Clinical Biomechanics xxx (2009) xxx–xxx

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

# A comparison of ultrasound and electromyography measures of force and activation to examine the mechanics of abdominal wall contraction

Stephen H.M. Brown [1], Stuart M. McGill *

*Department of Kinesiology, University of Waterloo, Waterloo, ON, Canada N2L 3G1*

ARTICLE INFO

*Article history:*
Received 15 July 2009
Accepted 5 October 2009
Available online xxxx

*Keywords:*
Ultrasonography
EMG
Abdominals
Abdominal muscles
Obliques
Composite

ABSTRACT

*Background:* Ultrasound imaging is a valuable tool which, when applied appropriately, has the potential to provide information regarding the mechanics of abdominal muscle contraction. Typically, changes in muscle thickness are obtained and interpreted. However, the link between ultrasound measures of muscle thickening and EMG measures of activation is not clear.

*Methods:* Five healthy males performed a series of abdominal muscle contractions while surface EMG and trunk posture were monitored and ultrasound images of the internal oblique and external oblique were captured both at relaxation and upon contraction. Ramped isometric flexor and extensor moment contractions were also assessed and compared between EMG and ultrasound.

*Findings:* No definitive relationship between increases in muscle activation and corresponding measures of thickening was observed. Correlations between the two measures, across all contraction types, were 0.14 for internal oblique and −0.22 for external oblique.

*Interpretation:* The lack of clear association between abdominal muscle activation and thickening may be due to the composite laminate-like structure of the abdominal wall, with force being transmitted between obliquely oriented muscle layers. Thus, ultrasound alone may not be a valid measure of muscle activation or force in the unique architecture of the abdominal wall.



## 1. Introduction

In recent years, ultrasound imaging has become an increasingly popular tool to assess the contraction of the abdominal wall muscles (e.g., Ferreira et al., 2004; Hodges et al., 2003; Misuri et al., 1997; Rankin et al., 2006; Whittaker, 2008). Muscle thickness obtained from ultrasound is often interpreted as an indicator of muscle force generation. In addition, with appropriate considerations, electromyogram (EMG) amplitude can be linked to muscle force. The relationship between ultrasound measured muscle thickness and EMG-based muscle activation has not be definitively tested, but has yielded interesting findings within a limited scope of abdominal contraction types. For example, Hodges et al. (2003) documented very little change in muscle thickness beyond activations greater than 20% MVC, and both John and Beith (2007) and Coghlan et al. (2008) demonstrated decreases in external oblique (EO) thickness during activation. These discrepancies motivated this comparative study of ultrasound and EMG measures of abdominal wall muscle activation.

Proper activation and contraction of the abdominal wall is considered important for several reasons. First, abdominal muscles generate forces to produce moments in flexion, lateral bend and axial twist (Gatton et al., 2001; Marras and Mirka, 1990; McGill, 1991, 1996; Pope et al., 1986; Thelen et al., 1994). Second, properly coordinated abdominal muscle contraction is necessary to maintain a stable spinal column (Brown and Potvin, 2005; Brown et al., 2006; Cholewicki and McGill, 1996; Gardner-Morse and Stokes, 1998). Finally, reports have highlighted the functional role of the abdominal muscles in pressurizing the abdominal cavity, which also can have a stiffening effect on the lumbar spine (Cholewicki et al., 1999, 2002; Cresswell and Thorstensson, 1989; Essendrop and Schibye, 2004). For these reasons, it is essential that assessments of abdominal muscle function and contraction be carefully considered, whether via ultrasound or EMG.

The morphology of the abdominal wall muscles creates a composite laminate-like structure. The external oblique (EO), internal oblique (IO), and transverse abdominis (TrA) are broad sheet-like muscles that overlay one another, have muscle fibres that are obliquely oriented with respect to each adjacent layer, and are tightly bound together through networks of connective tissue. These connective tissues play a mechanical role, enabling force and stiffness to be transmitted between the muscular layers (Brown and McGill, 2009), and likely influencing the resulting contraction dynamics and muscular deformations. Various approaches and magnitudes

* Corresponding author. Address: Department of Kinesiology, University of Waterloo, 200 University Ave West, Waterloo, ON, Canada N2L 3G1.
*E-mail address:* mcgill@healthy.uwaterloo.ca (S.M. McGill).
[1] Present address: Department of Orthopaedic Surgery, University of California San Diego, San Diego, CA, USA.

0268-0033/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.clinbiomech.2009.10.001

of torso contraction will differentially recruit muscles around the trunk (McGill et al., 2003), thereby affecting the force and stiffness generated in muscle synergists and antagonists, in fascial connections, and in the pressurized abdomen. Muscle thickness not only relies on a muscle's own force generation, but also on the forces generated in neighbouring muscles, particularly when its fibre orientation is oblique to its neighbour, due to the transmittal of force via intervening connective tissues (Huijing and Baan, 2003). All of these factors play a role in determining how the abdominal muscles will shorten and thicken upon contraction, thus creating a complex network from which to assess muscle function.

In addition, as abdominal muscles shorten, the site being measured on the muscle will move to a new location within the image (or, depending upon the amount of shortening, potentially outside of the image). A majority of the research that has been conducted has employed a standardized static location within the image to measure changes in muscle thickness with contraction, thus not accounting for potential shortening of the muscle. This may lead to error in the estimation of thickness changes as the observed muscle section shortens.

Considering the aforementioned affects that abdominal muscle morphology and measurement location may have on ultrasound measures of abdominal muscle thickening, this study was designed to evaluate the concordance of conclusions about contraction dynamics obtained from both ultrasound and EMG measures.

## 2. Methods

### 2.1. Participants

Five healthy males (average/standard deviation: age = 25.2/3.8 years; height = 1.80/0.04 m; mass = 76.4/5.3 kg) volunteered from the University population. All were free from any history of chronic or acute episodes of back pain and abdominal dysfunction. Informed consent, approved by the University Office of Research Ethics, was obtained from each participant.

### 2.2. 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). RA electrodes were placed at the level of the umbilicus approximately 2 cm lateral to the mid-line; EO electrodes were placed along the direction of the muscle fibres approximately 14 cm lateral to the mid-line; IO electrodes were placed along the direction of muscle fibres approximately 2 cm medial and inferior to ASIS; LD electrodes were placed along the direction of muscle fibres at the level of T9. Signals were differentially amplified (1000–5000 times; ±2.5 V; AMT-8, Bortec, Calgary, Canada; bandwidth 10–1000 Hz, CMRR = 115 db at 60 Hz, input impedance = 10 GΩ)) and digitally recorded (2048 Hz). EMG signals were then full-wave rectified, low-pass filtered (Butterworth 2.5 Hz), and normalized to the maximum signal obtained during standardized maximum voluntary contractions (MVCs; Brown and McGill, 2008a; 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).

### 2.3. Procedures

Prior to collection participants were provided training in the proper technique for performing abdominal brace and hollow maneuvers. For the abdominal hollow, instructions were given to slowly draw the umbilicus inward and upward; for the abdominal brace, instructions were given to slowly tighten and stiffen the abdominal muscles, neither sucking in nor pushing out the abdomen. For both maneuvers, participants were required to not hold their breath and to continue breathing as normally as possible throughout the contraction. At the end of training, once the experimenter and participant were confident in the ability to properly perform the maneuvers, a maximal brace was performed to obtain a maximal activation recorded by the biofeedback device. Fifty percent of this activation level was set as a target for each of the subsequent abdominal brace and hollow contractions. This corresponds to much lower levels of individual muscle activation when normalized to the standardized MVCs described earlier (see Section 3). This study employed abdominal hollowing and bracing as two different means of recruiting the abdominal muscles, in order to compare interpretations of activation between ultrasound and EMG measures. It must be noted that the hollowing techniques employed here may not match clinical usage, given that very low level contractions are usually coached; however, the primary goal here was to elicit different muscle activation strategies to compare between ultrasound and EMG. Therefore, no clinical comparisons between the two contraction techniques should be made based on this data, as the techniques were simply employed to assess different strategies of recruiting the abdominal muscles in relation to one another.

Participants performed the contractions in a modified sit-kneel position, designed to keep the spine in a neutral posture (Fig. 1). The upright position was considered prudent to assess the mechanics of the abdominal wall muscles, as previous research has documented changes to the geometry of the musculature while in the supine position (Jorgensen et al., 2005; McGill et al., 1996a).

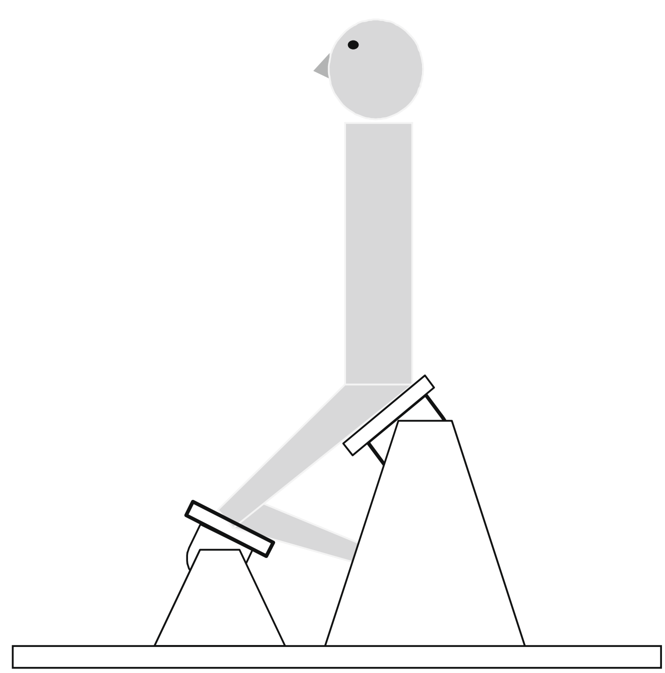

**Fig. 1.** Schematic representation of the participant testing posture.

Please cite this article in press as: Brown, S.H.M., McGill, S.M. A comparison of ultrasound and electromyography measures of force and activation to examine the mechanics of abdominal wall contraction. J. Clin. Biomech. (2009), doi:10.1016/j.clinbiomech.2009.10.001

For the comparison of bracing and hollowing techniques, participants performed six abdominal hollow and six abdominal brace contractions, two at each of three orientations of the ultrasound probe. All 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 allow a clear view of the three layers of the abdominal

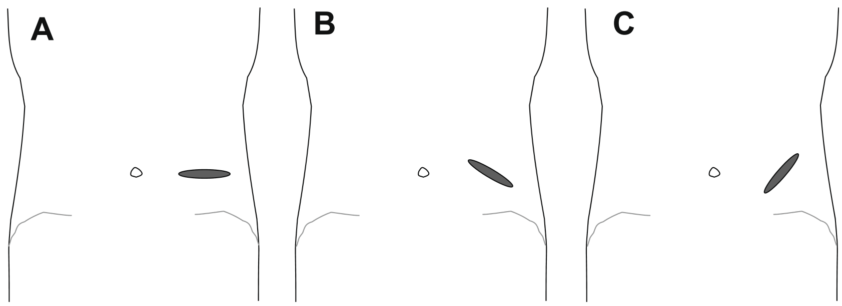


**Fig. 2.** Pictorial representation of the anterior torso to show locations (relative to the umbilicus and iliac crest) of the three probe orientations: (A) horizontal along the transverse plane, (B) oriented 35° inferior-laterally (along the approximate line of the IO fibres) and (C) oriented 60° superior-laterally (along the approximate line of the EO fibres).

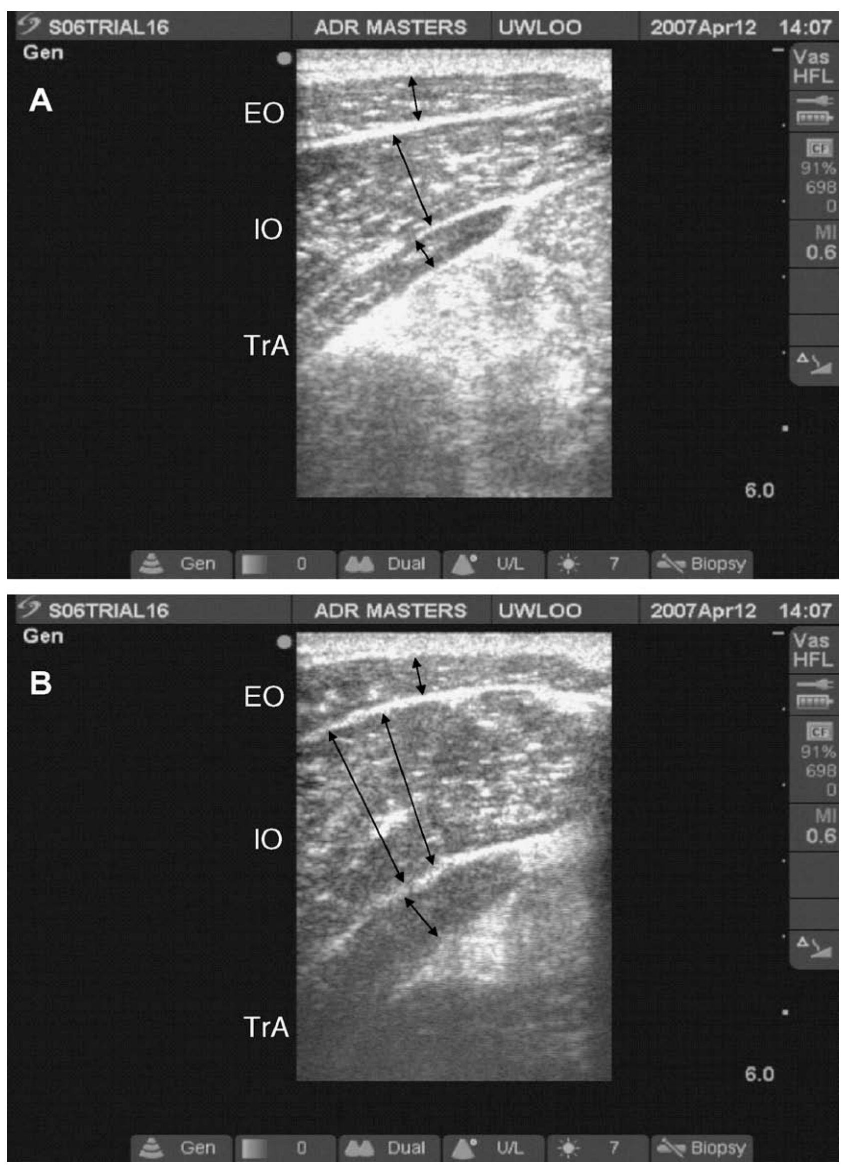


**Fig. 3.** Example of an ultrasound image captured for an abdominal brace trial during relaxation (A) and contraction (B). Arrowed lines indicate measures of the thickness of each muscle. The more laterally positioned arrowed line on the contracted IO is an example of where the measurement would have been taken considering potential shortening of the muscle (approximately 4 mm laterally along the line of the muscle). The medial side of the body is to the right of the image.

Please cite this article in press as: Brown, S.H.M., McGill, S.M. A comparison of ultrasound and electromyography measures of force and activation to examine the mechanics of abdominal wall contraction. J. Clin. Biomech. (2009), doi:10.1016/j.clinbiomech.2009.10.001

wall musculature. The three probe orientations were: (1) horizontal along the transverse plane, (2) angled 35° inferior-laterally (along the approximate line of the IO fibres, Urquhart et al., 2005) and (3) angled 60° superior-laterally (along the approximate line of the EO fibres, Urquhart et al., 2005) (Fig. 2). The mid point of the probe was positioned in the same location for each of the three orientations. 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. Two still ultrasound images were captured on a video cassette for each trial, the first when the muscles were relaxed and the second when they were contracted to the target level.

Additionally, each participant then performed four isometric ramped torque contractions, two producing a net flexor muscle moment, and two producing a net extensor muscle moment. Participants were seated, and secured around the hips, in the same apparatus as for the brace and hollow trials. A trunk harness was fit snuggly over the shoulders and attached through a cable in-series with a force transducer to a weight stack loaded so as to prevent any torso movement. Participants used their torso to slowly pull against the weight stack, ramping torque from zero up to maximum and back down to zero. Ultrasound images, with the probe oriented at the 35° angle (IO fibre line of action), were captured on video cassette at a rate of 30 frames/s over the course of each contraction.

### 2.4. Ultrasound image analysis

For the brace and hollow trials, the thickness of each of the three abdominal wall muscles (IO, EO, TrA) was measured in both the relaxed and contracted image. Measures of the deep edge of each muscle were standardized at the middle point of the image, and the thickness was measured along a line normal to the muscle at this standardized point (Fig. 3). To assess the effect of possible

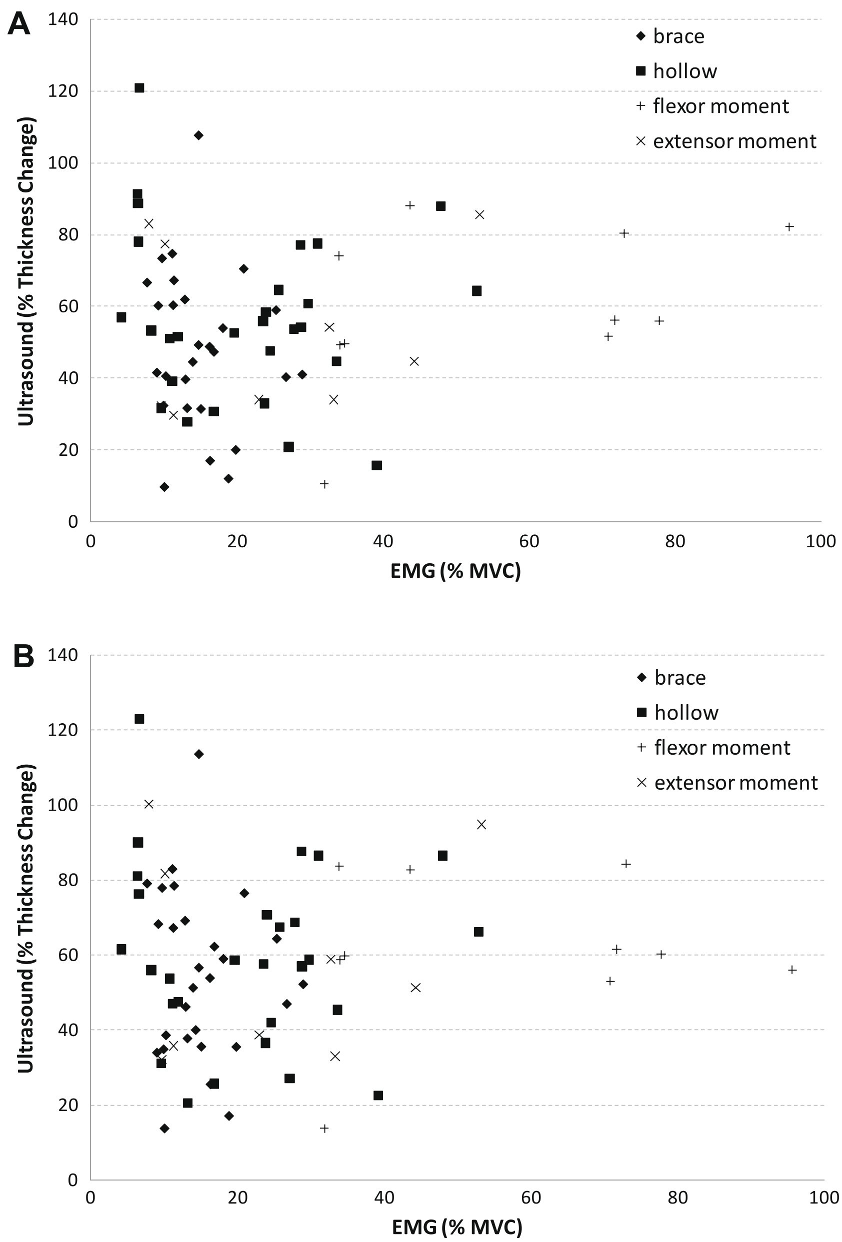


**Fig. 4.** Scatterplots of internal oblique EMG muscle activation levels versus ultrasound muscle thickness percent changes during each of the abdominal brace, abdominal hollow, flexor moment and extensor moment contractions. (A) All participants, ultrasound measures taken in the non-shortened position, (B) all participants, ultrasound measures taken accounting for potential muscle shortening and (C) single representative participant, ultrasound measures taken accounting for potential muscle shortening.

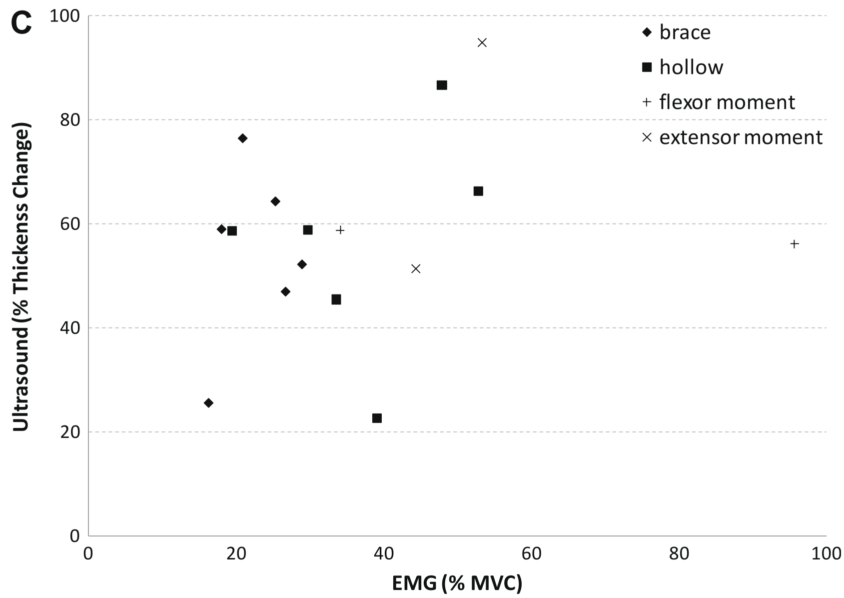


**Fig. 4** (*continued*)

muscle shortening, a second measure of the thickness upon contraction was taken assuming that the muscle had shortened approximately 4 mm along its line of action in the image. A magnitude of 4 mm was chosen as a fairly significant amount of shortening based on a corresponding study assessing muscle–tendon interaction (Brown and McGill, 2008b) during similar contractions. This independent variable will be referred to as measurement location.

For the ramped moment contractions, video was down-sampled to 3 frames/s, and the thickness of the EO and IO muscles were measured at each image frame to determine the thickness change between the rest and maximally contracted state for each contraction. The second measure of thickness upon contraction, accounting for 4 mm shortening, was also assessed in these contractions.

### 2.5. Reliability of image analysis

To determine the intra-rater reliability in determining the change in muscle thickness from rest to contraction, off-line measures were repeated (separated by 1 week) on 58 randomly chosen muscles and each of a Pearson correlation and a paired *t*-test were computed to test the relationship and mean difference, respectively, between the days.

### 2.6. Statistics

The percent change in thickness with respect to the resting thickness was calculated for each muscle in each trial. Bivariate correlations were assessed for the relationship between EMG activation and muscle thickness change for both EO and IO. A two-way Repeated Measures ANOVA was utilized to assess the effect of probe orientation and measurement location on the percent change in thickness for each of the three muscles. A Tukey HSD test was run to examine post hoc differences where significant differences were indicated by the ANOVA. The alpha level was set at 0.05 for all analyses.

## 3. Results

### 3.1. Comparison of ultrasound and EMG measures

The IO (Fig. 4) muscle did not demonstrate any clear relationship between ultrasound thickness change measures and EMG activation measures for the abdominal bracing and hollowing contractions, and showed even further discrepancies during the ramped moment contractions (across all contractions, $r = 0.14$; 95% confidence intervals: −0.09 to 0.35). Similarly, the EO muscle lacked a definitive relationship between the measures of ultrasound thickness change and EMG activation (across all contractions, $r = -0.22$; 95% confidence intervals: −0.42 to 0.01) (Fig. 5). Interestingly though, the EO muscle displayed a thinning in a number of contractions.

### 3.2. Ultrasound

The measurements appear to have been reliable as a very high correlation ($r = 0.99$) was found between the off-line measures taken on two separate days. Further, the paired *t*-test showed no significant difference between the days ($P = 0.131$).

No significant differences were found in the percent thickness change with respect to the orientation at which the probe was positioned for any of the muscles (Table 1). Accounting for potential shortening of the muscles by adjusting the position of measurement upon contraction resulted in a significantly higher percent change in thickness for the TrA ($P = 0.0021$; shortened position = 73.0% to original position = 42.5%) (Table 1). Trends also existed of a larger measured percent change when accounting for possible shortening in both the IO (shortened position = 56.7%; original position = 52.6%) and the EO (shortened position = 15.5%; original position = 7.7%).

## 4. Discussion

It appears that there are very complex dynamics between abdominal wall muscles during different strategies of contraction. This is most likely due to the wall forming a mechanical composite with the fibres of one layer adhered to an adjoining layer through an intervening sheet of connective tissue. This is akin to a "plywood-like" architecture. Due to the mechanical linkage between the muscular layers, contraction in one layer may directly affect the shortening and thickening of an adjacent layer. Thus, it is not surprising that there is little relationship between activation (via EMG amplitude) and thickening (via ultrasound) in muscles of the abdominal wall.

Please cite this article in press as: Brown, S.H.M., McGill, S.M. A comparison of ultrasound and electromyography measures of force and activation to examine the mechanics of abdominal wall contraction. J. Clin. Biomech. (2009), doi:10.1016/j.clinbiomech.2009.10.001

The muscular layers of abdominal wall are separated and linked by strong networks of connective tissues. These connective tissues have the ability to transmit force between the layers, thus providing a mechanical linkage and forming a composite structure (Brown and McGill, 2009). In this way, the force generated in one muscle layer will have a direct effect on its neighbouring muscles (Huijing and Baan, 2003), particularly in the regions where the muscles have fibres running obliquely to one another. As a muscle is activated it will attempt to shorten, dependent on the amount of force generated and the compliance of connective tissues to which it is attached in-series. As the muscle shortens it will thicken orthogonally in order to maintain an approximately constant volume. This thickening will apply a force directly opposing the shortening of an adjacent muscle layer with perpendicularly running fibres (Fig. 6). If this adjacent muscle is active, its amount of shortening, and thus thickening, will be constrained to levels less than if the muscle acted in isolation. If, on the other hand, the adjacent muscle is inactive or generates relatively less force than its neighbour, the response may become more complex, as the contraction of the first muscle would exert a transverse "bunching" force across the fibres of the second muscle, as well as a stretching force along the line of the fibres of the second muscle. In a case where this stretching force dominates the deformation, the second muscle may show a tendency to thin. This may partially explain the anomalous finding in the literature, and confirmed in this study, that the EO has showed very little increase in thickness, or even thinning, despite clear electrical activity (Coghlan et al., 2008; Ferreira et al., 2004; Hodges et al., 2003; John and Beith, 2007). Further, during contractions that synergistically recruit muscles supporting the entire torso, fascial layers will be tightened around the thoraco-lumbar and abdominal regions, merging to the abdominal wall muscle attachments (Barker et al., 2006; Farfan, 1973; Tesh et al., 1987), which will act to limit the amount of shortening possible for the abdominal muscles given a particular level of con-

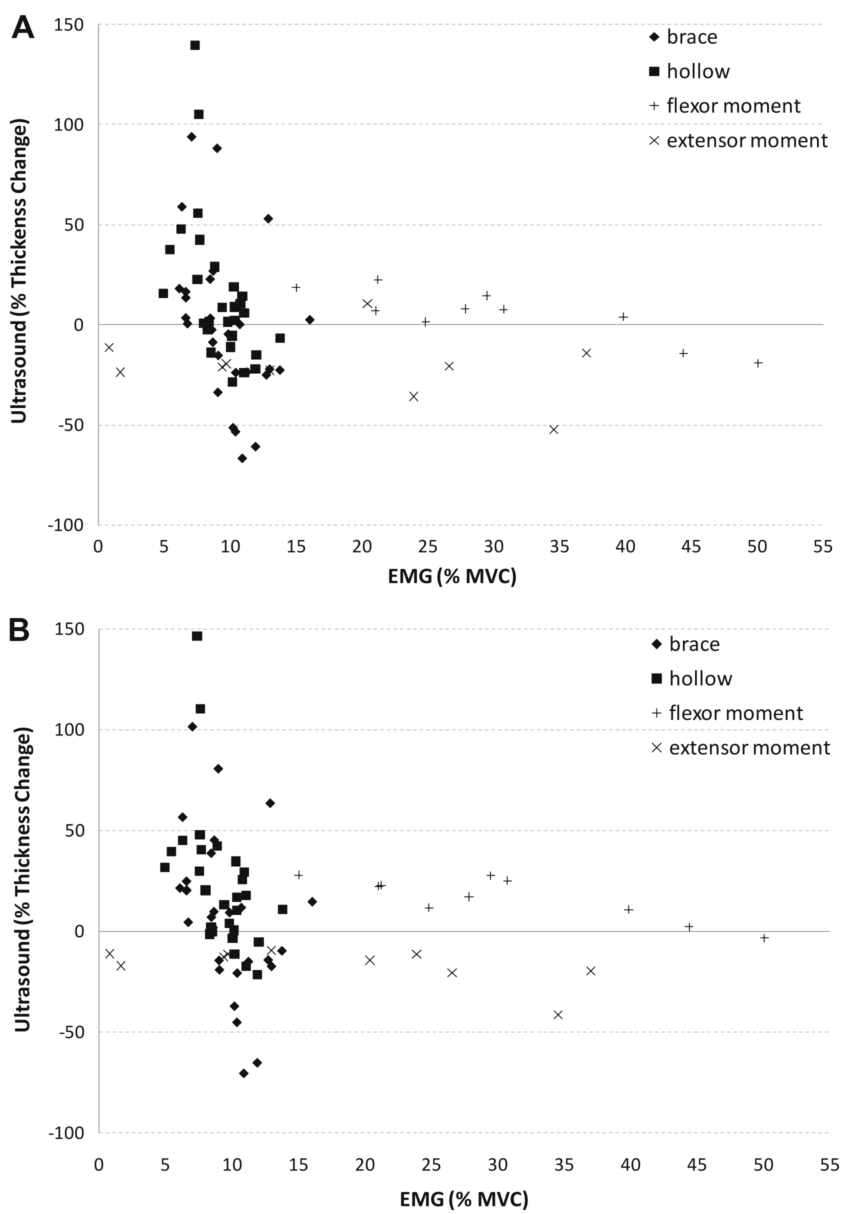


**Fig. 5.** Scatterplots of external oblique EMG muscle activation levels versus ultrasound muscle thickness percent changes during each of the abdominal brace, abdominal hollow, flexor moment and extensor moment contractions. (A) All participants, ultrasound measures taken in the non-shortened position, (B) all participants, ultrasound measures taken accounting for potential muscle shortening and (C) single representative participant, ultrasound measures taken accounting for potential muscle shortening.

Please cite this article in press as: Brown, S.H.M., McGill, S.M. A comparison of ultrasound and electromyography measures of force and activation to examine the mechanics of abdominal wall contraction. J. Clin. Biomech. (2009), doi:10.1016/j.clinbiomech.2009.10.001

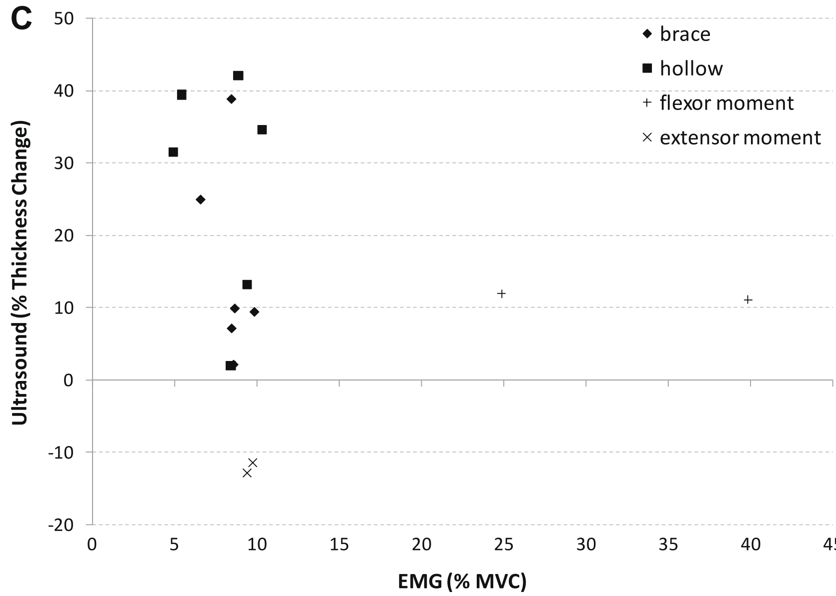


**Fig. 5** (*continued*)

traction. In addition, the build-up of intra-abdominal pressure will most likely serve to resist thickening of the abdominal wall muscles by creating hydrostatic forces within the abdomen (Cresswell and Thorstensson, 1989). The ramped moment contractions performed here resulted in high levels of co-contraction (greater than either the abdominal brace or hollow maneuvers) around the entire torso, which would result in an effective stiffening of the fascial attachments. Our unreported EMG data also showed that that the abdominal brace, when compared to the abdominal hollow, resulted in greater levels of activation of the overall musculature surrounding the torso. Thus, the stiffening of the connective tissues was most likely the greatest in the ramped moment contraction trials, followed by the brace and hollow trials, respectively, and this may be what ultimately dictates or limits the change in muscle thickness recorded and measured by imaging techniques.

Other researchers have uncovered conflicting results when comparing ultrasound and EMG measures of the abdominal muscles. Fairly high correlations ($r = 0.84$–$0.90$) have been reported for IO and TrA muscles (Hodges et al., 2003; McMeeken et al., 2004), but these studies only tested within specific abdominal muscle contraction types (Hodges et al., 2003, isometric contraction to target abdominal pressures; McMeeken et al., 2004, abdominal hollowing). Further, while McMeeken et al. (2004) demonstrated a consistent increase in TrA thickness up to 80% MVC, Hodges et al., showed little increase beyond 20% MVC for both TrA and IO, and no detectable relationship between ultrasound and EMG measures for EO ($r = 0.23$). Alternatively, John and Beith (2007) demonstrated a fairly good relationship ($r = 0.63$–$0.94$) for EO in a single scenario (isometric trunk twist), but the relationship degraded significantly ($r = 0.16$–$0.86$) in a different scenario (abdominal hollow). The divergent results seem to support the notion that the mechanical interaction between the abdominal muscle layers makes for complex deformation patterns that differ dependent upon the relative action of each muscles. This makes interpretation of these actions very difficult and problematic from ultrasound images alone.

As muscles increase in activation, they will shorten depending upon the compliance of the connective tissues to which they are attached, primarily in-series. The effect of this shortening on the measure of the change in muscle thickness was investigated by measuring the contracted muscle thickness at the same image location as the resting muscle thickness, and comparing this to a measure of the contracted muscle thickness taken approximately 4 mm laterally along the fibre direction. The change in muscle thickness was computed to be greater in all three muscles when accounting for potential shortening, with the TrA in particular displaying a statistically significant difference (73.0 to 41.4%). However, this consideration for the shortening of the abdominal wall muscles did not noticeably improve the agreement between the ultrasound and EMG measures.

**Table 1**
Mean and standard deviation (SD) of the percent increase in muscle thickness, with respect to the relaxed level, of the IO, TrA and EO muscles, averaged across subjects and brace and hollow contractions, for each of the three ultrasound probe orientations, and when the contracted image was measured in the same position as the relaxed position (original position), or when measured 4 mm laterally along the line of the muscle (to simulate potential shortening). Stars indicate statistically significant difference in the measurement of thickness between the original and shortened positioned.

| | | | IO | TrA | EO |
|---|---|---|---|---|---|
| Angle | Horizontal | Mean | 59.5 | 47.3 | 7.1 |
| | | SD | 22.5 | 24.3 | 30.5 |
| | 35° | Mean | 56.3 | 66.4 | 5.7 |
| | | SD | 22.3 | 67.5 | 21.8 |
| | 60° | Mean | 46.7 | 73.2 | 24.6 |
| | | SD | 23.2 | 27.7 | 57.9 |
| Location | Original | Mean | 52.6 | 42.5* | 7.7 |
| | | SD | 23.0 | 26.8 | 39.0 |
| | Shortened | Mean | 56.7 | 73.0* | 15.5 |
| | | SD | 23.1 | 51.1 | 38.4 |

There are certain considerations that should be made in the interpretation of this data. The first is the relatively small number of participants tested. This limits the generalizability of statistical tests comparing the effects of probe orientation and muscle shortening; therefore caution should be taken in interpreting this data. The relationship between ultrasound and EMG measures, however, is not likely to be improved with a greater number of tested participants, as the scatter within and amongst the five individuals in the current study was substantial. Second, EMG was recorded from the skin surface rather than within the muscle belly. However, care was taken to ensure that the bi-polar electrodes were arranged such that: (1) the desired muscle fibres aligned with the direction of the electrodes and (2) the desired muscle fibres were most

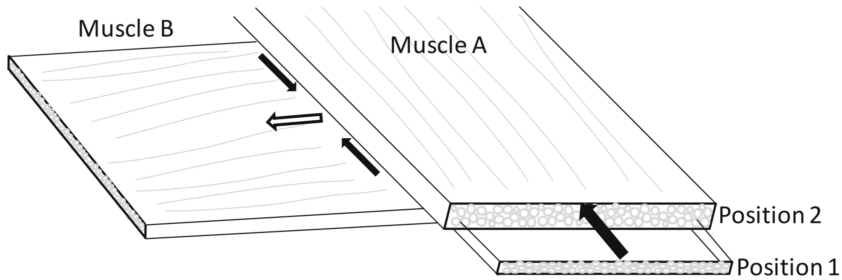


**Fig. 6.** Model representation of the effect of contraction of one muscle layer on its neighbour. Muscle A contracts and shortens from Position 1 to Position 2, and thickens in both orthogonal directions to maintain its volume. The large black arrow represents the shortening force. As Muscle A shortens and thickens transversely it transmits these forces to Muscle B, with the black arrows representing a force across the fibres, and the white arrow representing a force along the fibres opposing the shortening of Muscle B. These transmitted forces influence the deformation of Muscle B.

superficial to skin surface at the electrode location. For example, EO is the most superficial muscle over the majority of the abdominal wall, except below the ASIS where EO fibres terminate (Urquhart et al., 2005) and fibres of IO become the most superficial. Based on these electrode locations, McGill et al. (1996b) demonstrated reasonably good agreement between surface and in-dwelling sources of EMG recording for the EO and IO muscles. Finally, clinical assessment of abdominal muscle recruitment is often done, via ultrasound, in a supine position with initially relaxed musculature. In the current study an upright kneeling posture was used, necessary to maintain the functional geometry of the abdominal musculature (Jorgensen et al., 2005; McGill et al., 1996a). While we think it unlikely for the results between ultrasound and EMG to change based on this postural difference, future work will be needed to confirm this.

## 5. Conclusions

A very complex relationship exists between muscle activation and change in muscle thickness, as the relative activation of muscles surrounding the entire torso will in part dictate the extent to which the abdominal wall muscles can shorten and thicken during different types and levels of contraction. The composite laminate nature of the abdominal wall muscles acts such that contraction in one layer will cause forces to be transmitted through the intervening connective tissue attachments to adjacent muscle layers, which can directly affect the amount of thickening that that muscle will experience. This severely limits the ability to assess muscle effort and/or force production from ultrasound measures of muscle thickness alone.

Interpretation of ultrasound measures can be affected by the potential shortening of the muscle fibres during contraction, and ignoring this factor can lead to an underestimate of the thickening of the musculature. However, accounting for muscle shortening does not appear to improve the ability to interpret muscle activation and/or force production from ultrasound images alone.

## Conflict of interest

None declared.

## Acknowledgment

The authors thank the Natural Sciences and Engineering Research Council (NSERC), Canada, for financial support.

## References

Barker, P.J., Guggenheimer, K.T., Grkovic, I., Briggs, C.A., Jones, D.C., Thomas, C.D.L., Hodges, P.W., 2006. Effects of tensioning the lumbar fasciae on segmental stiffness during flexion and extension. Spine 31, 397–405.

Brown, S.H.M., McGill, S.M., 2008a. How the inherent stiffness of the in-vivo human trunk varies with changing magnitudes of muscular activation. Clin. Biomech. 23, 15–22.

Brown, S.H.M., McGill, S.M., 2008b. An ultrasound investigation into the morphology of the human abdominal wall uncovers complex deformation patterns during contraction. Eur. J. Appl. Physiol. 104, 1021–1030.

Brown, S.H.M., McGill, S.M., 2009. Transmission of muscularly generated force and stiffness between layers of the rat abdominal wall. Spine 34, E70–E75.

Brown, S.H.M., Potvin, J.R., 2005. Constraining spine stability levels in an optimization model leads to the prediction of trunk muscle cocontraction and improved spine compression force estimates. J. Biomech. 38, 745–754.

Brown, S.H.M., Vera-Garcia, F.J., McGill, S.M., 2006. Effects of abdominal muscle coactivation on the externally preloaded trunk: variations in motor control and its effect on spine stability. Spine 31, E387–E393.

Cholewicki, J., McGill, S.M., 1996. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. Clin. Biomech. 11, 1–15.

Cholewicki, J., Juluru, K., McGill, S.M., 1999. Intra-abdominal pressure mechanism for stabilizing the lumbar spine. J. Biomech. 32, 13–17.

Cholewicki, J., Ivancic, P.C., Radebold, A., 2002. Can increased intra-abdominal pressure in humans be decoupled from trunk muscle co-contraction during steady state isometric exertions? Eur. J. Appl. Physiol. 87, 127–133.

Coghlan, S., Crowe, L., McCarthyPersson, U., Minogue, C., Caulfield, B., 2008. Electrical muscle stimulation for deep stabilizing muscles in abdominal wall. In: Annual international conference of the IEEE engineering in medicine and biology society, pp. 2756–2759.

Cresswell, A.G., Thorstensson, A., 1989. The role of the abdominal musculature in the elevation of the intra-abdominal pressure during specified tasks. Ergonomics 32, 1237–1246.

Essendrop, M., Schibye, B., 2004. Intra-abdominal pressure and activation of abdominal muscles in highly trained participants during sudden heavy trunk loadings. Spine 29, 2445–2451.

Farfan, H.F., 1973. Mechanical Disorders of the Low Back. Lea & Febiger, Philadelphia, PA.

Ferreira, P.H., Ferreira, M.L., Hodges, P.W., 2004. Changes in recruitment of the abdominal muscles in people with low back pain: ultrasound measurement of muscle activity. Spine 22, 2560–2566.

Gardner-Morse, M., Stokes, I.A.F., 1998. The effects of abdominal muscle coactivation on lumbar spine stability. Spine 23, 86–91.

Gatton, M., Pearcy, M., Pettet, G., 2001. Modelling the line of action for the oblique abdominal muscles using an elliptical torso model. J. Biomech. 34, 1203–1207.

Hodges, P.W., Pengel, L.H.M., Herbert, R.D., Gandevia, S.C., 2003. Measurement of muscle contraction with ultrasound imaging. Muscle Nerve 27, 682–692.

Huijing, P.A., Baan, G.C., 2003. Myofascial force transmission: muscle relative position and length determine agonist and synergist muscle force. J. Appl. Physiol. 94, 1092–1107.

John, E.K., Beith, I.D., 2007. Can activity within the external abdominal oblique be measured using real-time ultrasound imaging? Clin. Biomech. 22, 972–979.

Jorgensen, M.J., Marras, W.S., Smith, F.W., Pope, M.H., 2005. Sagittal plane moment arms of the female lumbar region rectus abdominis in an upright neutral torso posture. Clin. Biomech. 20, 242–246.

Marras, W.S., Mirka, G.A., 1990. Muscle activities during asymmetric trunk angular accelerations. J. Orthopaed. Res. 8, 824–832.

McGill, S.M., 1991. Kinetic potential of the lumbar trunk musculature about 3 orthogonal orthopedic axes in extreme postures. Spine 16, 809–815.

McGill, S.M., 1996. A revised anatomical model of the abdominal musculature for torso flexion efforts. J. Biomech. 29, 973–977.

McGill, S.M., Juker, D., Axler, C., 1996a. Correcting trunk muscle geometry obtained from MRI and CT scans of supine postures for use in standing postures. J. Biomech. 29, 643–646.

McGill, S., Juker, D., Kropf, P., 1996b. Appropriately placed surface EMG electrodes reflect deep muscle activity (psoas, quadratus lumborum, abdominal wall) in the lumbar spine. J. Biomech. 29, 1503–1507.

McGill, S.M., Grenier, S., Kavcic, N., Cholewicki, J., 2003. Coordination of muscle activity to assure stability of the lumbar spine. J. Electromyogr. Kinesiol. 13, 353–359.

McMeeken, J.M., Beith, I.D., Milligan, P., Critchley, D.J., 2004. The relationship between EMG and change in thickness of transversus abdominis. Clin. Biomech. 19, 337–342.

Misuri, G., Colagrande, S., Gorini, M., Iandelli, I., Mancini, M., Duranti, R., Scano, G., 1997. In vivo ultrasound assessment of respiratory function of abdominal muscles in normal subjects. Eur. Respir. J. 10, 2861–2867.

Pope, M.H., Andersson, G.B.J., Broman, H., Svensson, M., Zetterberg, C., 1986. Electromyographic studies of lumbar trunk musculature during the development of axial torques. J. Orthopaed. Res. 4, 288–297.

Rankin, G., Stokes, M., Newham, D.J., 2006. Abdominal muscle size and symmetry in normal subjects. Muscle Nerve 34, 320–326.

Tesh, K.M., Shaw Dunn, J., Evans, J.H., 1987. The abdominal muscles and vertebral stability. Spine 12, 501–508.

Thelen, D.G., Schultz, A.B., Ashton-Miller, J.A., 1994. Quantitative interpretation of lumbar muscle myoelectric signals during rapid cyclic attempted trunk flexions and extensions. J. Biomech. 27, 157–167.

Urquhart, D.M., Barker, P.J., Hodges, P.W., Story, I.H., Briggs, C.A., 2005. Regional morphology of the transversus abdominis and obliquus internus and externus abdominis muscles. Clin. Biomech. 20, 233–241.

Vera-Garcia, F.J., Brown, S.H.M., Gray, J.R., McGill, S.M., 2006. Effects of different levels of torso coactivation on trunk muscular and kinematic responses to posteriorly applied sudden loads. Clin. Biomech. 21, 443–455.

Whittaker, J.L., 2008. Ultrasound imaging of the lateral abdominal wall muscles in individuals with lumbopelvic pain and signs of concurrent hypocapnia. Manual Ther. 13, 404–410.

Please cite this article in press as: Brown, S.H.M., McGill, S.M. A comparison of ultrasound and electromyography measures of force and activation to examine the mechanics of abdominal wall contraction. J. Clin. Biomech. (2009), doi:10.1016/j.clinbiomech.2009.10.001