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Cross-sectional area of the lumbar back muscles as a function of torso flexion

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Abstract

Objective. Quantification of the maximum anatomical cross-sectional area of the lumbar back muscles as a function of torso flexion angle and development of prediction equations as a function of torso flexion and anthropometric measures.

Background. Cross-sectional areas of the lumbar back muscles used as inputs into biomechanical models have traditionally been derived from subjects lying in the neutral supine posture. However, it is known that the cross-sectional area of muscle is altered as the torso angle changes.

Design. Experimental design consisted of a two-factor multivariate analysis of variance on the cross-sectional area of the lumbar torso muscle across the lumbar levels, as a function of gender and torso angle. Hierarchical linear regression was utilized to assess the association between cross-sectional area and individual and torso posture characteristics.

Method. Axial MRI scans, through and parallel to each of the lumbar intervertebral discs at four torso flexion positions were obtained from subjects in a lateral recumbent posture. Cross-sectional areas were quantified and converted into anatomical cross-sectional areas utilizing known fascicle orientations.

Results. The maximum anatomical cross-sectional area was located between the L_3/L_4 and L_4/L_5 level in the neutral posture. The anatomical cross-sectional areas at the L_4/L_5 and L_5/S_1 decreased during torso flexion, however, the percent change varied as a function of the individual level. The majority of the anatomical cross-sectional area variability was explained by gender and body mass. Lumbar curvature explained a larger proportion of the anatomical cross-sectional area variability at the lower lumbar levels than at the higher lumbar levels.

Conclusions. The maximum anatomical cross-sectional area of the lumbar back muscles occur at the neutral torso posture and did not decrease as a function of torso flexion. When using maximum anatomical cross-sectional area or specific lumbar level anatomical cross-sectional areas, it appears necessary to account for gender and body mass. At the lower lumbar levels, knowledge of spinal curvature plays an increasing role in the estimation of the size of the lumbar torso muscle cross-sectional area.

Relevance

This research indicates the lower lumbar level trunk muscle anatomical cross-sectional area decrease as torso flexion increases, however, the maximum lumbar trunk muscle anatomical cross-sectional area does not vary as a function of torso flexion. Accounting for gender, body mass, torso characteristics and lumbar curvature may help increase accuracy of anatomical cross-sectional area prediction, as well as muscle force predictions from biomechanical models.

Keywords: Lumbar back muscles; Anatomical cross-sectional area; Magnetic resonance imaging; Torso flexion; Lumbar spinal curvature; Biomechanical model inputs

1. Introduction

Biomechanical models of the torso have been developed to predict the loading on the spine in an effort to understand potential injury mechanisms to the low back

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from activities such as lifting and lowering. Several biomechanical models utilize electromyography (EMG) and torso geometry to predict internal torso muscle forces (Marras and Granata, 1997; McGill, 1992). The accuracy of the resulting predicted spinal loads, however, is highly dependent upon the inputs into these biomechanical models. The normalized EMG muscle activity, which represents the percent of the muscle maximum activity, is combined with muscle force-velocity and length–tension relationships, the cross-sectional area (CSA) of the muscle, as well as the maximum force producing capability of the muscle (gain or muscle stress) to derive estimates of internal muscle force. Since the erector spinae is the major extensor muscle of the torso (Macintosh and Bogduk, 1991), in order to increase the validity of the predicted spinal loading from the biomechanical models for activities such as lifting, accurate anatomical representation of the lumbar erector spinae is necessary.

Anatomical geometry of the lumbar erector spinae has been typically derived from medical imaging studies. Many imaging studies have reported on the CSA of the male (McGill et al., 1988; McGill et al., 1993; Wood et al., 1996; Tracy et al., 1989; Reid et al., 1987; Guzik et al., 1996; Tsuang et al., 1993; Tveit et al., 1994; Marras et al., 2001) and female (Tveit et al., 1994; Marras et al., 2001; Chaffin et al., 1990) lumbar torso extensor muscles. Because of constraints due to the physical design of computerized tomography (CT) and magnetic resonance imaging (MRI) equipment, all prior imaging studies have quantified the lumbar back muscle CSA from subjects oriented in a supine or prone posture. However, manual materials handling activities in the workplace involve bending of the torso (Marras et al., 1993; Norman et al., 1998; Hoogendoorn et al., 2000), and some evidence suggests that torso flexion alters the muscle geometry of the lumbar back muscles (Tveit et al., 1994). Utilizing MRI, Tveit et al. (1994) reported that the CSA of the lumbar erector mass from subjects in a supine posture decreased when the subjects voluntarily decreased their lumbar curvature. However, they did not quantify the lumbar curvature that corresponded to the change in the CSA, nor could they investigate the effect of torso flexion and the impact on lumbar muscle CSA due to the physical design of the MRI.

Knowledge of where the maximum CSA of the muscle in the lumbar spine occurs, as well as what posture the maximum CSA occurs in is important for accuracy considerations of the biomechanical models. Thus, quantification of these relationships would allow EMG-assisted biomechanical models of the torso to more accurately represent changes in internal trunk geometry that occur during torso flexion, and thus, improve the accuracy of the prediction of spinal loading.

The objectives of this research, therefore, were to quantify the lumbar back muscle CSA at different torso flexion positions, identify the torso position where the maximum anatomical cross-sectional area (ACSA) lies, and investigate variables, such as gender and anthropometric measures, that may be associated with the lumbar back muscle CSA as the torso changes posture in the sagittal plane.

2. Methods

Twelve males (mean age of 23.1 yrs [SD, 3.1 yrs], mean height of 177.1 cm [SD, 8.4 cm] and mean body mass of 74.5 kg [SD, 6.7 kg]), and 12 females (mean age of 23.8 yrs [SD, 4.4 yrs], mean height of 162.3 cm [SD, 6.2 cm], and mean body mass of 56.5 kg [SD, 6.0 kg]) recruited from the local community participated in this study.

T1 weighted ($TR = 400$ and $TE = 10$) MRI scans were performed using a 0.3 T Hitachi Aisis open MRI at a local hospital. Sagittal and transverse plane scans were performed with the subjects lying on their left side, at four different torso flexion postures (neutral, 15°, 30°, and 45° torso flexion), with the knees extended at each of the four torso positions.

Within the MRI, the subjects lied in a large size body coil, on top of a wooden pegboard to control the torso postures. The posterior aspect of S_1 was positioned at one mark on the pegboard. To achieve and control each torso flexion angle, lines were drawn from the S_1 marker in the cranial-anterior direction at angles of 0°, 15°, 30° and 45°. The posterior surface of the torso from S_1 to C_7 was aligned along each line to consistently achieve each torso angle for all subjects (Mitnitski et al., 1998), where a wooden dowel was placed along the line such that the C_7 spinous process would lie flush with. The thighs and hips were stabilized during the scanning, as well as during the changes in torso flexion postures between each scan by using Velcro straps attached to the positioning pegboard. To eliminate coronal sagging of the lumbar spine while in a lateral recumbent position, padding was placed between the iliac crest and ribcage, as well as between the knees and legs to abduct the hips (Bontrager, 1993).

A sagittal scout scan was performed at each of the torso flexion positions, from which 10 mm thick axial cross-sectional scans were set up. The axial scans were located through each of the five lumbar intervertebral disc spaces (L_1/L_2 to L_5/S_1) for each of the four torso flexion angles, and oriented parallel to each intervertebral disc (Fig. 1).

The images were converted to a 512×512 pixel digital image. Using custom calibrated digitizing software with a resolution of 0.75 mm, the right lumbar back muscle (combined iliocostalis, longissimus, multifidus) was outlined with a series of digitized points, and the CSA was derived from these digitized points using

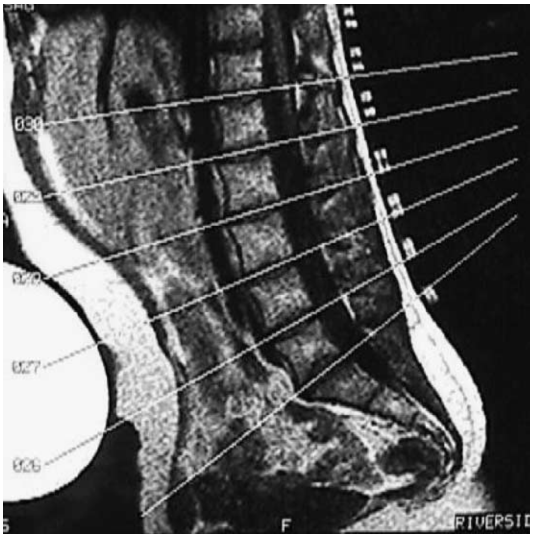

Fig. 1. Sagittal MRI scan of torso in 15° flexion, showing the scan lines for the axial slices through and parallel to the intervertebral discs.

methods of prior imaging studies (Wood et al., 1996; Reid et al., 1994).

The resulting CSAs represent the cross-sectional area of the lumbar back muscle that is parallel to the scan plane. However, it is likely that the muscle fascicles are oriented obliquely to the scan plane, and the muscle fascicle orientation would vary depending upon the vertebral level of origin (Macintosh et al., 1993), as well as the sagittal plane torso position (Macintosh et al., 1993; McGill et al., 2000). For use in biomechanical models, the CSAs must be perpendicular to the direction of the muscle fibers (Narici, 1999). Thus, using the approach of McGill et al. (1993), the raw CSAs from the MRI scans were converted to ACSAs by multiplying the raw CSA by the dot product between the perpendicular axis of the scan plane and the unit vector cosine of the approximate orientation of the lumbar back muscle. The coronal plane orientation of the muscle fascicles (average of the iliocostalis and longissimus) at each lumbar vertebral level were taken from Macintosh and Bogduk (1991) (Table 1). The sagittal plane fascicle orientations reported by Macintosh et al. (1993) at neutral and full flexion (average of the iliocostalis and longissimus) were assigned to the neutral and 45° torso flexion postures in this study. The sagittal plane fascicle orientation at the 15° and 30° torso positions were derived by assuming a linear relationship of the fascicle orientation between neutral and full flexion. The sagittal plane correction angle (θ) for the muscle fascicle was derived with respect to the vertebral body orientation (α) and the intervertebral scan angle (β) (see Fig. 2). First, each muscle fascicle angle (FA) in the MRI field of view (FoV) was determined utilizing the average orientation of the lumbar portions of the iliocostalis and longissimus (Table 1) and the vertebral body orientation (α) in the MRI FoV (Eq. (1))

$$\phi = \mathrm{FA} - \alpha \tag{1}$$

where ϕ: sagittal plane muscle fascicle orientation in the MRI FoV, FA: sagittal plane muscle fascicle orientation with respect to the vertebral body of origin, α: vertebral body orientation in the MRI FoV.

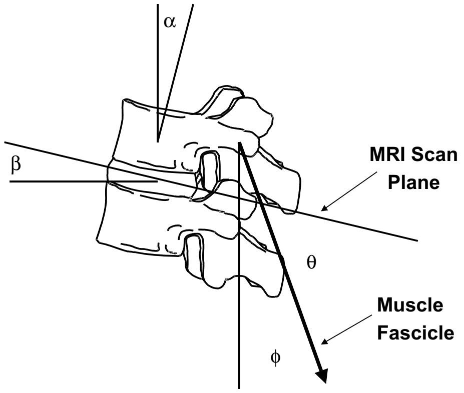

Fig. 2. MRI scan plane global angle (β), vertebra body orientation global angle (α), muscle fascicle global angle (ϕ) and muscle FA with respect to MRI scan plane (θ).

Table 1
Muscle fascicle sagittal and coronal plane orientation (deg) with respect to the vertebral body of origin

Torso angle	Vertebral body of fascicle origin									
	L_1		L_2		L_3		L_4		L_5	
	Iliocostalis	Longissimus	Iliocostalis	Longissimus	Iliocostalis	Longissimus	Iliocostalis	Longissimus	Iliocostalis	Longissimus
Sagittal plane muscle fascicle orientation (deg)										
Neutral	22	21	21	27	20	28	30	28	–	41
15°	15	13.3	15.7	19.3	16.7	21.7	26.9	24	–	37.3
30°	8	5.7	10.3	11.7	13.3	15.3	22.7	20	–	33.7
45°	1	−2	5	4	10	9	19	16	–	30
Coronal plane muscle fascicle orientation (deg)										
All	3	4	5	5	8	9	15	14	–	27

Next, as indicated in Eq. (2) and shown graphically in Fig. 2, the sagittal plane muscle fascicle orientation in the MRI FoV (ϕ) was utilized, along with the intervertebral disc scan plane angle in the MRI FoV to determine the orientation of the sagittal plane muscle fascicle orientation (θ) with respect to the intervertebral scan plane (β)

$$\theta = \phi + \beta \tag{2}$$

where θ: sagittal plane orientation of muscle fascicle with respect to the intervertebral scan plane, ϕ: sagittal plane muscle fascicle orientation in the MRI FoV, β: intervertebral scan plane orientation in the MRI FoV.

Utilizing the digitizing software, the Cobb method was used to determine the lumbar spinal curvature across different motion segments from the sagittal scout views for each of the lumbar torso flexion positions (Jackson et al., 2000; Gelb et al., 1995). This included the L_1/L_3, L_1/L_4, L_1/L_5 and L_1/S_1 lumbar curvature, as well as the segmental angles from L_1/L_2 to L_5/S_1.

Multivariate analysis of variance (MANOVA) was performed to assess the effect of gender and torso posture on the collective behavior of the lumbar back muscle ACSAs across all intervertebral levels. Follow-up ANOVAs were performed for significant independent variables, followed by post-hoc tests on planned comparisons using the least significant difference (LSD) to assess where the significant differences in the ACSA occurred as a function of the independent variable. Bonferroni adjustments for the number of comparisons were used to control for a Type I error ($\alpha = 0.05$).

A two-way ANOVA was performed on the maximum lumbar back muscle ACSA. The independent variables included gender, torso flexion angle, and a gender by torso flexion angle interaction. Significant effects were investigated using the LSD post-hoc test, utilizing a Bonferroni adjustment for the number of comparisons to control for a Type I error ($\alpha = 0.05$).

Hierarchical linear regression utilizing the forward selection method was used to investigate if the ACSAs at each intervertebral and the maximum ACSA were associated with measures of torso posture, gender and anthropometric measures. Variable selection for inclusion into the model was based on the variable with the highest adjusted R^2, followed by a partial F-test to determine if a significant incremental explanation of the ACSA variability resulted by inclusion of the new variable. The contribution to the explained total ACSA variability was investigated for each variable in the models by assessing the semi-partial correlation coefficients. Multicollinearity effects were assessed utilizing the Variance Inflation Factor.

3. Results

The mean male and female lumbar back muscle ACSAs at each intervertebral level, as well as the maximum lumbar back muscle ACSAs are shown in Table 2.

The MANOVA indicated that the lumbar back muscle ACSA varied significantly as a function of torso flexion (Wilks' lambda, $P = 0.0013$) and gender (Wilks' lambda, $P = 0.0001$), however, the torso flexion by gender effect was not significant (Wilks' lambda, $P = 0.7299$).

Follow-up ANOVAs indicated that males exhibited significantly larger ACSAs than females at all lumbar intervertebral levels, and that differences in the ACSA as a function of sagittal plane torso position were present at the L_4/L_5 and L_5/S_1 intervertebral levels. At L_4/L_5, the ACSA at 45° torso flexion posture was significantly smaller (by 11% for both males and females) than the ACSA at the neutral posture. At L_5/S_1, the ACSA at the neutral posture was significantly larger than the ACSA at 30° torso flexion (16% and 20.7% smaller than at neutral for females and males, respectively) and 45° torso flexion (20.8% and 28.2% smaller than at neutral for females and males, respectively).

The maximum lumbar erector spinae ACSA decreased by 1.2 cm^2 (8.1% decrease) for females and 0.8 cm^2 (3.4% decrease) for males as the torso went from neutral to the 45° flexion position (Table 2). The ANOVA indicated that the maximum lumbar back muscle ACSA varied as a function of gender ($P = 0.0001$), but not as a function of torso angle ($P = 0.6151$) or torso angle by

Table 2
Mean (SD) female and male ACSAs (cm^2) and the maximum ACSA (cm^2) for the right lumbar back muscles as a function of torso flexion angle

Gender	Torso angle	Intervertebral level					Maximum ACSA
		L_1/L_2	L_2/L_3	L_3/L_4	L_4/L_5	L_5/S_1	
Female	0°	10.7 (1.3)	12.1 (1.3)	13.7 (1.8)	14.5 (2.2)	10.6 (1.9)	14.8 (2.0)
	15°	10.8 (1.4)	12.5 (1.0)	13.5 (1.7)	13.7 (1.9)	9.7 (1.9)	14.2 (1.8)
	30°	10.8 (1.3)	12.6 (1.3)	13.3 (1.5)	13.1 (1.8)	8.9 (1.8)	13.9 (1.7)
	45°	11.7 (1.5)	12.6 (1.3)	13.2 (1.5)	12.9 (2.0)	8.4 (1.0)	13.6 (1.6)
Male	0°	20.2 (3.3)	22.1 (3.1)	22.3 (3.9)	22.7 (3.4)	17.4 (4.8)	23.7 (3.5)
	15°	20.1 (3.2)	22.3 (3.1)	22.3 (3.2)	21.4 (3.2)	15.1 (4.2)	23.3 (3.2)
	30°	21.7 (2.9)	22.2 (3.2)	22.5 (3.0)	20.6 (3.1)	13.8 (4.6)	23.1 (3.5)
	45°	19.6 (2.7)	21.9 (3.4)	22.5 (3.2)	20.2 (3.2)	12.5 (3.3)	22.9 (3.6)

Table 3
Multiple linear regression results for the prediction of the right lumbar back muscles ACSA from externally measured torso angle, internal lumbar lordosis measures and anthropometric measures, as a function of intervertebral level and gender

Level	L_1/L_2		L_2/L_3		L_3/L_4		L_4/L_5		L_5/S_1		Maximum ACSA	
Adj R^2	0.88		0.87		0.86		0.85		0.73		0.86	
P-value	0.0001		0.0001		0.0001		0.0001		0.0001		0.0001	
Std error	1.8		1.9		1.9		1.8		2.3		2.0	
Variable	Coefficient	Proportion of total explained variance	Coefficient	Proportion of total explained variance	Coefficient	Proportion of total explained variance	Coefficient	Proportion of total explained variance	Coefficient	Proportion of total explained variance	Coefficient	Proportion of total explained variance
Intercept	4.28		12.67		−8.63		−6.48		14.29		−10.11	
Gender	6.69	0.91	5.85	0.93	3.7	0.88	3.15	0.78			3.72	0.84
Mass	0.28	0.04	0.28	0.05			0.29	0.06			0.28	0.08
Ht × mass					0.001	0.02			0.002	0.58		
TDTWIC	−0.02	0.05			−0.02	0.02	−0.03	0.07			−0.02	0.03
TrCircum									−0.58	0.14		
TWIC			−0.59	0.02								
TWXP					0.74	0.05	0.52	0.02	0.69	0.08	0.61	0.02
L_1/S_1							0.08	0.07	0.13	0.20	0.07	0.04
L_1/L_5	0.04	0.01			0.07	0.03						

TDTWIC = product of trunk depth and width at the iliac crest (cm^2); TrCircum = trunk circumference at the iliac crest (cm); L_1/S_1 = lumbar curvature between superior surfaces of L_1 and S_1 (deg); L_1/L_5 = lumbar curvature between surperior surface of L_1 and inferior surface of L_5 (deg); mass = body mass (kg); TDIC = trunk depth at the iliac crest (cm); TWIC = trunk width at the iliac crest (cm); TWXP = trunk width at the xyphoid process (cm); Ht × mass = product of height and body mass (cm kg).

gender ($P = 0.9931$). The post-hoc test indicated that the maximum male ACSA was larger than the maximum female ACSA at every torso flexion angle.

The multiple linear regression models for the lumbar back muscle ACSA are shown in Table 3. Generally, the resulting linear regression models at all intervertebral levels found that the magnitude of the lumbar back muscle ACSA was associated with measures of body mass (either body mass or product of height and mass) and torso width (measured either at the level of the iliac crest or the xyphoid process). At all levels except L_2/L_3, the ACSA was associated with measures of torso size (either torso circumference at the iliac crest or the product of the torso width and depth at the iliac crest) and a measure of lumbar curvature. Additionally, at all levels except L_5/S_1, the lumbar back muscle ACSA was also associated with gender.

The explained ACSA variability (multiple R^2) from the regression models ranged from 74% at L_5/S_1 to 89% at L_1/L_2 as well as for the maximum ACSA. Assessing the contribution of the different independent variables to the overall explanation of the ACSA variability, the semi-partial correlations of the independent variables in each regression model were investigated. At all levels except L_5/S_1, gender accounted for the majority of the total explained ACSA variability, ranging from 78% of the total explained ACSA variability at L_4/L_5 to 93% at L_2/L_3. Where present, body mass accounted for between 4% and 8% of the total explained ACSA variability, torso area measures (e.g., trunk circumference, product of torso width and depth) accounted for between 2% and 14%, and torso depth measures accounted for between 2% and 8% of the total explained ACSA variability.

The regression models also indicated that as the torso moved from neutral to 45° flexion, measures of lumbar curvature were also associated with the lumbar back muscle ACSA at all intervertebral levels except L_2/L_3. L_1/S_1 lordosis was associated with the largest ACSA as well as the L_4/L_5 and L_5/S_1 ACSA, whereas L_1/L_5 lordosis was associated with the ACSA at L_1/L_2 and L_3/L_4. Between the L_1/L_2 and L_4/L_5 levels, measures of lumbar curvature accounted for a small percent of the total explained ACSA variability (1–7%), whereas at L_5/S_1, the lumbar curvature accounted for 20% of the total ACSA variability.

4. Discussion

Similar to the findings in other studies, anthropometric measures such as body mass (Reid et al., 1987; Marras et al., 2001; Chaffin et al., 1990), indicators of torso area (e.g., trunk circumference and product of trunk width and depth) (Reid et al., 1987; Chaffin et al., 1990), as well as torso depth (Chaffin et al., 1990) were associated with the magnitude of the lumbar back muscle ACSAs. Also consistent was the finding that gender differences existed (Marras et al., 2001; Reid and Costigan, 1985; Cooper et al., 1992), but it appears that as the torso moves from neutral to 45° flexion, gender accounts for the major proportion of the explained variability of the ACSA.

The main difference between our study and prior imaging studies was our investigation assessed the ACSA at different torso postures in the sagittal plane. Thus, it was anticipated that torso flexion, which alters the lumbar curvature, would influence the magnitude of the ACSA as suggested by Tveit et al. (1994). The more inferior the lumbar intervertebral level, the greater the contribution of the lumbar curvature to the overall explanation of the ACSA variability (1% at L_1/L_2 to 20% at L_5/S_1). Since the lower lumbar vertebral bodies have a larger range of motion during torso flexion (White and Panjabi, 1990), it may be that the rotating vertebral bodies at the lower lumbar level influence the size of the ACSA at the lower levels as a function of torso flexion.

Our study also found that the maximum ACSA of the lumbar back muscle occurs in the neutral torso posture, and torso flexion resulted in a slight but nonsignificant decrease in the maximum ACSA. On average, the location of the maximum ACSA varied between the L_3/L_4 and L_4/L_5 levels. Thus, most prior studies evaluating the CSA of the lumbar back muscle captured the level and posture where the maximum CSA occurred, however, most prior studies did not correct the cross-sectional areas for the obliquity of the muscle fascicle orientation with respect to the image scan planes. Nonetheless, biomechanical models that use the maximum ACSA to represent the maximum force producing capability of the muscle (Narici, 1999; Bamman et al., 2000) may be able to use the maximum ACSA found in the neutral posture to represent the ACSA for sagittal plane torso postures between neutral and 45° flexion.

In contrast to the maximum ACSA, the intervertebral level specific ACSAs decreased at the lower lumbar levels during torso flexion, with the percent decrease at L_5/S_1 larger than the percent decrease at L_4/L_5. This suggests that the decrease in the ACSA, which may be a concurrent effect of the lengthening lumbar back muscle fascicles due to torso flexion, occurs at different rates at different lumbar levels. This may also indicate that the muscle length–tension relationship is more complex than currently used in biomechanical models, possibly due to factors such as changes in the orientation of the muscle fascicle and lumbar curvature during torso flexion. This point may merit further research.

The results of this study should be viewed in light of several methodological considerations. The subjects were young healthy male and female adults, who may differ anthropometrically from those who perform MMH tasks in industry. Second, the lumbar erector spinae fascicle orientation data utilized to correct the cross-sectional areas are based on male data. It is unknown if significant gender differences exist in lumbar erector fascicle orientation, which could impact the resulting cross-sectional area correction factors. Third, the muscle fascicle orientation data were based on full upright and full flexion postures. The full flexion position may have been greater than the 45° torso flexion position in our study. The fascicle orientation was determined with respect to the vertebral body orientation, for which the 45° torso flexion position indicated a flattening of the lumbar spine. Thus, one would expect very little difference in vertebral body orientation between the two postures, very little difference in muscle fascicle orientation, as well as very little difference on the resulting ACSAs. Finally, the estimation of the ACSAs and lumbar curvature were derived from subjects lying in a lateral recumbent posture. Inspection of the literature indicated that the lateral recumbent spinal curvature at L_5/S_1 was somewhat smaller than that measured in the upright posture. This would tend to slightly underestimate the correction factor to convert the raw CSA into the ACSA, and result in an overestimation of the ACSA at the L_5/S_1 level. This would not, however, affect the ACSAs found at the other lumbar levels, nor would this affect the findings on the maximum lumbar erector spinae ACSA.

5. Conclusions

Several conclusions can be reached from this study. First, the maximum lumbar back muscle ACSAs occurred in the neutral posture, between the L_3/L_4 and L_4/L_5 level, and did not vary significantly as a function of sagittal plane torso posture. Second, the ACSAs at the L_4/L_5 and L_5/S_1 intervertebral levels decreased by different percentages as the torso moved from neutral to 45° flexion in the sagittal plane, suggesting that the lengthening of the lumbar back muscles may not be uniform throughout the muscle during torso flexion. Third, although the torso position ranged between neutral and 45° flexion, lumbar curvature had the largest association with the varying ACSA at the L_5/S_1 level.

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