Lumbar Mechanics From Ultrasound Imaging

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ABSTRACT

The feasibility of estimating lumbar mechanics in-vivo was evaluated using ultrasound imaging. Images were obtained while subjects were seated, with the pelvis fixed, and pulled on an anchored cable by isometrically contracting trunk muscles at different force levels. Linear regression analysis was used to identify ultrasound measurements which were correlated with trunk force. Results suggest that ultrasound is more suitable for estimating lumbar mechanics during lateral flexion than extension of the trunk. A linear trend was found between changes in thickness of some muscles and trunk force, which could provide an alternative to invasive intramuscular electrodes for measuring the activity of non-superficial muscles. A significant limitation, however, is that the magnitude of the changes were frequently very close to the ultrasound resolution.

SOMMAIRE

La possibilité d'estimer la mécanique lombaire in-vivo a été évaluée par imagerie ultrasonique. Les images ont été obtenues, alors que le patient était assis, le bassin fixé, et étiré au moyen d'un câble, contractant isométriquement les muscles du tronc à différents niveaux de force. Une régression linéaire a été utilisée pour identifier les mesures d'ultrasons corrélées avec la force du tronc. Les résultats suggèrent que les ultrasons sont mieux adaptés à l'estimation de la mécanique lombaire durant une flexion latérale que pendant une extension du tronc. Une relation linéaire a été trouvée entre les changements d'épaisseur de certains muscles et la force du tronc, ce qui pourrait fournir une alternative aux électrodes intramusculaires invasives utilisées pour mesurer l'activité des muscles non-superficiels. Cependant, l'amplitude des changements, fréquemment très proche de la résolution ultrasonique, représente une limitation significative.

1. INTRODUCTION

Images of muscle can be obtained using B-mode or real-time ultrasound scanning techniques. Normal muscle parenchyma appears as a homogeneous echogenic matrix separated internally by hyperechogenic fascial planes (Fischer et al. 1988; Cady et al. 1983). Muscle fibers themselves generate few echoes because of their highly regular internal structure (Heckmatt and Dubowitz 1988; Ferrel et al. 1989; Walker et al. 1990) which does not reflect sound well. Furthermore, muscle fibers conduct sound anisotropically. Typically, it has been difficult to obtain images of muscles that lie over one another. As technology has evolved, this has become less of a problem but still remains a challenge in deeper structures, such as the psoas or paraspinal complexes (Walker et al. 2004).

Because most architectural parameters change with muscle contraction, ultrasonography may be used as a non-invasive method to detect or measure activity of specific muscles during isometric contractions. Ultrasound has been routinely used to estimate the cross-sectional area of muscles for clinical purposes such as the identification of dystrophic muscle (Heckmatt et al. 1988), the wasting of lumbar muscle in patients with low back pain (Hide et al. 1994) and the function of respiratory muscles during dynamic pulmonary changes (McKenzie et al. 1994), but only recently has it been applied to investigating muscle mechanics.

The first published study using ultrasound to quantify muscle mechanical parameters was conducted by Rutherford and Jones (1992) and examined changes in the angle of pennation of the vastus lateralis and vastus intermedius muscles with extension of the knee during isometric contraction. Herbert and Gandevia (1995) conducted a similar study of the brachialis muscles in which they also investigated changes in pennation angle with elbow torque. Pennation angle has also been measured in isometrically contracting triceps surae (Kawakami et al. 1998) and tibialis anterior (Maganaris and Baltzopoulos 1999) muscles. Changes in fascicle length of the gastrocnemius (Narici et al. 1996; Maganaris et al. 1998) and soleus (Maganaris et al. 1998) have also been measured during isometric contraction. Ultrasound has also been used for in vivo measurements of changes in tendon length to estimate tendon stress and strain (Maganaris and Paul. 1999; Muraoka et al. 2002), as well as to estimate muscle moment arms (Maganaris 2000; Ito et al. 2000). While ultrasound imaging of the lower limb for in vivo characterization of muscle and tendon mechanics is becoming common-place, few ultrasound imaging studies have examined the paraspinal muscles in relation to lumbar mechanics.

The objective of this project was to test whether changes in the shape of lumbar muscles that can be measured from ultrasound images are correlated with changes in trunk force. Our hypothesis was that the pennation angle and thickness of contracting muscles would increase with trunk force.

2 METHODS

Ten subjects, 6 female and 4 male, participated in this study. These subjects were all in good physical condition between the ages of 18 and 45 and had no history of disabling lower back pain in the past two years. Ethics approval was obtained from both the University of British Columbia and Simon Fraser University's Research Ethics Review Committees.

2.1 Apparatus

The subject sat in an apparatus consisting of an octagonal frame constructed from sections of 2 inch aluminum tubing. The pelvis was restrained by hip pads so that trunk movement would only involve bending of the spine. The subject wore a chest harness to which a cable was attached. During the experiment, the subject pulled isometrically on the cable, which was anchored to the frame (Fig. 1), while observing the output of a force transducer, in series with the cable, on a computer screen. The force was displayed as a bar whose length varied in proportion to the force. The subject was instructed to match the length of a target bar displayed beside the force.

2.2 Data Acquisition

Two-dimensional ultrasound images of the key lumbar muscles were recorded unilaterally (right side) using a GE Medical Systems Voluson 730 ultrasound machine equipped with a 4 – 8 MHz software adjustable transducer (RAB4-8P). All measurements from ultrasound images were made with software calipers by a professional sonographer. The calipers are a set of cross hairs that can be positioned anywhere on the image. The sonographer positioned the calipers but was not provided with information about the measured values to reduce observer bias. The force signal was sampled at 2000 Hz and stored for later analysis.

Figure 1. Apparatus used to fix the pelvis and allow isometric trunk contraction such as extension (shown) and lateral flexion.

2.3 Protocol

Ultrasound images were obtained for 4 different transducer positions while subjects performed either isometric extension or lateral flexion of the trunk. Four contraction levels were compared: 0%, 10%, 25% and 50% of the subject's maximum voluntary contraction (MVC). Each contraction was repeated 3 times.

The transducer was first positioned to obtain an image in the sagittal plane to the right of the midline, at the tips of the L1 and L2 transverse processes. Three caliper measurements were made from this image: erector spinae diameter at L1, erector spinae diameter at L2 and pennation angle of a longissimus fascicle (Fig. 2). The transducer was next positioned to obtain a transverse scan of the erector spinae muscles at the level of L2. Two caliper measurements were made from this image: diameter of the erector spinae at facet joint and diameter of the erector spinae at the tip of the transverse process. Subjects performed both trunk extension and lateral flexion for the first two transducer positions. The transducer was then moved laterally to obtain an image of the quadratus lumborum in the transverse plane at the L3 level (Fig. 3). This image included the lateral tip of the L3 transverse process. Three caliper measurements were made from this image: distance from the quadratus lumborum to the skin, anterior-posterior (A-P) diameter of the quadratus lumborum and

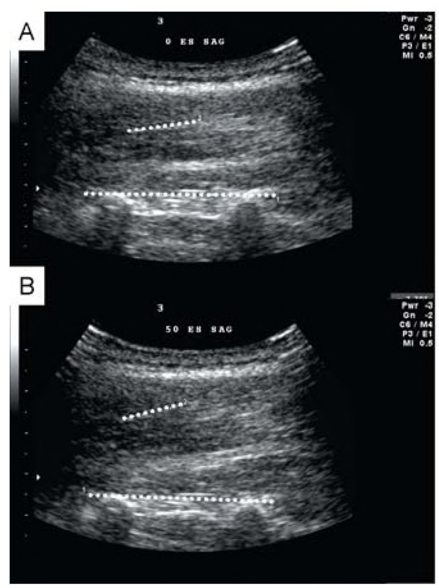

Figure 2 - B-mode ultrasound image of longissimus thoracis relaxed (A) and during exertion of 50% of maximal trunk extension force (B).

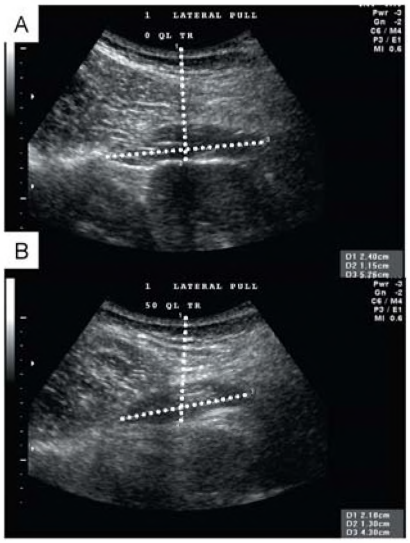

Figure 3 - B-mode ultrasound image of quadratus lumborum (right side) relaxed (A) and during exertion of 50% of maximal right lateral flexion force (B). Both images show the distance from the muscle to the skin (D1) A-P thickness (D2) and M-L thickness (D3).

medial-lateral (M-L) diameter of the quadratus lumborum. Finally, the transducer was placed at the iliac spine to obtain an image in the transverse plane, with the lower border of the transducer placed immediately superior to the iliac crest. This image included the three muscles of the abdominal group (external oblique, internal oblique and transversus abdominis). Measurements from this image were made in the M-L plane from a point located 2 cm to the right of the lateral tip of the transversus abdominis aponeurosis. The measurements included M-L diameter of the external oblique muscle, M-L diameter of the internal oblique muscle and M-L diameter of the transversus abdominis muscle. Subjects performed only lateral flexion for the last two transducer positions.

2.4 Statistical Analysis

Separate ultrasound images were obtained for each contraction (trial), providing 3 sets of measurements for each parameter. We used the coefficient of variation or CV (standard deviation/mean) of the repeated measurements of a given parameter as a measure of reliability. The CV is a useful statistic for comparing the degree of variation from one data series to another, even if the means are drastically different from each other. The ability of the ultrasound measurements to provide reliable information about a given anatomical feature was assessed from the mean coefficient of variation computed across all subjects. Linear regression was used to determine whether change in a particular parameter was correlated with trunk force. This was assessed from the R2 value. R2 is a measure of the ability of the chosen parameter to predict trunk force. R2 performs this by giving the ratio between the sum of squares (SS) of the regression line and the SS of the data points on a scale from 0 to 1. The closer R2 is to 1 the better the parameter is at predicting trunk force. The slope of the linear regression was also tested for statistical significance ($p<0.05$).

3 RESULTS

3.1 Ultrasound Images - Descriptive Statistics

The mean of the coefficients of variation for the three repeated measurements (trials) for the 10 subjects are listed in Tables 1 and 2. The least reliable parameters for lateral flexion were the longissimus thoracis pennation angle and the transversus abdominis diameter, with average coefficients of variation (CV) of approximately 0.14. The most reliable parameters were the longissimus thoracis at L1 diameter, longissimus thoracis at L2 diameter, erector spinae - lateral diameter and quadratus lumborum – distance from skin, all with an average CV of approximately 0.04. Similarly, for extension the longissimus thoracis pennation angle had the largest average CV (0.14), whereas the longissimus thoracis at L1 diameter, longissimus thoracis at L2 diameter and erector spinae - lateral diameter had the smallest average CV (0.04).

The mean coefficient of variation of the parameter values averaged across all force levels for the entire subject group were calculated. As with the repeated measurements, the longissimus thoracis pennation angle was the least reliable parameter for lateral flexion with an average CV of 0.34. However, the CV of most other parameters was also high, indicating that variability across subjects was greater than the variability of repeated measurements. The most reliable parameters across subjects were the erector spinae lateral and longissimus thoracis at L2 diameters with an average CV of 0.14. As in the case of the repeated measurements, the least reliable parameter for extension was the longissimus thoracis pennation angle with a CV of 0.27 whereas the longissimus thoracis at

Structure	Parameter	Coefficient of Variation
Longissimus thoracis	Pennation angle	0.14
Longissimus thoracis	Diameter at L1	0.04
Longissimus thoracis	Diameter at L2	0.04
Erector spinae	Diameter – Medial[1]	0.05
Erector spinae	Diameter – Lateral[2]	0.04
Quadratus lumborum	Distance from Skin[3]	0.08
Quadratus lumborum	Diameter – ML[4]	0.06
Quadratus lumborum	Diameter – AP[5]	0.06
External oblique	Diameter	0.08
Internal oblique	Diameter	0.08
Transversus abdominis	Diameter	0.14

Table 1 - Mean coefficients of variation for repeated measurements in lateral flexion (N=10)

Structure	Parameter	Coefficient of Variation
Longissimus thoracis	Pennation angle	0.14
Longissimus thoracis	Diameter at L1	0.04
Longissimus thoracis	Diameter at L2	0.04
Erector spinae	Diameter – Medial[1]	0.05
Erector spinae	Diameter – Lateral[2]	0.04

[1]Diameter measured at facet
[2]Diameter measured at tip of L2 transverse process
[3]Distance from skin to posterior plane of quadratus lumborum
[4]Diameter of quadratus lumborum in medial-lateral plane
[5]Diameter of quadratus lumborum in anterior-posterior plane

Table 2 - Mean coefficients of variation for repeated measurements in extension (N=10)

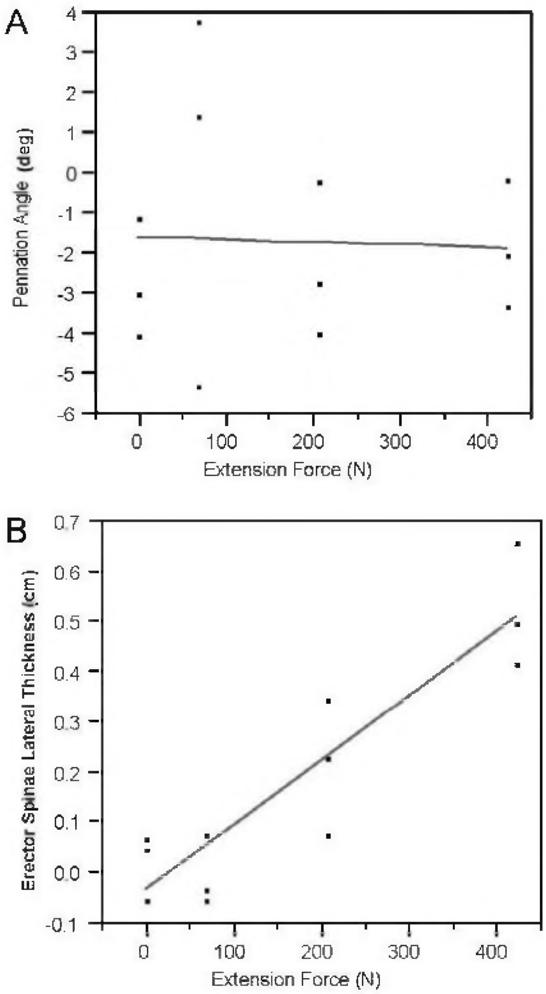

Figure 4 - Scatter plots of the ultrasound parameter with the lowest (A - longissimus thoracis – pennation angle) and the highest (B - erector spinae - lateral) correlation with trunk force in extension from one subject. (Normalized to 10% MVC).

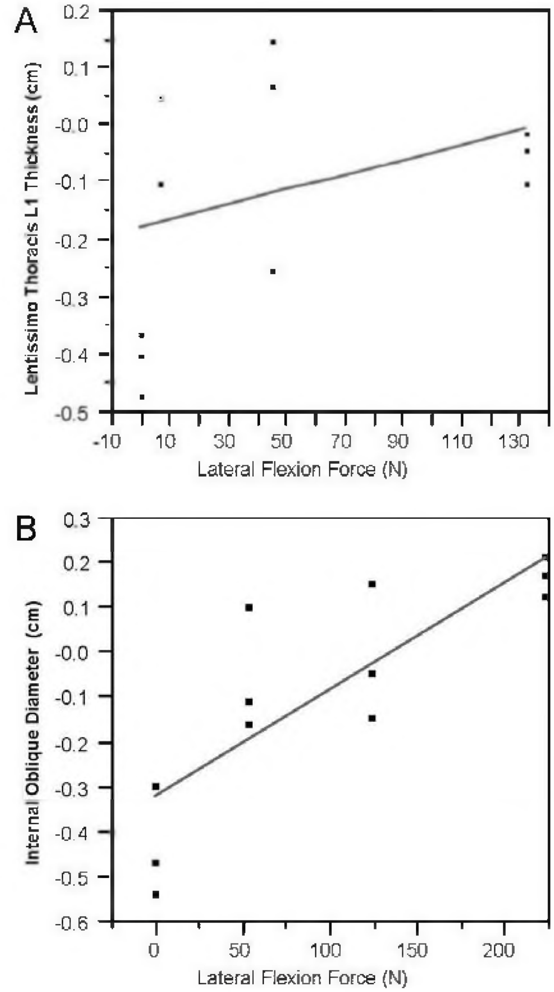

Figure 5 - Scatter plot of the ultrasound parameter with the lowest (A - longissimus thoracis – L1) and the highest (B - internal oblique diameter) correlation with trunk force in lateral flexion from one subject. (Normalized to 10% MVC).

L2 diameter again had the smallest CV (0.14).

3.2 Linear Regression Analysis

Linear regression analysis was conducted to determine the correlation between measured parameters and trunk force. To reduce the effect of anthropometric differences among subjects, the data for each subject were normalized by dividing parameter values by their average value at 10% MVC. Scatter plots for the parameters with the lowest and highest correlations are shown in Figs. 4 and 5 for lateral flexion and extension, respectively. Table 3 summarizes the results of linear regressions performed on the individual subject data. The heading "Significant" indicates the number of subjects for which the slope of the linear regression was significantly different from zero ($p<0.05$).

We found that the erector spinae lateral thickness was the best predictor of trunk extension force (average R2 = 0.60) and that the internal oblique diameter was the best predictor of lateral flexion force (average R2 = 0.68). Longissimus thoracis pennation angle was least correlated with trunk extension force (average R2 = 0.17) and longissimus thoracis thickness at L1 was least correlated with lateral flexion force (average R2 = 0.16).

Table 3 also indicates characteristic differences in the variability of different parameters. For example, in extension longissimus thoracis thickness at L2 and erector spinae medial have similar average R2, indicating that the spread of data points around the regression line is similar in both measurements. However, the average p-values are 0.14 (longissimus thoracis L2 thickness) and 0.037 (erector spinae medial thickness), indicating that the relationship between force and muscle thickness is much stronger for the medial measurement. Further, the standard deviation of the p-value for the longissimus thoracis thickness at L2 was relatively large (0.30), indicative of an unreliable measurement.

A second linear regression analysis was performed using the

Extension	LT-Pennation	LT - L1	LT - L2	ES-Medial	ES-Lateral	QL- Skin	QL-AP	QL-ML	EO	IO	TA
Significant[1]	2	6	8	7	8						
Intercept	-0.004	-0.040	-0.096	-0.083	-0.140						
Slope	0.012	0.0008	0.001	0.0009	0.002						
R^2	0.17	0.34	0.41	0.43	0.60						
P-value	0.35	0.25	0.14	0.037	0.013						
Lateral Flexion											
Significant[1]	3	1	2	2	5	4	4	4	7	10	6
Intercept	-0.026	-0.026	0.016	0.021	-0.065	-0.012	-0.032	-0.153	-0.081	-0.251	-0.044
Slope	0.017	0.0007	0.0009	0.0009	0.001	0.0006	0.00	0.002	0.001	0.003	0.0009
R^2	0.24	0.16	0.17	0.21	0.32	0.18	0.30	0.251	0.41	0.68	0.42
P-value	0.26	0.24	0.32	0.21	0.24	0.37	0.30	0.32	0.076	0.0030	0.13

Table 3 - Mean linear regression intercepts, slopes, R2 values and significance levels for individual subject data (N=10)

Extension	LT-Pennation	LT - L1	LT - L2	ES-Medial	ES-Lateral	QL- Skin	QL-AP	QL-ML	EO	IO	TA
Intercept	0.195	-0.059	-0.086	-0.071	-0.095						
Slope	0.003	0.0009	0.0009	0.0007	0.001						
R^2	0.047	0.45	0.41	0.56	0.48						
P-value	0.18	<0.0001	<0.0001	<0.0001	<0.0001						
Lateral Flexion											
Intercept	0.498	-0.031	0.022	0.016	-0.072	-0.043	-0.054	-0.189	-0.072	-0.187	-0.026
Slope	0.001	0.00006	0.0002	0.00008	0.001	0.0003	0.0008	0.0009	0.001	0.003	0.0008
R^2	0.001	0.001	0.017	0.0030	0.23	0.018	0.20	0.070	0.49	0.61	0.48
P-value	0.79	0.84	0.42	0.74	0.002	0.41	0.004	0.097	<0.0001	<0.0001	<0.0001

LT (longissimus thoracis), ES (erector spinae), QL (quadratus lumborum), EO (external oblique), IO (internal oblique), TA (transversus abdominis)
Parameters are defined in Table 1 (columns in Tables 3 and 4 correspond to rows in Table 1)
[1]Number of subjects for which the slope of the linear regression was significantly different from zero ($p<0.05$).

Table 4 - Linear regression intercepts, slopes, R2 values and significance levels for combined data from all subjects (N=10)

same data averaged over all subjects. As before, in order to reduce the effect of individual differences in resting anatomy the data for each subject were first normalized by the average value at 10% MVC. Figures 6 and 7 show scatter plots for the parameters which were best and least correlated with trunk force. We expected all of the muscle parameters being measured in the extension condition to be significantly correlated with trunk extension force since the measured parameters were selected to quantify changes in muscle geometry that occurred during contraction of the erector spinae muscles. Indeed, in contrast to the individual subject data, when averaged across subjects significant relations were found between all parameters and extension force ($p<0.0001$), with the exception of pennation angle (Table 4).

Since lateral flexion was not the primary function of most of the muscles that could be examined we did not expect many of the parameters to be significantly correlated with lateral flexion force. Nevertheless, the erector spinae lateral thickness ($p=0.002$), quadratus lumborum – anterior/posterior thickness ($p=0.004$), external oblique thickness ($p<0.0001$), internal oblique thickness ($p<0.0001$) and the transversus abdominis thickness ($p<0.0001$) were all significantly correlated with lateral flexion force, although the quadratus lumborum - medial/lateral diameter and quadratus lumborum – distance to skin and most of parameters measured from the erector spinae muscles were not significantly correlated with lateral flexion force.

4 DISCUSSION

In general, the relations between muscle thickness and trunk force were statistically significant. However, the correlation coefficients were generally low suggesting that changes in the shape of muscles at the lumbar level do not provide a good indication of the force being produced by the trunk muscles. Furthermore, pennation angle did not change significantly with trunk force. This is in marked contrast to studies measuring pennation angle in muscles surrounding the ankle and the elbow (Herbert and Gandevia 1995; Narici et al. 1996; Maganaris et al. 1998; Ito et al., 1998; Maganaris and Baltzopoulos 1999; Hodges et al. 2003). However, changes in pennation angle from rest to MVC can be very small, depending on the joint angle. In particular, Ito et al. (1998) and Maganaris and Baltzopoulos (1999) showed that changes in pennation angle of the tibialis anterior can be as small as 2 deg. Since the

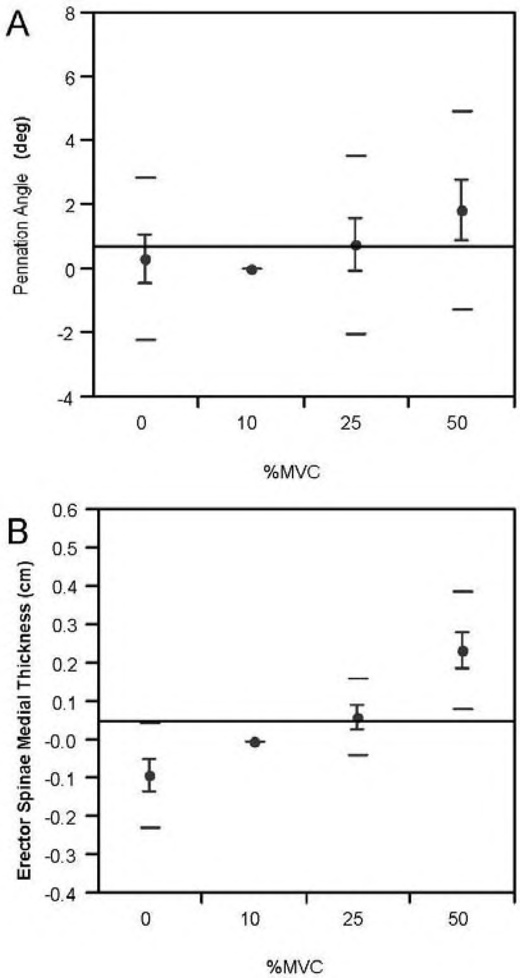

Figure 6 - Mean (dot), ±1 standard error (solid bar) and ±1 standard deviation (broken bar) for scatter plot of the ultrasound parameter with the lowest (A - longissimus thoracis – pennation angle) and highest (B - erector spinae – medial) correlation with trunk force in extension averaged over 10 subjects. (Normalized to 10% MVC).

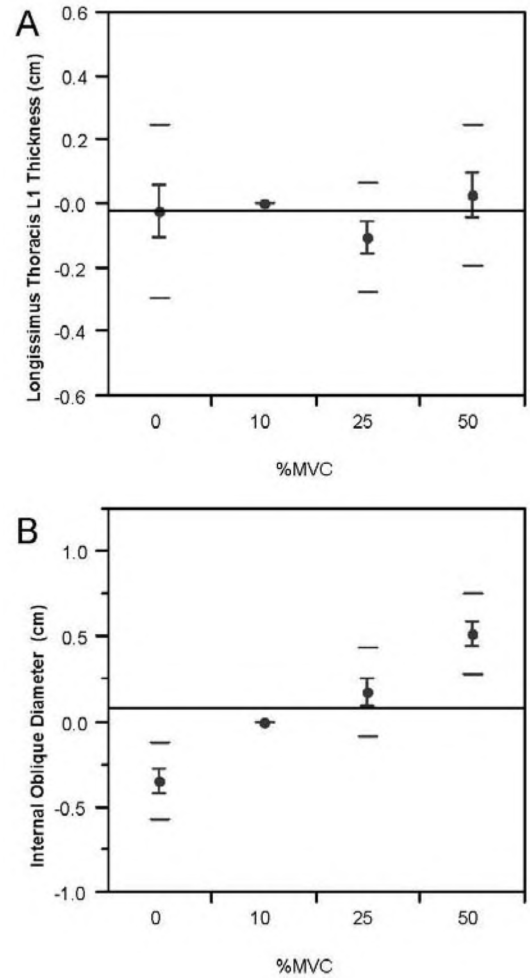

Figure 7 - Mean (dot), ±1 standard error (solid bar) and ±1 standard deviation (broken bar) for scatter plot of the ultrasound parameter with the lowest (A - longissimus thoracis – L1) and highest (B - internal oblique diameter) correlation with trunk force in lateral flexion averaged over 10 subjects. (Normalized to 10% MVC).

resting fascicle length of the longissimus thoracis (Delp et al. 2001) is about twice that of the tibialis anterior, even smaller changes in the pennation angle from rest to 50% MVC could be expected than for tibialis anterior. We observed that the orientation of the trunk changed slightly with increasing trunk force, particularly from rest. Therefore, changes in the muscle length due to changes in the angle or curvature of the spine may have obscured any systematic change in pennation angle with trunk force.

Further, the results of the descriptive statistics and the linear regression analysis showed that our CV values were larger and our R2 values for the linear regressions were lower than CV's and R2 values of similar studies of the lower limb (Rutherford et al. 1992; Narici et al. 1996; Fukunaga et al. 1997; Kawakami et al. 1998; Maganaris et al. 1998; Maganaris et al. 1999; Muramatsu et al. 2002). This indicates greater variance in our data, which was likely due to several factors. For example, compliance in the chest harness, the cable and the soft tissues of the torso allowed the trunk angle to change for different force levels. However, even if it had been possible to prevent the trunk angle from changing, the curvature of the spine might still have changed with increasing force. Changes to the geometry of the spine with trunk force could alter the muscle moment arms and, hence, change the relation between muscle force and trunk force.

Hodges et al. (2003) discuss other factors that can reduce the correlation between muscle shape changes and activation. In particular, muscle deformation varies due to variations in the pressure applied to the skin by the transducer, pressure applied by neighbouring active muscles and changes in internal pressure of the abdominal cavity. Although we attempted to minimize the effects of these sources of variability by having the sonographer try to apply a consistent amount of pressure to the transducer on all trials and by instructing the subjects not to breathe during the scan, we could not completely eliminate them.

The study of Hodges et al. (2003) is the only previously published study investigating contraction of trunk muscles with ultrasound images. Although they examined three of the same muscles as we did, namely the external oblique, internal oblique and transversus abdominis, they performed the scans from the anterior rather than the latero-posterior surface of the body, i.e., they obtained images of the muscles from the front rather than from the side of the body. Furthermore, they had the subjects perform isolated contractions of the abdominal wall, whereas our subjects performed isometric lateral flexion of the entire trunk. Hence, the task performed by their subjects was entirely different so the two experiments are not directly comparable. Hodges et al. (2003) reported that the thickness of the external oblique muscle was not strongly correlated with contraction level of the abdominal wall (R=0.23). In contrast, we found that the thickness of the external oblique was relatively highly correlated with trunk force (R=0.70 for mean subject data).

A recent study in which EMG of external oblique, internal oblique and extensor muscles of the trunk was recorded found that external oblique is maximally activated during lateral flexion and multifidus during extension (Ng et al. 2002). None of the other muscles were maximally activated in these force directions. This would correspond to the relatively strong correlation of external oblique thickness with trunk force during lateral flexion. We were unable to obtain clear images of multifidus due to its proximity to the vertebrae so we could not confirm a similar relation for extension. Thickness of the erector spinae muscles, including the longissimus thoracis muscle may have been affected by similar factors to those discussed for pennation angle. In addition, Watanabe et al. (2004) have shown that the thickness of erector spinae muscles increases with trunk extension angle. As well, it is more difficult to distinguish the boundaries of erector spinae muscles than the muscles of the abdominal wall which are more echogenic because of the surrounding aponeuroses. Thus, measurements tended to be less accurate for erector spinae muscles, introducing variability.

Analysis of the individual subject data showed that none of the three parameters for the quadratus lumborum were correlated with lateral flexion force, although averaged across all subjects the quadratus lumborum – anterior/posterior thickness was significantly correlated. The quadratus lumborum originates from the iliolumbar ligament, the transverse processes of the lumbar vertebrae and the twelfth rib and inserts on the posterior portion of the iliac crest. These lines of action would act to extend and laterally flex the torso as in our protocol. However, our measurements do not indicate this as they did not correlate strongly with either trunk extension or lateral flexion force. Andersson et al. (1996) showed that the quadratus lumborum is active for both dynamic trunk extension and lateral flexion activities, although these results cannot be strictly compared to the results of our study as our protocol involved isometric versions of these actions. McGill et al. (1996) showed that for lifting tasks the quadratus lumborum was activated to 74% of its MVC, on average. The same study also showed that for isometric side support postures where the body is held horizontally, almost parallel to the ground as the subjects supported themselves on one elbow and both feet, the quadratus lumborum was on average activated to 54% of its MVC. However, both studies did comment that even though the quadratus lumborum was generally active during extension and lateral flexion its activity depended on the specificity of the tasks. Although there is some evidence for contraction of the quadratus lumborum during the period of isometric lateral flexion, the results are equivocal. One explanation may lie in the ultrasound measurement itself. Figure 3 clearly shows that the lateral border of the muscle is not as echogenic as the rest of the cross section of the muscle. This is a function of the angle of incidence of the ultrasound beam. When the transducer angle is altered the image of the lateral border improves. However, the medial border no longer reflects with intensity strong enough to be seen. Hence, it was not possible to obtain an ideal image of quadratus lumborum for measuring shape changes.

Our calibration tests with the RAB4-8P ultrasound probe indicate that the resolution for measurements in the axial and lateral planes are about 1 mm and 2 mm, respectively. Therefore, in order to make reliable caliper measurements, changes in features being analyzed should be at least 1 mm for axial (along the direction of beam penetration) measurements and at least 2 mm for lateral measurements (along the direction of the beam scan). The mean changes from 0% to 50% MVC for axial measurements during lateral flexion were greater than 1 mm only for ES-Lateral, EO, IO and TA. As might be expected, the parameters with the largest changes from 0% to 50% MVC produced the highest correlations with trunk force. The single parameter that was measured in the plane of the beam scan was QL-ML, which had a mean change of 2 mm and was also significantly related to trunk force. In the case of trunk extension, the average change in all of the parameters measured in the axial plane was at least 1 mm and as such, they were all highly related to trunk force. Mean changes in pennation angle for both extension and lateral flexion were 1.6 and 0.9 deg, respectively. It is difficult to determine whether or not this is large enough to detect changes. However, it should be noted that the measurements (Fig. 2) were made in the plane of the beam scan where the resolution is worst, which likely contributed to our inability to detect systematic changes with trunk force.

In conclusion, ultrasound measurements were better correlated with parameters of lumbar mechanics during isometric lateral flexion than extension of the trunk. There was a statistically significant linear trend between change in muscle thickness and trunk force, although the correlation coefficients were generally low. This may have been partly due to the fact that changes in many parameters were below or near the limits of the resolution of measurements from ultrasound images. Although further research is required, findings indicate that muscle thickness measured by ultrasound may be used as a substitute for electromyography in estimating the activity of some muscles during isometric contraction. This would allow the invasive procedures required for intramuscular recording of deep muscles of the lower back to be avoided.

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