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Effect of torso flexion on the lumbar torso extensor muscle sagittal plane moment arms

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Abstract

BACKGROUND CONTEXT: Accurate anatomical inputs for biomechanical models are necessary for valid estimates of internal loading. The magnitude of the moment arm of the lumbar erector muscle group is known to vary as a function of such variables as gender. Anatomical evidence indicates that the moment arms decrease during torso flexion. However, moment arm estimates in biomechanical models that account for individual variability have been derived from imaging studies from supine postures.

PURPOSE: Quantify the sagittal plane moment arms of the lumbar erector muscle group as a function of torso flexion, and identify individual characteristics that are associated with the magnitude of the moment arms as a function of torso flexion.

STUDY DESIGN/SETTING: Utilization of a 0.3 Tesla Open magnetic resonance image (MRI) to image and quantify the moment arm of the right erector muscle group as a function of gender and torso flexion.

METHODS: Axial MRI images through and parallel to each of the lumbar intervertebral discs at four torso flexion angles were obtained from 12 male and 12 female subjects in a lateral recumbent posture. Multivariate analysis of variance was used to investigate the differences in the moment arms at different torso flexion angles, whereas hierarchical linear regression was used to investigate associations with individual anthropometric characteristics and spinal posture.

RESULTS: The largest decrease in the lumbar erector muscle group moment arm from neutral to 45-degree flexion occurred at the L5–S1 level (9.7% and 8.9% for men and women, respectively). Measures of spinal curvature (L1–S1 lordosis), body mass and trunk characteristics (depth or circumference) were associated with the varying moment arm at most lumbar levels.

CONCLUSIONS: The sagittal plane moment arms of the lumbar erector muscle mass decrease as the torso flexes forward. The change in moment arms as a function of torso flexion may have an impact on prediction of spinal loading in biomechanical models.

Keywords: Open MRI; Biomechanical modeling; Torso flexion; Moment arms; Lumbar erector muscle mass

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Introduction

Valid estimates of internal spinal loading using biomechanical models of the torso are dependent on the accuracy of anatomical inputs, such as the muscle moment arms [1,2] and muscle lines of action [2,3]. Because torso extension occurs during lifting motions, and the lumbar erector muscle group is the major extensor muscle of the torso [4], accurate anatomical representation of the lumbar erector muscles is of particular interest to those modeling the torso.

FDA device/drug status: not applicable.

Nothing of value received from a commercial entity related to this research.

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In order to counteract an externally applied moment, such as in lifting an object, the torso extensor muscles (e.g., lumbar erector spinae) must exert higher forces compared with the weight of the load. This results from a mechanical disadvantage of the muscles, where the distance of torso extensor muscles from the spine is much shorter than the distance of the external load from the spine. When modeling spinal loading of the torso during sagittal plane motion, error in the estimation of the torso lumbar erector muscle group sagittal plane moment arms would result in error of the resulting predicted spinal loads.

Several biomechanical models of the torso use anatomical geometry of the lumbar erector muscle group derived from imaging studies [5–9]. Many imaging studies have reported on the moment arms of the male lumbar erector muscle group [10–20] and the female lumbar erector muscle group [11,12,14,15,21]. Some of these studies have attempted to predict muscle moment arm distances from external anthropometry [11,12,14,17,20,21]. Significant predictive equations were found between the L3 and L4 levels for women [11,14], and between the L3 and L5 intervertebral levels for men [11,14,17,20].

All prior imaging studies that quantified moment arms of the torso muscles have been performed with subjects in the supine position. However, it is known that extreme torso flexion results in a decrease of the lumbar erector muscle sagittal plane moment arms when compared with the neutral torso posture [22,23]. Macintosh et al. [22] found that sagittal plane moment arms of the individual muscle fascicles of the lumbar erector spinae and multifidus decreased at most lumbar levels in full torso flexion compared with standing upright. Tveit et al. [23], using magnetic resonance imaging (MRI), reported that the moment arms of the erector muscle group decreased as subjects voluntarily altered their lumbar spinal curvature from maximum lordosis to maximum kyphosis, while in a supine posture. Neither of these studies, however, quantified the relationship between torso flexion or spinal curvature and the moment arm at intermediate sagittal plane torso postures. Additionally, using the magnitudes of the moment arms reported in these studies may introduce error into spinal loading estimates because individual and gender differences are known to exist regarding muscle size characteristics [11,24].

Quantification of the relationship between different torso flexion angles and the sagittal plane moment arms would allow biomechanical models of the torso to more accurately represent changes in internal trunk geometry that occur during torso flexion, as well as more accurately predict the spinal loading. When accounting for the varying orientation of the lumbar erector spinae muscle fascicles, Macintosh et al. [22] estimated that for a maximal extension torque, a 2% increase in compression force and a 185% increase and direction reversal of the anterior/posterior shear force on L5–S1 resulted at full torso flexion as compared with the neutral upright posture. Van Dieën and de Looze [2] used a single equivalent extensor muscle biomechanical model and varied the initial lordosis as well as used a polynomial relationship between torso angle, moment arm of the single equivalent extensor muscle and the orientation of the lumbosacral disc. They indicated that not accounting for the decreasing moment arm and changing orientation of the single equivalent muscle with respect to L5–S1 would underestimate the compression force by 46% and overestimate the anterior/posterior shear force by more than 300%.

The above discussion clearly indicates that the validity of estimated spinal loading from biomechanical models is dependent on the accuracy of the anatomical inputs into the model (e.g., moment arms), as well as how the models account for the anatomical muscle geometry changes during motion of the torso (e.g., moment arms) [22,23]. Additionally, because individual differences (e.g., height, body mass) and gender are known to affect the torso muscle geometry [11,24], which would affect the accuracy of estimated loading if not properly accounted for, it is necessary to investigate the relationship of these variables in relation to the magnitude of the moment arms at different torso postures in the sagittal plane.

The objectives of this research are twofold. The first objective was to quantify the magnitude of the sagittal plane moment arms of the male and female lumbar erector muscle group at different torso flexion angles. The second objective was to determine if the moment arms of the erector muscle group were associated with individual, gender, or quantifiable measures of torso posture in the sagittal plane.

Materials and methods

Twelve men (mean age 23.1 years [SD, 3.1 years], mean height 177.1 cm [SD, 8.4 cm] and mean body mass 74.5 [SD, 6.7 kg]) and 12 women (mean age 23.8 years [SD, 4.4 years], mean height 162.3 cm [SD, 6.2 cm] and mean body mass 56.5 kg [SD, 6.0 kg]) recruited from the local community participated in this study. Before participation, subjects read and signed an informed consent form.

T1-weighted (TR=400, TE=25) 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 angles (neutral, 15 degrees, 30 degrees and 45 degrees), with the knees extended at each of the four torso angles.

Within the MRI, the subjects lay in a large size body coil, on top of a wooden pegboard to control the torso postures. The posterior aspect of S1 was positioned at one mark on the pegboard. To achieve and control each torso flexion angle, lines were drawn from the S1 marker in the cranial-anterior direction at angles of 0, 15, 30 and 45 degrees. The posterior surface of the torso from S1 to C7 was aligned along each line to consistently achieve each torso angle for all subjects [25], where a wooden dowel was placed along the line such that the C7 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 board. The torso-positioning method was evaluated using an electrogoniometer of the torso at the four torso postures, where repeated positioning resulted in an average absolute deviation across the four torso positions ranging from 0.82 to 0.99 degrees.

To minimize 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 [26]. If the lumbar spine was not straight on the initial coronal slice, padding was placed between the legs until subsequent coronal slice scans revealed that the lumbar coronal sag was minimized.

A sagittal scout scan was performed at each of the torso flexion angles, from which 10-mm-thick axial scans were set up. The location and orientation of the axial scans were determined visually from the sagittal scout scan on the MRI computer screen. For each torso flexion angle, the axial scan planes were located through each of the six lumbar intervertebral disc spaces (T12–L1 to L5–S1) 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 border of the intervertebral disc and the right erector muscle group (the longissimus, iliocostalis and multifidus) were outlined by a series of points using a computer mouse. The *x*- and *y*-coordinates for each point were recorded, and the *x*- and *y*-centroids of the intervertebral disc and right erector muscle group were derived using methods from previous studies [20,27].

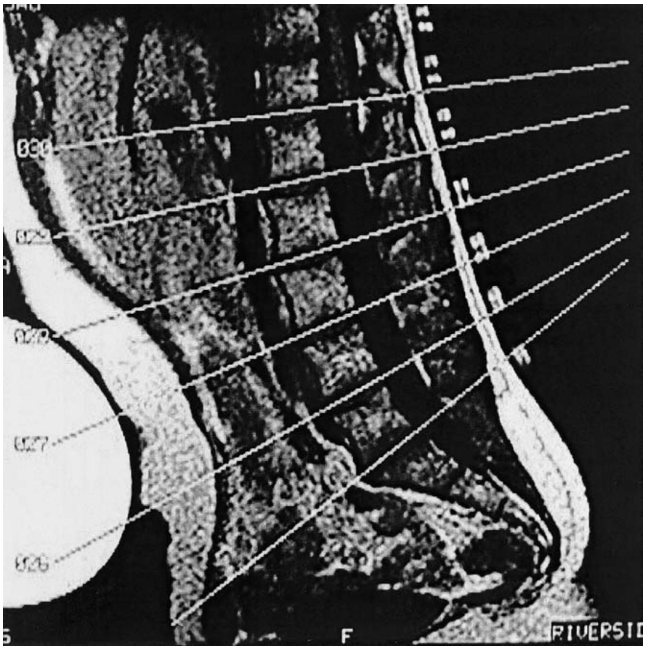

Fig. 1. Sagittal magnetic resonance imaging scan of torso in 15-degree flexion, showing the scan lines for the axial slices through and parallel to the intervertebral discs.

The sagittal plane moment arms were derived by calculating the distance between the intervertebral disc centroid and the right erector muscle group centroid, in the sagittal plane defined by a line intersecting the centroid of the intervertebral disc and the digitized location of the spinous process [11,21,28]. Only the right erector muscle group was digitized because the left side showed deformation resulting from the subjects lying on their left side on the MRI table. Using the digitizing software, the Cobb method was used to determine the L1–S1 and L1–L5 sagittal plane lumbar lordosis, as well as the segmental lordosis (i.e., T12–L1 to L5–S1) from the sagittal scout views at each of the four controlled torso flexion angles [29,30].

The effect of gender and torso posture on lumbar lordosis was investigated using a two-way analysis of variance (ANOVA) using gender and torso angle as independent variables. To investigate the collective effect of torso flexion and gender on the moment arms, a multivariate analysis of variance (MANOVA) was performed using the moment arms at each intervertebral level as dependent variables, where gender, torso angle, as well as the gender by torso angle interaction served as the independent variables. Significance of the independent variables was assessed using the Wilks' lambda, where follow-up ANOVAs for each of the intervertebral levels were performed for the significant independent variables. Significant follow-up ANOVAs were investigated by using the least significant difference (LSD) post-hoc test and a Bonferroni adjustment for the number of planned comparisons to control for a Type 1 error ($\alpha=0.05$).

Hierarchical linear regression using the forward select method was used to investigate if individual characteristics as well as torso posture variables were associated with the magnitude of the muscle group moment arm during torso flexion. 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 moment arm variability resulted by inclusion of the new variable ($p \leq .05$). Along with gender, the independent variables available for inclusion are identified and described in Table 1). Multicollinearity effects were investigated using the variance inflation factor [31].

Results

As the torso angle went from neutral to 45-degree flexion, the L1–L5 and L1–S1 lumbar lordosis decreased (Table 2). The two-way ANOVA indicated there were no significant gender differences for either the L1–L5 ($p=.6632$) or L1–S1 ($p=.9356$) lordosis measure. However, both lordosis measures varied significantly as a function of torso flexion angle ($p<.0001$ for L1–L5 and $p<.0001$ for L1–S1).

The female and male sagittal plane moment arms as a function of torso flexion angle and intervertebral level are

Table 1
Independent variables used in the development of the multiple linear regression equations for the prediction of the sagittal plane moment arms of the lumbar erector muscle mass

Variable	Units	Description
TorsoAngle	degrees	Torso flexion angle
L1–L5	degrees	L1–L5 lumbar lordosis
L1–S1	degrees	L1–S1 lumbar lordosis
SegLord	degrees	Segmental lordosis
Height	cm	Standing height
Mass	kg	Body mass
BMI	kg/m^2	Body mass index
TrCircum	cm	Trunk circumference measured at the iliac crest
TDIC	cm	Trunk depth measured at the iliac crest
TWIC	cm	Trunk width measured at the iliac crest
TDXP	cm	Trunk depth measured at the xyphoid process
TWXP	cm	Trunk width measured at the xyphoid process

shown in Table 3, with the percent change of the moment arm at each of the torso flexion angles with respect to the neutral moment arm shown in Table 4. The moment arms tended to increase from T12–L1 to L5–S1 at each of the four torso flexion angles. However, as the torso approached the 30-degree and 45-degree flexion angles, the moment arms displayed small changes between the L3–L4 and L5–S1 level. The largest change in the moment arms occurred at the L5–S1 intervertebral level for both women and men. As the torso went from neutral to 45-degree flexion, the moment arm decreased 8.9% and 9.7% for women and men, respectively.

The MANOVA indicated an overall significant gender effect and torso flexion effect ($p<.0001$), however, the gender by torso flexion interaction was not significant ($p=.9969$). Follow-up ANOVAs for the significant gender effect indicated that gender significantly affected the moment arms at each of the intervertebral levels. Planned comparisons between gender at each torso angle using the LSD method, and using a Bonferroni adjustment to control for a Type 1 error ($\alpha_{adj}=0.0125$) indicated that at every intervertebral level, men exhibited significantly larger moment arms than women at every torso angle except at the L1–L2 level at 15-degree torso flexion ($p=.0159$). Follow-up ANOVAs on the overall significant torso angle effect indicated that a significant torso angle effect was present only at the L5–S1 level ($p<.0001$). Planned comparisons between the moment arm at neutral compared with the other three torso angles at the L5–S1 level, using the LSD method with a Bonferroni adjustment ($\alpha_{adj}=0.0167$), indicated that for both genders, the moment arms at 30 and 45 degrees were significantly smaller than at the neutral posture.

The multiple linear regression models developed to assess the association of individual and spinal position variables with the moment arms at the different intervertebral levels are shown in Table 5. A measure of lordosis and subject mass was significantly associated with the moment arm at each intervertebral level as the torso went from neutral to 45 degrees. The segmental lordosis was associated with the moment arm at T12–L1, whereas an overall lordosis measure (L1–S1) was associated with the moment arms between L1–L2 and L5–S1. Generally, as the intervertebral level became more caudal, the greater the explained variability of the moment arm from torso characteristics and lordosis measures.

The moment arm distance was also associated with gender, but only at the L4–L5 and L5–S1 intervertebral levels. Thus, gender-specific regression models are reported separately in Table 5.

Discussion

As the torso flexes forward in the sagittal plane from an upright neutral posture, the lumbar vertebral bodies rotate and translate anteriorly [32–34], resulting in a flattening of the lumbar spine. As the spine flattens during torso flexion and the torso extensor muscles lengthen, moment arms at most lumbar levels have been shown to decrease [22,23]. Tveit et al. [23] found that the sagittal plane moment arms of the erector muscle mass decreased between 9 mm and 12 mm for men, and decreased between 6 mm and 10 mm for women when going from maximal lordosis to maximal kyphosis in a supine posture, depending on the intervertebral level (between L1–L2 and L4–L5). Macintosh et al. [22] studied the individual fascicles of the lumbar erector spinae, where average decreases of the moment arms of the lumbar portions of the iliocostalis and longissimus fascicles at full flexion compared with upright neutral ranged from 2 mm at L5–S1 to 13 mm at L3–L4. The decrease in the moment arms of the lumbar erector muscle group in our study fell between the results of the other studies, where the mean decrease at L5–S1 was 5.0 mm (8.9%) and 6.2 mm (9.7%)

Table 2
Mean (SD) lumbar lordosis (degrees) as a function of gender and external torso flexion angle

	Torso flexion angle							
	Neutral		15 degrees		30 degrees		45 degrees	
Gender	L1–L5 lordosis	L1–S1 lordosis	L1–L5 lordosis	L1–S1 lordosis	L1–L5 lordosis	L1–S1 lordosis	L1–L5 lordosis	L1–S1 lordosis
Female	37.8 (10.0)	44.0 (10.6)	27.2 (8.5)	31.8 (7.9)	20.9 (9.5)	23.3 (10.4)	15.8 (12.0)	19.2 (12.4)
Male	34.9 (9.4)	43.2 (12.0)	26.7 (11.3)	31.4 (11.9)	20.7 (11.6)	23.5 (13.8)	15.6 (12.1)	19.4 (13.6)

Table 3
Mean (SD) sagittal plane moment arms (mm) of the female and male right lumbar erector muscle mass as a function of torso flexion angle

	Intervertebral level					
Torso angle	T12–L1	L1–L2	L2–L3	L3–L4	L4–L5	L5–S1
Female						
Neutral	46.9 (3.7)	48.0 (3.4)	49.8 (4.1)	51.8 (3.5)	54.1 (3.1)	56.4 (3.4)
15 degrees	44.8 (2.9)	47.3 (3.1)	48.3 (3.6)	51.6 (3.6)	53.4 (3.0)	54.5 (3.2)
30 degrees	44.5 (3.2)	46.9 (2.6)	48.9 (3.3)	51.2 (3.2)	52.5 (2.5)	52.6 (2.7)
45 degrees	45.1 (3.7)	47.1 (3.5)	49.7 (4.1)	51.6 (3.8)	51.3 (3.2)	51.4 (2.7)
Male						
Neutral	51.9 (4.7)	52.6 (4.4)	54.6 (4.2)	57.4 (3.4)	59.0 (4.4)	64.0 (4.3)
15 degrees	49.6 (3.8)	51.1 (4.1)	53.6 (3.8)	56.2 (3.5)	57.8 (3.9)	61.5 (4.7)
30 degrees	48.9 (4.1)	51.1 (4.1)	53.8 (3.7)	56.8 (3.9)	57.9 (4.4)	59.6 (4.4)
45 degrees	49.7 (3.7)	52.3 (4.7)	54.0 (4.1)	56.8 (4.2)	56.9 (4.2)	57.8 (4.1)

for women and men, respectively, and 2.8 mm (5.2%) and 2.1 mm (3.6%) for women and men, respectively, at L4–L5.

The largest decrease in the lumbar erector muscle group moment arm between neutral and 45-degree torso flexion occurred at L5–S1. The location of the largest decrease may be partly explained by the action of the lumbar spine during torso flexion. The lumbar portions of the iliocostalis lumborum and longissimus thoracis arise from different locations along the transverse processes of the lumbar vertebrae (L1 to L4 for the iliocostalis lumborum and L1 to L5 for the longissimus thoracis) and attach to the pelvis on the dorsal side of the iliac crest [4]. The multifidus arises from the spinous processes of each of the lumbar vertebral bodies and attaches to lower vertebral bodies, the sacrum and the iliac crest [35]. Thus, the majority of these muscle fascicles that arise from the lumbar levels pass through and act on the L5–S1 level. The L5–S1 motion segment demonstrates the largest rotation of all lumbar motion segments during flexion, followed by the L4–L5 motion segment [36]. Thus, the largest decrease in the moment arm, which occurred at the L5–S1 intervertebral level, may be the result of the combined rotation and flattening of these lower motion segments, resulting in a decreased distance between the muscle mass and spine. These findings indicate that as the torso flexes forward in the sagittal plane, as occurs in manual material handling (MMH) tasks such as lifting or lowering, the extensor muscle group of the spine at the lower lumbar levels becomes closer to the spine. The smaller moment arm may then decrease the torso extensor muscles' ability to offset the external moment generated by the external load and torso. Thus, it appears likely that the torso extensor muscles must generate larger forces at forward flexed postures than previously predicted from biomechanical models that do not account for the changing moment arm. This may help explain why epidemiological studies have consistently found large degrees of torso flexion during MMH tasks to be associated with an increased risk of low back disorders [37–39].

Table 4
Mean percent change from neutral for the right lumbar erector muscle mass sagittal plane moment arms as a function of torso flexion angle

	Intervertebral level					
Torso angle	T12–L1	L1–L2	L2–L3	L3–L4	L4–L5	L5–S1
Female						
15 degrees	−4.5	−1.5	−3.0	−0.4	−1.3	−3.4
30 degrees	−5.1	−2.3	−1.8	−1.2	−3.0	−6.7*
45 degrees	−3.8	−1.9	−0.2	−0.4	−5.2	−8.9*
Male						
15 degrees	−4.4	−2.9	−1.8	−2.1	−2.0	−3.9
30 degrees	−5.8	−2.9	−1.5	−1.1	−1.9	−6.9*
45 degrees	−4.2	−0.6	−1.1	−1.1	−3.6	−9.7*

*Statistically significant difference in the moment arm from the neutral torso angle ($p \leq .0167$).

The multiple linear regression models derived from external anthropometric measures and spinal curvature resulted in larger adjusted R^2s than many prior investigators found when investigating sagittal plane moment arms in the neutral torso posture. Jorgensen et al. [11] found significant univariate regression models at L3 and L4 (R^2s between 0.21 and 0.23 for women, and between 0.57 and 0.81 for men) but not at L5. Kumar [12], Tracy et al. [18] and Chaffin et al. [21] did not find any models that significantly predicted the sagittal plane lumbar erector muscle mass moment arm at any lumbar level. Wood et al. [20] reported that sitting height was associated with the L5–S1 sagittal plane moment arm (R^2 of 0.45). Moga et al. [14] found regression models at L3–L4 with R^2s ranging from 0.26 for men to 0.91 for women, and Reid et al. [17] reported a regression model of the erector muscle mass muscle moment arm at L5 with an overall R^2 of 0.85. Although several investigations have found significant associations between the sagittal plane moment arms of the lumbar erector muscle group and anthropometric measures in the neutral torso posture, our research has now identified significant associations with external anthropometry as well as variables that account for changes in torso posture (segmental lordosis and lumbar lordosis).

The multiple regression models indicate that the magnitude of the moment arms along the lumbar spine during torso flexion is multifactorial in nature. Consistent with prior studies [11,14], torso and body mass characteristics were associated with the sagittal plane moment arms. However, neither segmental nor lumbar lordosis has previously been

Table 5
Multiple linear regression results for the prediction of the right lumbar erector muscle mass sagittal plane moment arms (mm) from externally measured torso angle, internal lumbar lordosis measures and anthropometric measures, as a function of intervertebral level and gender

Level	Gender	Regession equation	Standard error	Adjusted R^2	p Value
T12–L1	Both	45.33 + 0.26SegLord−1.11TDIC + 0.37Mass	3.1	0.50	.0001
L1–L2	Both	30.65 + 0.09L1/S1 + 0.25Mass	3.1	0.49	.0001
L2–L3	Both	39.61 + 0.08L1/S1−0.67TDIC + 0.34Mass	3.2	0.48	.0001
L3–L4	Both	44.74 + 0.06L1/S1−1.06TDIC + 0.42Mass	2.8	0.60	.0001
L4–L5	Male	69.85 + 0.12L1/S1−1.73TDXP + 0.28Mass	2.7	0.65	.0001
	Female	64.62 + 0.12L1/S1−1.73TDXP + 0.28Mass	2.7	0.65	.0001
L5–S1	Male	91.57 + 0.21L1/S1−0.74TrCircum + 0.34Mass	2.7	0.76	.0001
	Female	83.89 + 0.21L1/S1−0.74TrCircum + 0.34Mass	2.7	0.76	.0001

investigated as a measure associated with the moment arms. The L1–S1 lordosis was associated with the moment arms between the L1–L2 and L5–S1 levels at torso flexion angles between neutral and 45 degrees. Because lumbar lordosis is known to vary among individuals in the same torso postures (e.g., supine or upright), it would also be expected that the change in lordosis during torso flexion would be different across individuals. This may be why an internal measure of sagittal plane torso posture (i.e., lumbar lordosis, which was not controlled in this study) may be associated with moment arm changes rather than the controlled externally measured torso flexion. The implication of these findings is that accounting for individual differences in body mass and torso measures, as well as accounting for individual differences in lumbar lordosis during torso flexion, would increase the accuracy of the prediction of the sagittal plane moment arms. This in turn would increase the accuracy of the estimates of spinal loading from biomechanical models of the torso.

The findings of this study should be viewed in light of several application and methodological considerations. First, these data were derived from young healthy male and female adults, who may differ anthropometrically from those who perform manual materials handling tasks in industry. Second, although this study reported only the moment arms of the right lumbar erector muscle mass, no difference between the right and left side would be expected, because prior studies have found no difference between right and left lumbar erector muscle mass moment arms [11,12,14, 19,21,40]. Third, this research indicated that lumbar lordosis was a significant predictor of the moment arms. However, it must be remembered that this was a lateral recumbent lumbar lordosis measure. Inspection of the literature indicated that the lateral recumbent lordosis was somewhat smaller than that measured in the upright posture, where the segmental L5–S1 angle appeared to be responsible for this difference [29,30,41–49]. Thus, a relationship between upright and lateral recumbent lordosis may need to be derived. Additionally, it is known that rotation of the pelvis impacts the curvature of the lumbar spine. However, we were unable to measure the pelvic rotation from the MRI scans.

Finally, the moment arms reported in this study were derived without consideration of the muscle fiber orientation of the lumbar erector muscles. Thus, for these relationships to be used in biomechanical models to investigate spinal loading, these data may need to be combined with muscle fiber orientation as a function of torso flexion.

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