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Sagittal plane moment arms of the female lumbar region rectus abdominis in an upright neutral torso posture

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Abstract

Background. Prior imaging studies of torso muscle moment arms for use as inputs into biomechanical models have been derived from subjects lying supine. Recent research suggests moment arms of the rectus abdominis are larger when standing versus lying supine.

Methods. Axial MRI images, through and parallel to the intervertebral discs were obtained from five females in a standing upright neutral posture. Digitizing software was utilized to quantify the distance in the sagittal plane between the centroids of the intervertebral disc and the rectus abdominis muscle, and converted to the transverse plane to allow comparisons with studies with subjects in a supine posture.

Findings. The mean sagittal plane moment arms in the transverse plane were 9.7, 9.1, 8.5, 8.5 and 9.8 cm at the L_1/L_2, L_2/L_3, L_3/L_4, L_4/L_5 and L_5/S_1 intervertebral levels, respectively. Compared with a study on females of a similar age group, the moment arms from this study were larger at each level, increasing from 7.3% larger at L_1/L_2 to 43.7% larger at L_5/S_1.

Interpretation. Accurate anatomical geometrical representation in biomechanical models is necessary for valid estimates of internal loading. Sagittal plane rectus abdominis moment arms were larger from the upright neutral torso posture in this study compared to studies with subjects lying supine. This suggests the torso internal moment generating capability would be represented differently in biomechanical models that use data from studies where subjects were upright, which is more reflective of the postures biomechanical models are utilized for, than when using anatomical geometry derived from supine postures.

Keywords: Positional MRI; Biomechanical modeling; Torso; Moment arms; Rectus abdominis

1. Introduction

Biomechanical models of the torso have been increasing in complexity since they were first introduced almost four decades ago. Many biomechanical models of the torso are now three-dimensional, incorporate multiple torso muscles, and utilize electromyography as a method to estimate torso muscle forces and internal moment generation (Marras and Granata, 1997; McGill, 1992; Nussbaum and Chaffin, 1996). In order to have valid estimates of internal muscle forces and moments, it is necessary to have valid estimates of torso muscle geometry (McGill and Norman, 1987).

The anatomical geometry inputs into the multiple muscle biomechanical models of the torso have typically been derived from muscle imaging studies (Jorgensen et al., 2001; Kumar, 1988; Marras et al., 2001; McGill et al., 1993) which used methods such as magnetic

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resonance imaging (MRI) or computed tomography (CT). All of these imaging studies have been performed with subjects oriented in the supine position, thus, the anatomical geometry also reflect subjects in a supine position. However, McGill et al. (1996) have suggested that the rectus abdominis muscle geometry of individuals in a supine posture is not the same as when individuals are standing upright. Utilizing ultrasound technology, they estimated that the distance between the spine and the rectus abdominis in the sagittal plane at the L_3 level is 30% larger in the upright neutral torso posture than in the supine posture. This suggests that if biomechanical models of the torso utilize moment arm distances for the upright stance derived from imaging studies on supine subjects, where the moment arms may actually be smaller, then error in the estimates of internal muscle moment generation will result, as well as erroneous estimates of muscle force and the resulting spinal loading. The increase in the rectus abdominis moment arm by McGill et al. (1996) was only observed at the L_3 level, utilizing ultrasound technology. Thus, the relationship of the moment arms of the rectus abdominis between an upright neutral torso posture and a supine posture along multiple lumbar levels is not known.

The objective of this research, therefore, was to quantify the magnitude of the sagittal plane moment arms of the rectus abdominis along the lumbar levels from subjects in an upright neutral torso posture, and compare with findings from previous studies that quantified sagittal plane moment arms of the rectus abdominis from subjects in a supine posture.

2. Methods

The data from five female volunteers (mean age 30.2 yr [SD 4.4 yr]; stature range 162.6–177.8 cm; body mass range 49.9–68.0 kg) from existing upright MRI scans were utilized for this study. The scans were from a larger study aimed at investigating loads held in the hands and the affects on intervertebral disc appearance in an upright neutral standing posture. Subjects were asked to stand straight upright and not shift the body weight from one foot to the other, and were told to relax and breathe normally. To ensure the subjects maintained an upright neutral posture, a small retaining bar was placed across the abdomen to keep from bending forward. T1 weighted MR images were collected using a 0.6 T FONAR positional open MRI. Sagittal plane scans (TR = 3262 and TE = 140) were performed with subjects standing in an upright neutral torso posture with no loads in the hands. Axial scans (4.5 mm thick) were next performed (TR = 870, TE = 140), with the scan slices oriented parallel with and passing through the approximate center of the lumbar intervertebral discs (L_1/L_2 to L_5/S_1).

Digital MRI images were converted to a 512×512 image format and analyzed using ImageJ software (resolution of 0.59 mm per pixel), developed by the US National Institutes of Health. The border of the intervertebral disc and the right and left rectus abdominis at each of the lumbar intervertebral levels were outlined by a mouse (Fig. 1), and the x- and y-coordinates of the centroid for each structure were recorded from the ImageJ software.

The raw sagittal plane moment-arms were derived by calculating the absolute difference between the intervertebral disc centroid and the muscle centroid. However, the resulting raw moment arm represents the distance between the centroid of the intervertebral disc and the rectus abdominis centroid along the scan planes, which were parallel to the orientation of the intervertebral disc. Previous studies that quantified the sagittal plane moment arm of the female rectus abdominis were performed in the supine posture with the axial scan slices perpendicular to the scan table. Thus, to allow comparison of the resulting moment arms from this study to the results from previous studies, the raw moment arms in the scan plane were corrected such that the moment arm was oriented along the transverse plane (see Fig. 2), similar to previous studies on supine subjects (Jorgensen et al., 2001; Nemeth and Ohlsen, 1986).

Descriptive statistics (mean and standard deviation) were derived for both right and left rectus abdominis sagittal plane moment arms, at each intervertebral level, with respect to the original scan plane and in the transverse plane. For the transverse plane moment arms, a two-factor Analysis of Variance (ANOVA) was performed to determine if there were differences between the right and left side, as well as differences between

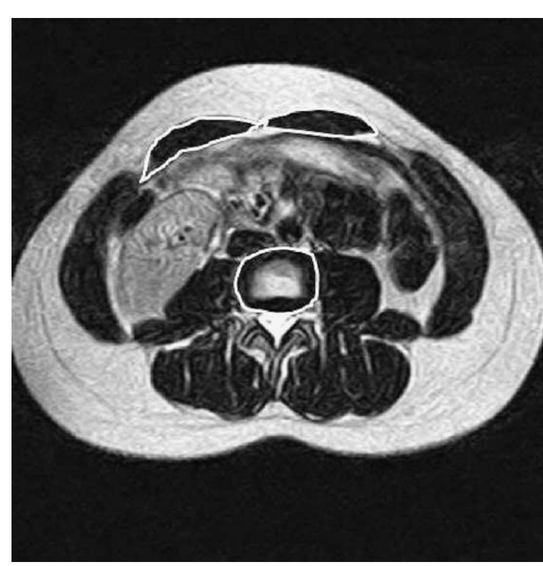

Fig. 1. Cross-sectional scan at L_3/L_4 showing outlined borders of the intervertebral disc and the right and left rectus abdominis.

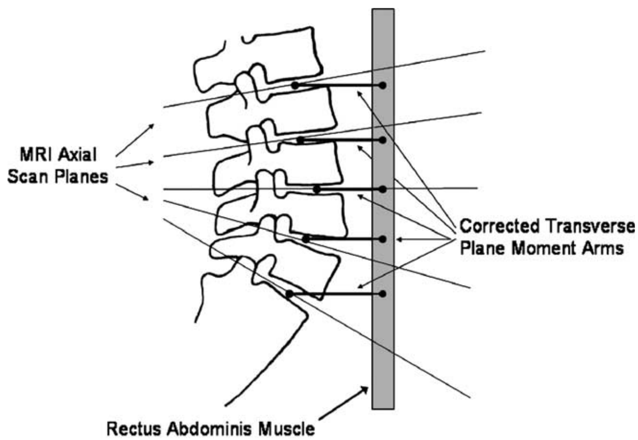

Fig. 2. Graphical representation of correction of raw moment arms from the MRI scan planes to moment arms in the transverse plane.

intervertebral levels. The independent variables consisted of side (right and left) and the intervertebral level. The dependent variable consisted of the sagittal plane moment arm. Significant main effects were investigated via Tukey pair-wise comparisons, utilizing a family-wise $\alpha = 0.05$, and significant interactions were investigated via the least significant difference (LSD) post hoc test, utilizing a Bonferroni adjustment with an overall significance level of $\alpha = 0.05$ to reduce the probability of a Type I error from multiple comparisons. All statistical analysis was performed by SAS software.

3. Results

Descriptive statistics (mean, standard deviation) for the sagittal plane moment arms parallel with the transverse plane for the right and left rectus abdominis are shown in Table 1. The moment arms were larger at the lower and upper regions of the lumbar spine, and shortest in the middle region of the lumbar spine. The mean scan plane rectus abdominis moment arms are shown in Table 2, along with sagittal plane moment arms from previous studies for comparison purposes.

The ANOVA indicated that the right and left side rectus abdominis sagittal plane moment arms were not significantly different from each other ($P = 0.4721$), and there was not a significant intervertebral level by

Table 1
Mean (SD) sagittal plane female lumbar rectus abdominis moment arms (cm) parallel to the transverse plane

Side	Intervertebral level				
	L_1/L_2^A	$L_2/L_3^{A,B}$	L_3/L_4^B	L_4/L_5^B	L_5/S_1^A
Right	9.8 (0.9)	9.1 (0.7)	8.6 (0.5)	8.6 (0.2)	9.9 (0.4)
Left	9.6 (0.7)	9.0 (0.6)	8.5 (0.2)	8.4 (0.6)	9.8 (0.9)

Intervertebral levels with the same letters (A or B) indicate no significant difference in moment arm distance between intervertebral levels.

Table 2
Mean (SD) sagittal plane female lumbar rectus abdominis moment arms (cm) from this study and others in the literature

Study	Intervertebral level										
	L_1	L_1/L_2	L_2	L_2/L_3	L_3	L_3/L_4	L_4	L_4/L_5	L_5	L_5/S_1	S_1
This study: transverse plane		9.8 (0.9)		9.1 (0.7)		8.6 (0.5)		8.7 (0.2)		9.9 (0.4)	
This study: scan plane		9.7 (1.1)		9.1 (0.8)		8.7 (0.5)		8.8 (0.4)		11.6 (0.5)	
Jorgensen et al. (2001)	9.6 (1.0)		8.5 (0.9)		7.0 (0.9)		6.1 (0.9)		6.5 (1.0)		7.5 (1.3)
Chaffin et al. (1990)				7.0 (1.5)		7.0 (1.9)		6.9 (2.0)			
Kumar (1988)					10.4 (2.8)				10.6 (2.8)		
Nemeth and Ohlsen (1986)										8.0 (0.6)	
Left side											
This study: transverse plane		9.6 (0.7)		9.0 (0.6)		8.5 (0.2)		8.4 (0.6)		9.8 (0.9)	
This study: scan plane		9.4 (0.7)		9.2 (0.8)		8.6 (0.3)		8.7 (0.9)		11.4 (0.8)	
Jorgensen et al. (2001)	9.7 (1.1)		8.5 (1.1)		6.9 (1.1)		6.0 (0.9)		6.1 (1.0)		7.3 (1.2)
Chaffin et al. (1990)				7.2 (1.6)		7.2 (1.9)		7.0 (2.0)			
Kumar (1988)					10.4 (2.8)				10.6 (2.8)		
Nemeth and Ohlsen (1986)										8.0 (0.6)	

side interaction effect ($P = 0.9986$). However, the moment arms did vary as a function of the intervertebral level ($P < 0.0001$). Follow-up Tukey post-hoc tests indicated that there was no statistical difference between the moment arms at levels L_1/L_2, L_2/L_3 and L_5/S_1, and there was no statistical difference between levels L_3/L_4, L_4/L_5 and L_5/S_1 (Table 1).

4. Discussion

The rectus abdominis, a torso flexor muscle, has been shown to be almost vertically oriented with respect to the transverse plane (85.3°), running in an inferior/posterior direction (Dumas et al., 1991). As indicated from the ANOVA, the upper and lower regions of the lumbar spine were the locations of the largest rectus abdominis sagittal plane moment arms, whereas the shortest moment arms were located at the middle region of the lumbar spine. Thus, since the rectus abdominis runs almost vertical with respect to the transverse plane, the moment arm distances at the various lumbar levels appear to reflect the contour of the lumbar spine.

The objective of this study was to quantify the rectus abdominis sagittal plane moment arms from subjects in an upright neutral torso posture, and to determine if the moment arms are larger in an upright stance versus lying supine. For comparison purposes, very few studies exist that have assessed the female rectus abdominis moment arms (Chaffin et al., 1990; Jorgensen et al., 2001; Kumar, 1988). Chaffin et al. (1990) performed a CT imaging study on a female population with a mean age of 49.6 yr, and Kumar (1988) studied a female population with a mean age of 57 yr, however, the orientation of the scan planes was not reported. Our previous study on female moment arms may be the most comparable dataset, where the mean age of subjects was 25.0 yr and the MRI scans were in the transverse plane (Jorgensen et al., 2001). As shown in Table 2, there was a similar trend of larger moment arms at the upper and lower lumbar regions, with smaller moment arms in the middle lumbar region. Additionally, the moment arms from the current study and our previous study resulted in similar moment arms at the upper lumbar level. However, the moment arms in the current study from upright standing subjects become increasingly larger than the moment arms from supine subjects in our previous study in the inferior direction of the lumbar spine (Table 2). Our previous study used scan planes through the vertebral bodies, however, the current study used scan planes through the intervertebral disc. Thus, to allow comparison between the moment arms, the average moment arm between adjacent lumbar levels in our previous study (e.g., L_1 and L_2) was utilized and compared to the moment arms in the current study at a comparable level (e.g., L_1/L_2). Additionally, since no significant differences between moment arms as a function of side were found in the current study or in our previous study, the mean of the right and left side moment arms were used for comparison purposes. The comparison indicated that the moment arms of the current study (upright neutral torso posture) were larger at every level, with percent increases of 7.3%, 17.3%, 31.4%, 37.8% and 43.7%, at the L_1/L_2, L_2/L_3, L_3/L_4, L_4/L_5 and L_5/S_1 levels, respectively, for an average of a 27.5% increase along the whole lumbar region of the torso.

The differences in the moment arms between supine and upright postures may be reflective of a larger lumbar curvature in an upright posture, especially at the lower lumbar levels, which may result in displacement of the intervertebral disc in the posterior direction. The difference in the moment arms at the lower lumbar levels may also be a result of the effects of gravity acting upon the internal visceral structures when standing versus lying supine, which may displace the rectus abdominis muscle in the anterior direction.

Although the increases in the moment arms when comparing the two datasets appear to be quite large, there are consistencies with the findings from previous research. First, the moment arms at the upper lumbar level between the current study and our previous study (Jorgensen et al., 2001) are very similar, with a mean difference of only 0.6 cm at the L_1/L_2 intervertebral level. Second, the percent increase is similar to that found by McGill et al. (1996). McGill et al. (1996) utilized ultrasound technology and an anthropometer to estimate the percent change between the distance of the rectus abdominis and the spine at the L_3 level. Their finding of a 30% increase in this distance at the L_3 level compares favorably to our finding that the moment arm in the transverse plane from an upright neutral torso posture is 31.4% larger than that found in the supine posture at the L_3/L_4 level (Jorgensen et al., 2001).

Biomechanical models of the torso are often utilized to estimate the internal loading characteristics on soft tissues while subjects perform activities such as lifting, which are performed in an upright stance, not supine. In part, the moment arms utilized in the biomechanical model contribute to the prediction of the internal moment, as well as the predicted muscle forces. However, as already indicated, the anatomical geometric representation of the internal muscular structures, such as the moment arms, are derived from imaging studies with subjects in the supine position. McGill et al. (1996) found that the increase in the moment arm from supine to standing was independent of subject height and body mass, and thus suggested that the moment arms of the rectus abdominis of current biomechanical models be adjusted by a factor of 1.3. The findings of this study suggest that at least for the rectus abdominis of relatively young females, consideration should be given for adjustments to the moment arms at various lumbar levels in the upright neutral posture for use in the biomechanical models, with potentially larger adjustments at the lower lumbar levels than suggested by McGill et al. (1996).

The findings of this study should be viewed in light of several application and methodological considerations. First, these data were derived from young female adults, who may differ anthropometrically from those who perform manual materials handling tasks in industry. More research is necessary to determine if the findings from this study would apply to other populations such as males, or other individuals of various heights and body mass characteristics. Second, the results of this study are based on a small sample size, however, the standard deviations of the moment arms were small compared to the mean moment arm distances, suggesting the moment arms distances in this small sample size are very consistent. Finally, the moment arms of the female rectus abdominis muscle reported in this study reflect an upright neutral torso posture. It is unknown what effect torso postures away from upright neutral (e.g., torso flexion) would have on the rectus abdominis moment arms.

5. Conclusions

The sagittal plane moment arms of the rectus abdominis were observed to be larger when subjects were in an upright neutral torso posture as compared to those found when subjects were lying supine, by as much as 43.7% at the lower lumbar level. These findings suggest that biomechanical models of the torso utilizing moment arms from imaging studies on supine subjects may under represent the rectus abdominis moment arms, which would result in prediction error of the true moment generating capability of the rectus abdominis muscle.

References

Chaffin, D.B., Redfern, M.S., Erig, M., Goldstein, S.A., 1990. Lumbar muscle size and locations from CT scans of 96 women of age 40 to 63 years. Clin. Biomech. 5, 9–16.

Dumas, G.A., Poulin, M.J., Roy, B., Gagnon, M., Jovanovic, M., 1991. Orientation and moment arms of some trunk muscles. Spine 16, 293–303.

Jorgensen, M.J., Marras, W.S., Granata, K.P., Wiand, J.W., 2001. MRI-derived moment-arms of the female and male spine loading muscles. Clin. Biomech. 16, 182–193.

Kumar, S., 1988. Moment arms of spinal musculature determined from CT scans. Clin. Biomech. 3, 137–144.

Marras, W.S., Granata, K.P., 1997. The development of an EMG-assisted model to assess spine loading during whole-boy free-dynamic lifting. J. Electromyogr. Kinesiol. 7, 259–268.

Marras, W.S., Jorgensen, M.J., Granata, K.P., Wiand, B., 2001. Female and male trunk geometry: size and prediction of the spine loading trunk muscles derived from MRI. Clin. Biomech. 16, 38–46.

McGill, S.M., Norman, R.W., 1987. Effects of an anatomically detailed erector spinae model on L4/L5 disc compression and shear. J. Biomech. 20, 591–600.

McGill, S.M., 1992. A myoelectrically based dynamic three-dimensional model to predict loads on lumbar spine tissues during lateral bending. J. Biomech. 25, 395–414.

McGill, S.M., Santaguida, L., Stevens, J., 1993. Measurement of the trunk musculature from T5 to L5 using MRI scans of 15 young males corrected for muscle fibre orientation. Clin. Biomech. 8, 171–178.

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

Nemeth, G., Ohlsen, H., 1986. Moment arm lengths of trunk muscles to the lumbosacral joint obtained in vivo with computed tomography. Spine 11, 158–160.

Nussbaum, M.A., Chaffin, D.B., 1996. Development and evaluation of a scalable and deformable geometric model of the human torso. Clin. Biomech. 11, 25–34.