechanical analysis of the role of the transversus abdominis and other abdominal muscles. Therefore, whatever role transversus abdominis isolation training has in rehabilitation, it cannot be explained by a mechanically based stability principle. If spinal stiffness is the ultimate goal in a training program, then bracing of the abdominal muscles is a clear winner over hollowing. In reality, a single focus on either strategy may not be optimal (or even possible) for functional tasks that show a great diversity in load and velocity.

CONCLUSIONS

This biomechanically based assessment suggests that bracing of the abdominal muscles provides greater lumbar spine stability than hollowing. According to our simulations, the potential of the transversus abdominis to enhance stability, on its own, appears to be very limited. The inability to isolate the transversus abdominis in a functional context may be a moot point because in healthy men bracing increases spine stability with minimal increase in spine compression loads. Muscles other than the transversus abdominis contribute relatively more to avoiding an unstable spine. Whatever the benefit underlying low-load transversus abdominis activation training, it is unlikely to be mechanical. There seems to be no mechanical rationale for using stabilization exercises to enhance a hollow for stabilization purposes; rather a brace creates patterns that better enhance stability.

Acknowledgment: We thank Jay Green for assistance in data collection.

References

1. Hides JA, Jull GA, Richardson CA. Long-term effects of specific stabilizing exercises for first-episode low back pain. Spine 2001; 26:E243-8.
2. O'Sullivan PB, Phyty GD, Twomey LT, Allison GT. Evaluation of specific stabilizing exercise in the treatment of chronic low back pain with radiologic diagnosis of spondylolysis or spondylolisthesis. Spine 1997;22:2959-67.
3. McGill SM. Low back disorders: evidence-based prevention and rehabilitation. Champaign: Human Kinetics. 2002.
4. Hodges PW. Is there a role for transversus abdominis in lumbo-pelvic stability? Man Ther 1999;4:74-86.
5. Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. Spine 1996;21:2640-50.
6. Richardson CA, Snijders CJ, Hides JA, Damen L, Pas MS, Storm J. The relation between the transversus abdominis muscles, sacroiliac joint mechanics, and low back pain. Spine 2002;27:399-405.
7. Allison GT, Henry SM. The influence of fatigue on trunk muscle responses to sudden arm movements, a pilot study. Clin Biomech (Bristol, Avon) 2002;17:414-7.
8. Newcomer KL, Jacobson TD, Gabriel DA, Larson DR, Brey RH, An KN. Muscle activation patterns in subjects with and without low back pain. Arch Phys Med Rehabil 2002;83:816-21.
9. Hodges PW, Richardson CA. Altered trunk muscle recruitment in people with low back pain with upper limb movement at different speeds. Arch Phys Med Rehabil 1999;80:1005-12.
10. Radebold A, Cholewicki J, Panjabi MM, Patel TC. Muscle response pattern to sudden trunk loading in healthy individuals and in patients with chronic low back pain. Spine 2000;25:947-54.
11. Suter E, Lindsay D. Back muscle fatigability is associated with knee extensor inhibition in subjects with low back pain. Spine 2001;26:E361-6.
12. McGill S, Grenier S, Bluhm M, Preuss R, Brown S, Russell C. Previous history of LBP with work loss is related to lingering deficits in biomechanical, physiological, personal, psychosocial and motor control characteristics. Ergonomics 2003;46:731-46.
13. Juker D, McGill S, Kropf P, Steffen T. Quantitative intramuscular myoelectric activity of lumbar portions of psoas and the abdominal wall during a wide variety of tasks. Med Sci Sports Exerc 1998;30:301-10.
14. Vezina MJ, Hubley-Kozey CL. Muscle activation in therapeutic exercises to improve trunk stability. Arch Phys Med Rehabil 2000;81:1370-9.
15. Davidson KL, Hubley-Kozey CL. Trunk muscle responses to demands of an exercise progression to improve dynamic spinal stability. Arch Phys Med Rehabil 2005;86:216-23.
16. Koumantakis GA, Watson PJ, Oldham JA. Trunk muscle stabilization training plus general exercise versus general exercise only: randomized controlled trial of patients with recurrent low back pain. Phys Ther 2005;85:209-25.
17. Hicks GE, Fritz JM, Delitto A, McGill SM. Preliminary development of a clinical prediction rule for determining which patients with low back pain will respond to a stabilization exercise program. Arch Phys Med Rehabil 2005;86:1753-62.
18. Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. Clin Biomech (Bristol, Avon) 1996;11:1-15.
19. McGill SM. Low back stability: from formal description to issues for performance and rehabilitation. Exerc Sport Sci Rev 2001;29: 26-31.
20. Jull GA, Richardson CA. Motor control problems in patients with spinal pain: a new direction for therapeutic exercise. J Manipulative Physiol Ther 2000;23:115-7.
21. Kavcic N, Grenier S, McGill SM. Quantifying tissue loads and spine stability while performing commonly prescribed low back stabilization exercises. Spine 2004;29:2319-29.
22. McGill SM, Grenier S, Kavcic N, Cholewicki J. Coordination of muscle activity to assure stability of the lumbar spine. J Electromyogr Kinesiol 2003;13:353-9.
23. McGill SM. Ultimate back fitness and performance. Waterloo: Wabuno Publishers; 2004.
24. McGill S, Cholewicki J, Peach JP. Methodological considerations for using inductive sensors (3SPACE ISOTRAK) to monitor 3-D orthopaedic joint motion. Clin Biomech (Bristol, Avon) 1997;12: 190-4.
25. Basmajian JV, De Luca CJ. Muscles alive: their functions revealed by electromyography. 5th ed. Baltimore: Williams & Wilkins; 1985.
26. McGill SM. Electromyographic activity of the abdominal and low back musculature during the generation of isometric and dynamic axial trunk torque: implications for lumbar mechanics. J Orthop Res 1991;9:91-103.

27. Biering-Sorensen F. Physical measurements as risk indicators for low back trouble over a one year period. Spine 1984;9:106-19.
28. Cresswell AG, Thorstensson A. Changes in intra-abdominal pressure, trunk muscle activation and force during isokinetic lifting and lowering. Eur J Appl Physiol Occup Physiol 1994;68:315-21.
29. Simitses GJ. An introduction to the elastic stability of structures. Malabar: RE Krieger; 1986.
30. Lucas DB, Bresler B. Stability of the ligamentous spine. San Francisco: Univ California, Biomechanics Laboratory; 1961; Technical report no. 40.
31. Crisco JJ III, Panjabi MM, Yamamoto I, Oxland T. Euler stability of the human ligamentous lumbar spine. Part II: Experiment. Clin Biomech 1992;7:27-32.
32. Crisco JJ III, Panjabi MM. The intersegmental and multisegmental muscles of the lumbar spine. A biomechanical model comparing lateral stabilizing potential. Spine 1991;16:793-9.
33. White AA, Panjabi M. Clinical biomechanics of the spine. Toronto: Lippincott; 1978.
34. McGill S, Seguin J, Bennett G. Passive stiffness of the lumbar torso in flexion, extension, lateral bending, and axial rotation. Effect of belt wearing and breath holding. Spine 1994;19:696-704.
35. Kavcic N, Grenier S, McGill SM. Determining the stabilizing role of individual torso muscles during rehabilitation exercises. Spine 2004;29:1254-65.
36. Ma S, Zahalak GI. A distribution-moment model of energetics in skeletal muscle. J Biomech 1991;24:21-35.
37. Tesh KM, Evans JH, Shaw Dunn J, O'Brien JP. The contribution of skin, fascia, and ligaments to resisting flexion and the lumbar spine. In: Whittle M, Harris D, editors. Biomechanical measurement in orthopaedic practice. Oxford: Clarendon Pr; 1985. p 179-87.
38. Cholewicki J, VanVliet JJ IV. Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. Clin Biomech (Bristol, Avon) 2002;17:99-105.
39. R Development Core Team. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing; 2006.
40. Panjabi MM, Lydon C, Vasavada A, Grob D, Crisco JJ 3rd, Dvorak J. On the understanding of clinical instability. Spine 1994;19:2642-50.
41. Hodges P, Kaigle Holm A, Holm S, et al. Intervertebral stiffness of the spine is increased by evoked contraction of transversus abdominis and the diaphragm: in vivo porcine studies. Spine 2003;28:2594-601.
42. Hurwitz EL, Morgenstern H, Chiao C. Effects of recreational physical activity and back exercises on low back pain and psychological distress: findings from the UCLA Low Back Pain Study. Am J Public Health 2005;95:1817-24.
43. Cresswell AG. Responses of intra-abdominal pressure and abdominal muscle activity during dynamic trunk loading in man [published erratum in: Eur J Appl Physiol 1993;67:97]. Eur J Appl Physiol Occup Physiol 1993;66:315-20.
44. Grenier SG. Stabilization strategies of the lumbar spine in vivo [PhD dissertation]. Waterloo: Faculty of Applied Health Sciences, Univ Waterloo; 2002. p 170.
45. Tesh KM, Shaw Dunn J, Evans JH. The abdominal muscles and vertebral stability. Spine 1987;12:501-8.
46. van Dieen JH, Thissen CE, van de Ven AJ, Toussaint HM. The electro-mechanical delay of the erector spinae muscle: influence of rate of force development, fatigue and electrode location. Eur J Appl Physiol Occup Physiol 1991;63:216-22.
47. Granata KP, Orishimo KF, Sanford AH. Trunk muscle coactivation in preparation for sudden load. J Electromyogr Kinesiol 2001;11:247-54.
48. Howarth SJ, Allison AE, Grenier SG, Cholewicki J, McGill SM. On the implications of interpreting the stability index: a spine example. J Biomech 2004;37:1147-54.

Suppliers

a. Polhemus, 40 Hercules Dr, PO Box 560, Colchester, VT 05446.
b. Graphic Controls Corp, Medical Products Div, PO Box 1274, Buffalo, NY 14240.
c. Bortec Biomedical, 239 Springborough Wy, Calgary, AB T3H 5M8, Canada.
d. R statistical package. Available at: http://www.R-project.org. Accessed October 6, 2006.