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MRI-derived moment-arms of the female and male spine loading muscles

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Abstract

Objective. Develop a comprehensive gender-specific database of trunk muscle moment-arms across multiple levels of the lower thoracic and lumbar spine, determine if gender differences exist across the different vertebral levels, and develop prediction equations for the moment-arms as a function of external anthropometric measures.

Design. This study quantified trunk muscle moment-arms relative to the spine from T_8 to S_1 of male and female spine loading muscles.

Background. Knowledge of trunk muscle geometry is important for biomechanical modeling of the low back and for understanding of spinal loading. However, there currently is a lack of comprehensive data regarding the moment-arms of the female spine loading muscles. Additionally, little is known regarding gender differences in moment-arms for the same muscles.

Methods. Magnetic resonance imaging scans through the vertebral bodies from T_8 through S_1 were performed on 20 females and 10 males. Moment-arms in the coronal and sagittal plane between the muscle centroid and vertebral body centroid were recorded at each vertebral level. Linear regression techniques taking into account anthropometric measures were utilized to develop prediction equations for the moment-arms for each muscle.

Results. Anthropometric measures were better predictors of coronal plane moment-arms than sagittal plane moment-arms for both genders. Measures consisting of height and weight were consistent predictors of female moment-arms. Measures about the xyphoid process and combinations of height and weight were consistent predictors of coronal plane moment-arms for males at several lower lumbar levels. Males exhibited larger moment-arms than for females, for most muscles at most levels.

Conclusions. Trunk muscle moment-arms of females and males are different, and should be considered in the development of biomechanical models of the torso. Similar to other studies, external anthropometric measures were better predictors of coronal plane moment-arms than sagittal plane moment-arms.

Relevance

Gender specific moment-arms of spine loading muscles are needed to estimate the moments produced by the trunk muscles during trunk motion.

Keywords: Biomechanical model; Low back pain; Muscle moment arms; Gender differences

1. Introduction

Biomechanical models of the human trunk have been developed to predict the magnitude and pattern of spine loading during task performance. These models are necessary as direct quantification of muscle forces and spinal loading are currently infeasible. However, accurate moment-arm data across multiple levels of the spine are needed in order to generate accurate estimates of spinal loading from these biomechanical models.

Moment-arm data in most biomechanical models are based on male data. Our previous study has shown muscle cross-sectional area to vary significantly between females and males [1]. Differences in trunk muscle cross-sectional areas between genders, especially for those muscles bounded by bony structures on one side (e.g., the oblique muscles bounded by the ribs, or the erector spinae bounded by the spine) indicates that the moment-

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arms may differ. Thus, the use of current biomechanical models to estimate spinal loading of females may result in inaccurate estimates of spinal loading, as the differences between male and female moment-arms have not been described.

Few studies have measured trunk muscle moment-arm lengths for multiple spine loading muscles of females [2–5]. These studies were performed on middle-age to elderly female populations which may not be representative of young healthy females involved in industrial material handling activities.

Many studies have been performed which describe moment-arm data for males for different muscles and different vertebral levels. These data have been derived from cadaver dissections [6,7], via CT technology [3–5,8,9], and with the use of magnetic resonance imaging (MRI) [10–16]. Of these studies, few have described moment-arms across more than a few vertebral levels, few have attempted to develop prediction equations of the moment-arms to account for individual differences [4,12,14], and none have compared gender differences.

1.1. Objectives

The objectives of this study were threefold: First, develop a comprehensive database of trunk muscle moment-arm distances across multiple levels of the spine for multiple trunk muscles, for both females and males; second, identify if gender differences exist for the moment-arm distances across multiple vertebral levels; and third, develop gender specific prediction equations for moment-arm distances for multiple levels along the spine.

2. Methods

2.1. Subjects

Twenty female and 10 male subjects were recruited from the local community. None of the subjects reported a history of activity limiting chronic back or leg injuries, nor were any experiencing any low back pain at the time of the MRI scan. Anthropometric measurements are shown in Table 1.

2.2. Data extraction

A Philips 1.5 T GyroScan MRI was set to a spin echo sequence of $TR = 240$ and $TE = 12$, generating T1-weighted slices 10 mm in thickness. Subjects were positioned in a supine posture with knees extended and hands lying across their abdomen. A single set of 11 torso musculature scans was performed, which were perpendicular to the table at transverse levels through approximate centers of the vertebral bodies from T_8 to S_1.

The scans were transferred onto a Philips GyroView, which allowed an object of interest to be inscribed using a computer mouse. From the inscribed muscles and vertebral body, the three-dimensional location of the area centroid relative to the scan origin was determined. The quantified muscles included the right and left pairs of the erector spinae group, latissimus dorsi, internal obliques, external obliques, rectus abdominis, psoas major, and the quadratus lumborum.

The moment-arms at each vertebral level were determined by calculating the absolute difference between the coordinates of the muscle centroid and the vertebral body centroid, in both the sagittal plane and the coronal plane (Figs. 1 and 2), and were adjusted for the angle between the spinous process and the vertebral body centroid. The average of three observations was used as the data point for each moment-arm. Sign designations were given to the moment-arms in the sagittal plane,

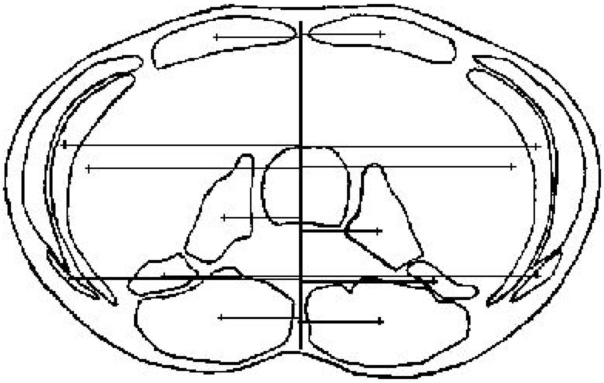

Fig. 1. Coronal plane moment-arms at the L_3 level.

Table 1
Mean (SD) anthropometric and demographic data for the male and female subjects

Gender	Age (yr)	Height (cm)*	Weight (kg)*	Trunk depth at iliac crest (cm)*	Trunk width at iliac crest (cm)*	Trunk depth at xyphoid process (cm)*	Trunk width at xyphoid process (cm)*	Body mass index (kg/m^2)*
Female ($N = 20$)	25.0 (7.2)	165.5 (5.9)	57.9 (6.4)	19.8 (2.1)	28.0 (2.4)	18.4 (1.8)	27.0 (1.9)	21.2 (2.5)
Male ($N = 10$)	26.4 (5.5)	175.9 (9.1)	79.8 (13.3)	22.3 (2.2)	30.3 (2.2)	22.9 (2.2)	32.4 (2.0)	25.7 (2.3)

* Indicates males significantly different than females ($P \leqslant 0.05$).

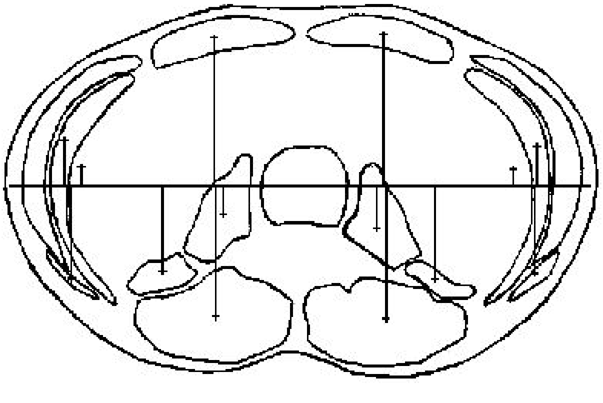

Fig. 2. Sagittal plane moment-arms at the L_3 level.

Table 2
Linear regression independent variables and descriptions for the prediction of the trunk muscle moment-arms

Independent variable	Description
TDXP (cm)	Trunk depth measured at the level of the xyphoid process (cm)
TWXP (cm)	Trunk width measured at the level of the xyphoid process (cm)
TDIC (cm)	Trunk depth measured at the level of the iliac crest (cm)
TWIC (cm)	Trunk width measured at the level of the iliac crest (cm)
TDTR (cm)	Trunk depth measured at the level of the trochanter (cm)
TWTR (cm)	Trunk width measured at the level of the trochanter (cm)
TDICW (cm/kg)	Trunk depth at iliac crest (cm) divided by subject weight (kg)
TWICW (cm/kg)	Trunk width at iliac crest (cm) divided by subject weight (kg)
TDICH (cm/m)	Trunk depth at iliac crest (cm) divided by subject height (m)
TWICH (cm/m)	Trunk width at iliac crest (cm) divided by subject height (m)
TDXPW (cm/kg)	Trunk depth at xyphoid process (cm) divided by subject weight (kg)
TWXPW (cm/kg)	Trunk width at xyphoid process (cm) divided by subject weight (kg)
TDXPH (cm/m)	Trunk depth at xyphoid process (cm) divided by subject height (m)
TWXPH (cm/m)	Trunk width at xyphoid process (cm) divided by subject height (m)
TCIRW (cm/kg)	Trunk circumference about iliac crest (cm) divided by subject weight (kg)
TCIRH (cm/m)	Trunk circumference about iliac crest (cm) divided by subject height (m)
BMI (kg/m^2)	Body mass index: subject weight (kg) divided by square of subject height (m^2)
HTWT (m kg)	Height (m) multiplied by weight (kg)
Weight (kg)	Subject weight (kg)
HTDWT (cm/kg)	Subject height (cm) divided by subject weight (kg)
WTDHT (kg/cm)	Subject weight (kg) divided by subject height (cm)

such that positive and negative values represented anterior and posterior positions, respectively, relative to the vertebral body centroid.

2.3. Statistical analysis

Descriptive statistics were generated for the moment-arms for each muscle, in the coronal and sagittal planes. Differences between male and female moment-arms at each vertebral level were determined by using *t*-tests with independent observations, with either equal or unequal variances where appropriate.

Linear regression was used to predict the moment-arms for each gender at several vertebral levels based upon external anthropometric measures. The external anthropometric measures consisted of variables used by other researchers, as well as other combinations of these variables (Table 2) [2,4,10,17]. Three different vertebral levels were investigated (L_3, L_4 and L_5) since different biomechanical models have predicted spinal loading among these various vertebral levels [18–20].

All statistical analyses were performed by the use of SAS statistical software, with significance indicated when $P \leqslant 0.05$.

3. Results

The moment-arms in the coronal plane at each of the vertebral levels for females and males are shown in Table 3. Generally, all but one muscle (left rectus abdominis) possessed significantly different moment-arms between males and females. The moment-arms for males were all statistically larger than the females for the latissimus dorsi, erector spinae (except for the right erector spinae from L_4 to S_1), the right rectus abdominis (except at L_5), and the right sides of the external obliques, psoas major and quadratus lumborum. The left sides of these muscles had at least one level that was not different between the males and females. For moment-arms in the sagittal plane (Table 4), five of seven muscles exhibited larger male than female moment arms. The erector spinae exhibited significantly larger moment-arms for males than females except for L_1–L_3 and L_5 on the right side. Males also had larger moment-arms than females for the rectus abdominis at all levels except S_1. Finally, there were sporadic differences between males and females for both internal and external obliques, and the psoas major.

Several differences existed when comparing the right and left side moment-arms on a vertebral level by level basis. In the coronal plane, post-hoc tests found that females exhibited larger right side than left side moment-arms for the external obliques at L_4; Males had larger right side than left side moment-arms for the latissimus dorsi at T_9, and for the psoas major from L_4 to S_1. All

Table 3
Mean (SD) *coronal plane* moment-arms (cm), for each muscle and gender[a]

Muscle	Gender	T_8	T_9	T_{10}	T_{11}	T_{12}	L_1	L_2	L_3	L_4	L_5	S_1
R. Lat. Dorsi	F	*13.2 (1.0)*	*12.4 (0.9)*	*11.4 (0.9)*	*10.9 (0.9)*	*10.4 (0.9)*	*9.9 (0.9)*	*9.3 (1.0)*	*9.0 (1.1)*			
	M	*15.3 (1.0)*	*14.5 (0.9)*	*13.5 (1.0)*	*12.8 (0.9)*	*12.2 (0.8)*	*11.6 (0.6)*	*10.9 (0.7)*	*10.3 (0.8)*			
L. Lat. Dorsi	F	*13.1 (0.9)*	*12.2 (0.9)*	*11.4 (1.0)*	*10.8 (1.0)*	*10.4 (0.9)*	*10.1 (0.9)*	*9.4 (1.1)*	*9.2 (1.1)*			
	M	*15.0 (0.7)*	*14.0 (0.8)*	*13.2 (0.9)*	*12.6 (0.9)*	*12.1 (0.9)*	*11.6 (0.9)*	*11.0 (0.7)*	*10.5 (0.8)*			
R. Er. Spinae	F	*2.6 (0.3)*	*2.8 (0.3)*	*2.9 (0.3)*	*3.1 (0.3)*	*3.2 (0.3)*	*3.4 (0.3)*	*3.5 (0.3)*	*3.4 (0.3)*	3.4 (0.3)	2.6 (0.6)	1.9 (0.3)
	M	*3.1(0.2)*	*3.2 (0.3)*	*3.4 (0.3)*	*3.6 (0.3)*	*3.6 (0.3)*	*4.0 (0.4)*	*4.1 (0.3)*	*3.8 (0.3)*	3.6 (0.3)	3.0 (0.7)	1.9 (0.3)
L. Er. Spinae	F	*2.7 (0.4)*	*2.8 (0.3)*	*3.1 (0.2)*	*3.2 (0.3)*	*3.4 (0.4)*	*3.5 (0.3)*	*3.5 (0.3)*	*3.5 (0.3)*	*3.5 (0.3)*	*2.7 (0.5)*	*1.9 (0.2)*
	M	*3.3 (0.4)*	*3.4 (0.4)*	*3.6 (0.3)*	*3.8 (0.3)*	*3.8 (0.3)*	*4.2 (0.3)*	*4.3 (0.4)*	*4.0 (0.2)*	*3.8 (0.3)*	*3.2 (0.5)*	*2.2 (0.2)*
R. Rect. Abd.	F					*2.9 (0.8)*	*3.4 (0.9)*	*3.6 (0.8)*	*3.9 (0.8)*	*4.0 (0.8)*	3.8 (0.9)	*3.3 (0.7)*
	M					*3.9 (0.6)*	*4.6 (1.1)*	*4.9 (1.1)*	*4.7 (0.7)*	*4.6 (0.5)*	4.1 (0.5)	*3.8 (0.5)*
L. Rect. Abd.	F					3.5 (0.5)	3.7 (0.7)	3.4 (0.8)	3.3 (0.9)	3.5 (0.8)	3.2 (0.8)	3.3 (0.6)
	M					3.5 (0.7)	4.1 (0.8)	3.9 (0.8)	4.0 (0.7)	3.6 (0.8)	3.3 (0.8)	2.9 (0.5)
R. Ext. Oblique	F					*10.8 (0.8)*	*10.9 (1.0)*	*10.9 (0.8)*	*10.8 (0.7)*	*11.2 (0.8)*	*11.6 (0.3)*	
	M					*12.9 (1.0)*	*13.0 (1.2)*	*13.2 (1.0)*	*12.8 (0.7)*	*12.8 (0.7)*	*12.6 (0.6)*	
L. Ext. Oblique	F					*11.2 (1.0)*	*11.0 (0.9)*	*10.8 (1.0)*	*10.6 (0.9)*	*10.8 (0.9)*	11.3 (1.1)	
	M					*12.4 (0.9)*	*12.6 (0.9)*	*12.4 (1.1)*	*12.4 (1.0)*	*12.2 (0.9)*	12.5 (1.1)	
R. Int. Oblique	F							9.9 (1.4)	*9.7 (1.1)*	*10.1 (0.8)*	*10.4 (0.3)*	
	M							11.4 (1.6)	*11.5 (0.8)*	*11.4 (0.6)*	*10.9 (0.3)*	
L. Int. Oblique	F							10.2 (1.5)	*9.4 (1.4)*	*9.8 (0.8)*	10.3 (1.0)	
	M							10.7 (1.3)	*11.1 (1.4)*	*10.7 (0.8)*	10.6 (0.9)	
R. Psoas Major	F						2.3 (0.2)	*2.7 (0.2)*	*3.3 (0.2)*	*4.0 (0.3)*	*4.7 (0.4)*	*5.0 (0.4)*
	M						2.6 (–)	*3.3 (0.3)*	*3.9 (0.3)*	*4.7 (0.3)*	*5.3 (0.3)*	*5.6 (0.4)*
L. Psoas Major	F						*2.3 (0.1)*	*2.7 (0.1)*	*3.2 (0.2)*	*3.8 (0.3)*	*4.5 (0.3)*	5.1 (0.3)
	M						*2.8 (0.2)*	*3.3 (0.3)*	*3.9 (0.3)*	*4.4 (0.4)*	*5.0 (0.5)*	5.4 (0.5)
R. Quad. Lumb.	F						3.8 (0.6)	*4.1 (0.4)*	*5.5 (0.7)*	*6.8 (0.5)*		
	M						3.8 (–)	*5.0 (0.6)*	*6.4 (0.6)*	*7.5 (0.5)*		
L. Quad. Lumb.	F						*3.7 (0.3)*	4.2 (0.3)	*5.7 (0.7)*	*6.8 (0.7)*		
	M						*4.4 (0.4)*	4.7 (1.0)	*6.5 (0.7)*	*7.3 (0.6)*		

[a] Italicized cells represent statistically significantly larger male than female moment-arms ($P \leqslant 0.05$).

significant differences were on the order of 5 mm or less, hence, the differences were small. Post-hoc tests for significant differences between right and left side moment-arms in the sagittal plane revealed many sporadic differences, most less than 5 mm. However, males did exhibit right side moment-arms for the latissimus dorsi between 1.1 and 1.3 cm larger than the left side between T_8 and T_{11}, whereas females had larger right side than left side moment-arms at T_8 and T_9 by 0.8 and 0.9 cm, respectively, for the same muscle. Males and females also exhibited larger differences in moment-arms as a function of side for the external oblique. The right external oblique was 0.9 and 1.0 cm larger than the left side for females at L_3 and L_4, respectively, whereas the male left external oblique was 0.7 cm larger than the right external oblique moment arm at L_1.

Table 4
Mean (SD) *sagittal plane* moment-arms (cm), for each muscle and gender[a]

Muscle	Gender	T_8	T_9	T_{10}	T_{11}	T_{12}	L_1	L_2	L_3	L_4	L_5	S_1
R. Lat. Dorsi	F	−1.6 (10.2)	−1.9 (1.1)	−2.3 (0.9)	−2.6 (0.8)	−2.9 (0.8)	−3.2 (1.0)	−3.4 (1.1)	*−3.1 (1.2)*			
	M	−1.8 (0.9)	−2.2 (1.0)	−2.4 (0.9)	−2.7 (0.8)	−2.9 (0.7)	−3.8 (0.9)	−4.1 (0.7)	*−4.2 (0.8)*			
L. Lat. Dorsi	F	−0.7 (1.0)	−1.1 (0.9)	−1.6 (0.9)	−2.0 (0.8)	−2.6 (0.8)	−3.1 (1.0)	−3.9 (1.1)	−4.0 (1.2)			
	M	−0.7 (1.1)	−0.9 (1.1)	−1.3 (1.1)	−1.6 (1.0)	−2.2 (1.0)	−3.0 (1.2)	−4.0 (1.1)	−3.9 (1.1)			
R. Er. Spinae	F	*−4.4 (0.3)*	*−4.5 (0.4)*	*−4.4 (0.4)*	*−4.4 (0.4)*	*−4.4 (0.4)*	−4.7 (0.5)	−4.8 (0.4)	−5.0 (0.5)	*−4.9 (0.4)*	−5.4 (0.5)	*−5.4 (0.5)*
	M	*−5.2 (0.4)*	*−5.3 (0.4)*	*−5.2 (0.4)*	*−5.1 (0.4)*	*−5.0 (0.4)*	−5.2 (0.5)	−5.4 (0.7)	−5.7 (0.7)	*−5.6 (0.6)*	−6.1 (0.7)	*−6.2 (0.7)*
L. Er. Spinae	F	*−4.2 (0.3)*	*−4.3 (0.3)*	*−4.2 (0.3)*	*−4.2 (0.4)*	*−4.3 (0.4)*	*−4.7 (0.5)*	*−5.1 (0.6)*	*−5.3 (0.6)*	*−5.3 (0.5)*	*−5.7 (0.6)*	*−5.6 (0.5)*
	M	*−4.9 (0.5)*	*−4.9 (0.6)*	*−4.8 (0.5)*	*−4.7 (0.5)*	*−4.8 (0.5)*	*−5.0 (0.6)*	*−5.4 (0.6)*	*−5.6 (0.6)*	*−5.7 (0.5)*	*−6.1 (0.7)*	*−6.3 (0.8)*
R. Rect. Abd.	F					*10.4 (0.9)*	*9.6 (1.0)*	*8.5 (0.9)*	*7.0 (0.9)*	*6.1 (0.9)*	*6.5 (1.0)*	7.5 (1.3)
	M					*13.5 (1.7)*	*12.4 (1.2)*	*10.7 (1.2)*	*8.9 (1.3)*	*7.7 (1.5)*	*7.6 (1.4)*	8.4 (1.2)
L. Rect. Abd.	F					*10.5 (1.0)*	*9.7 (1.1)*	*8.5 (1.1)*	*6.9 (1.1)*	*6.0 (0.9)*	*6.1 (1.0)*	7.3 (1.2)
	M					*13.7 (1.7)*	*12.7 (1.1)*	*10.8 (1.3)*	*9.2 (1.3)*	*7.8 (1.4)*	*7.6 (1.5)*	8.2 (1.2)
R. Ext. Oblique	F					*6.8 (0.7)*	*5.6 (1.2)*	4.0 (1.1)	2.4 (1.2)	2.2 (1.2)	3.2 (2.0)	
	M					*8.5 (1.2)*	*6.7 (1.0)*	4.6 (0.6)	2.2 (1.0)	2.1 (0.8)	3.9 (1.2)	
L. Ext. Oblique	F					*6.6 (1.2)*	*5.7 (1.3)*	*3.7 (1.2)*	1.5 (1.3)	1.2 (1.3)	*2.5 (0.9)*	
	M					*9.2 (1.4)*	*7.4 (1.3)*	*5.0 (1.4)*	2.7 (1.4)	2.0 (1.1)	*3.5 (1.2)*	
R. Int. Oblique	F							*5.5 (1.5)*	3.3 (1.2)	2.1 (1.1)	3.6 (1.5)	
	M							*7.2 (1.7)*	3.4 (1.3)	2.5 (1.1)	4.5 (1.0)	
L. Int. Oblique	F							*5.0 (1.9)*	*3.0 (1.5)*	*1.6 (1.0)*	3.0 (1.5)	
	M							*7.7 (1.6)*	*4.3 (1.5)*	*2.7 (1.0)*	4.5 (1.3)	
R. Psoas Major	F						−0.7 (0.9)	−0.9 (0.3)	*−0.8 (0.4)*	−0.4 (0.5)	0.7 (0.7)	2.3 (1.0)
	M						−0.5 (–)	−0.7 (0.5)	*−0.4 (0.4)*	−0.1 (0.3)	0.8 (0.5)	2.4 (0.7)
L. Psoas Major	F						*−0.2 (0.7)*	*−1.0 (0.4)*	*−1.0 (0.5)*	*−0.7 (0.5)*	*0.2 (0.6)*	2.0 (0.8)
	M						*−0.9 (0.5)*	*−0.6 (0.5)*	*−0.3 (0.4)*	*−0.02 (0.5)*	*0.8 (0.6)*	2.4 (0.7)
R. Quad. Lumb.	F						−2.9 (0.4)	−3.0 (0.4)	−3.1 (0.7)	−2.6 (0.8)		
	M						−2.7 (–)	−3.1 (0.6)	−3.1 (0.7)	−3.0 (0.6)		
L. Quad. Lumb.	F						−2.6 (0.3)	−3.2 (0.6)	−3.6 (1.0)	−3.2 (1.0)		
	M						−3.0 (0.4)	−3.1 (0.6)	−3.1 (0.7)	−3.1 (0.7)		

[a] Italicized cells represent statistically significantly larger male than female moment-arms ($P \leqslant 0.05$). Positive and negative moment-arms correspond to anterior and posterior to vertebral body, respectively.

Table 5
Significant regression equations predicting the moment-arms (cm) in the *sagittal* plane for females and males from various anthropometric measures

Muscle	Female					Male				
	Level	Regression equation	R^2	S.E. of Prediction	*P*-value	Level	Regression equation	R^2	S.E. of prediction	*P*-value
L. Lat. Dorsi						L_3	−13.5 + 73.5TDXPH	0.462	0.82	0.0305
R. Erector Spinae	L_3	−2.48 − 0.043 WT	0.307	0.42	0.0113					
	L_3	−2.73 − 0.023 HTWT	0.313	0.42	0.0103					
	L_3	−7.22 + 0.79 HTDWT	0.261	0.44	0.0213					
L. Erector Spinae						L_3	1.83 − 0.042 HT	0.475	0.43	0.0276
						L_3	−9.3 + 12.8 TDXPW	0.448	0.44	0.0344
L. Rect. Abdominis						L_3	−0.85 + 0.44 TDXP	0.530	0.95	0.0170
						L_3	−4.9 + 108.2 TDXPH	0.644	0.83	0.0052
						L_3	−0.83 + 0.4 BMI	0.461	1.02	0.0309
L. Ext. Oblique						L_3	−13.8 + 126.7 TDXPH	0.780	0.69	0.0007
R. Int Oblique	L_3	11.1 − 69.5 TDXPH	0.412	0.95	0.0041					
	L_3	11.09 − 0.42 TDXP	0.375	0.98	0.0069					
	L_3	9.16 − 0.28 BMI	0.268	1.06	0.0277					
L. Quad. Lumborum						L_3	−9.25 + 42.57 TDXPH	0.423	0.57	0.0418
R. Erector Spinae	L_4	−3.02 − 0.095 TDIC	0.261	0.35	0.0214					
	L_4	−3.39 − 0.016 HTWT	0.229	0.36	0.0329					
L. Erector Spinae						L_4	2.33 − 0.046 HT	0.627	0.34	0.0064
						L_4	−9.96 + 14.6 TDXPW	0.652	0.33	0.0047
						L_4	−4.1 0.01 HTWT	0.415	0.43	0.0445
L. Rect. Abdominis	L_4	1.83 + 0.071 WT	0.248	0.82	0.0254	L_4	−1.55 + 0.409 TDXP	0.428	1.09	0.0402
	L_4	2.14 + 0.04 HTWT	0.269	0.81	0.0191	L_4	−4.83 + 97.1 TDXPH	0.481	1.04	0.0262
L. Ext. Oblique						L_4	−8.9 + 83.6 TDXPH	0.582	0.73	0.0103
R. Int Oblique						L_4	−5.367 + 0.35 TDIC	0.556	0.74	0.0133
						L_4	−13.5 + 32.3 TCIRH	0.572	0.91	0.0113
L. Int Oblique	L_4	−13.71 + 0.092 HT	0.264	0.89	0.0292	L_4	−6.8 + 0.37 TDTR	0.595	0.69	0.0089
						L_4	−5.56 + 0.36 TDXP	0.588	0.70	0.0096
						L_4	−8.47 + 85.8 TDXPH	0.663	0.63	0.0041
L. Quad. Lumborum						L_4	−9.56 + 49.63 TDXPH	0.477	0.54	0.0271
R. Rect. Abdominis						L_5	−5.52 + 103.3 TDICH	0.448	1.11	0.0343
						L_5	−13.2 + 42.1 TCIRH	0.541	1.01	0.0153
L. Rect. Abdominis	L_5	2.44 + 0.04 HTWT	0.202	0.94	0.0468	L_5	−3.03 + 0.46 TDXP	0.472	1.13	0.0283
						L_5	−7.14 + 113.2 TDXPH	0.559	1.04	0.0129
						L_5	−12.8 + 41.4 TCIRH	0.477	1.13	0.0271
R. Psoas Major	L_5	−2.77 + 0.15 TDTR	0.207	0.65	0.0437	L_5	−3.07 + 0.17 TDIC	0.577	0.35	0.0108
	L_5	4.27 − 10.3 TDICW	0.223	0.65	0.0357	L_5	−6.14 + 14.05 TCIRH	0.461	0.40	0.0310
L. Psoas Major	L_5	−3.0 + 0.06 WT	0.337	0.52	0.0073	L_5	−3.1 + 0.18 TDIC	0.406	0.50	0.0477
	L_5	−3.07 + 9.44 WTDHT	0.333	0.52	0.0077	L_5	−4.4 + 0.21 TDTR	0.499	0.46	0.0224
	L_5	3.24 − 1.04 HTDWT	0.293	0.54	0.0138	L_5	−4.6 + 42.7 TDICH	0.400	0.51	0.0499

Table 6
Significant regression equations predicting the moment-arms (cm) in the *coronal* plane for females and males from various anthropometric measures

Muscle	Female					Male				
	Level	Regression equation	R^2	S.E. of prediction	P-value	Level	Regression equation	R^2	S.E. of prediction	P-value
R. Lat. Dorsi	L_3	15.58 − 2.24 HTDWT	0.419	0.87	0.0050					
	L_3	2.5 + 18.9 WTDHT	0.396	0.89	0.0068					
	L_3	3.45 + 0.27 BMI	0.381	0.90	0.0083					
L. Lat. Dorsi	L_3	0.6 + 18.8 TCIRH	0.328	1.07	0.0130	L_3	17.2 − 6.06TCIRW	0.725	0.49	0.0018
	L_3	15.3 − 2.07 HTDWT	0.317	0.97	0.0150	L_3	16.1 − 2.5 HTDWT	0.717	0.45	0.0020
	L_3	3.93 + 0.25 BMI	0.308	0.98	0.0169					
R. Erector Spinae	L_3	1.99 + 0.024 WT	0.198	0.32	0.0493	L_3	6.14 − 2.1 TCIRW	0.806	0.12	0.0004
	L_3	2.05 + 0.014 HTWT	0.230	0.31	0.0326	L_3	6.0 − 5.7 TWICW	0.790	0.13	0.0006
						L_3	2.16 + 3.73 WTDHT	0.661	0.16	0.0042
L. Erector Spinae	L_3	2.44 + 0.011 HTWT	0.211	0.27	0.0415	L_3	5.76 − 1.6 TCIRW	0.672	0.13	0.0037
						L_3	5.7 − 4.42 TWICW	0.662	0.13	0.0042
						L_3	5.35 − 0.6 HTDWT	0.555	0.15	0.0135
L. Rect. Abdominis						L_3	−2.15 + 0.24 BMI	0.546	0.53	0.0146
R. Ext. Oblique	L_3	5.9 + 13.9 WTDHT	0.491	0.55	0.0006	L_3	1.15 + 0.066 HT	0.710	0.41	0.0022
	L_3	15.5 − 1.6 HTDWT	0.484	0.55	0.0007	L_3	10.0 + 0.02 HTWT	0.690	0.42	0.0029
	L_3	6.49 + 0.20 BMI	0.455	0.57	0.0011	L_3	9.34 + 0.043 WT	0.649	0.45	0.0049
L. Ext. Oblique	L_3	3.48 + 0.26 TWXP	0.272	0.83	0.0183	L_3	4.84 + 16.6 WTDHT	0.830	0.45	0.0002
	L_3	15.0 − 1.52 HTDWT	0.269	0.83	0.0192	L_3	20.1 − 3.45 HTDWT	0.818	0.46	0.0003
	L_3	6.2 + 12.4 WTDHT	0.248	0.84	0.0255	L_3	2.09 + 0.4 BMI	0.801	0.48	0.0005
R. Int Oblique	L_3	0.97 + 0.42 BMI	0.677	0.67	0.0001					
	L_3	1.26 + 24.2 WTDHT	0.609	0.74	0.0001					
	L_3	17.7 − 2.77 HTDWT	0.595	0.75	0.0002					
L. Int Oblique	L_3	0.45 + 0.43 BMI	0.481	1.03	0.0014	L_3	−21.5 + 188.3 TWICH	0.504	1.03	0.0322
	L_3	17.4 − 2.77 HTDWT	0.403	1.10	0.0047					
	L_3	1.1 + 23.8 WTDHT	0.398	1.11	0.0050					
R. Psoas Major						L_3	0.41 + 0.11 TWXP	0.531	0.22	0.0169
						L_3	−0.2 + 0.02 HT	0.496	0.23	0.0229
L. Psoas Major						L_3	0.7 + 0.1 TWXP	0.412	0.25	0.0456
L. Quad. Lumborum						L_3	0.83 + 0.18 TWIC	0.401	0.54	0.0492
						L_3	0.46 + 0.174 TWTR	0.412	0.54	0.0453
R. Erector Spinae	L_4	2.27 + 0.02 WT	0.200	0.26	0.0478					
	L_4	2.33 + 0.011 HTWT	0.229	0.26	0.0328					
L. Erector Spinae	L_4	−0.82 + 0.026 HT	0.259	0.27	0.0219	L_4	2.9 − 5.6 TWICW	0.525	0.22	0.0178
	L_4	2.096 + 0.024 WT	0.259	0.27	0.0219	L_4	6.1 − 2.1 TCIRW	0.567	0.21	0.0119
	L_4	2.05 + 0.015 HTWT	0.350	0.25	0.0060					
L. Rect. Abdominis						L_4	−5.44 + 0.278 TWXP	0.443	0.67	0.0357
						L_4	−6.94 + 57.0 TWXPH	0.400	0.70	0.0497
R. Ext. Oblique	L_4	3.96 + 0.27 TWXP	0.355	0.69	0.0056	L_4	1.22 + 0.066 HT	0.771	0.34	0.0008
	L_4	6.93 + 0.073 WT	0.312	0.72	0.0105	L_4	10.0 + 0.05 HTWT	0.749	0.36	0.0012
	L_4	6.83 + 12.34 WTDHT	0.310	0.72	0.0108	L_4	4.86 + 0.261 TWIC	0.736	0.37	0.0015

L. Ext. Oblique	L_4	4.58 + 0.23 TWXP	0.232	0.81	0.0316	L_4	6.93 + 0.066 WT	0.897	0.32	0.0001
	L_4	14.6 − 1.32 HTDWT	0.224	0.82	0.0349	L_4	5.13 + 15.6 WTDHT	0.891	0.32	0.0001
	L_4	6.96 + 11.0 WTDHT	0.215	0.82	0.0396	L_4	19.44 − 3.24 HTDWT	0.883	0.33	0.0001
R. Int Oblique	L_4	3.49 + 0.247 TWXP	0.308	0.71	0.0169	L_4	5.2 + 0.2 TWIC	0.502	0.48	0.0219
	L_4	4.25 + 12.7 TCIRH	0.305	0.66	0.0214	L_4	3.4 + 0.045 HT	0.411	0.52	0.0456
	L_4	6.14 + 11.4 WTDHT	0.258	0.73	0.0312					
L. Int Oblique	L_4	4.87 + 0.236 BMI	0.404	0.67	0.0046	L_4	16.4 − 2.57 HTDWT	0.744	0.43	0.0013
	L_4	14.3 − 1.55 HTDWT	0.346	0.70	0.0102	L_4	5.1 + 12.3 WTDHT	0.745	0.43	0.0013
	L_4	5.1 + 13.54 WTDHT	0.353	0.69	0.0093	L_4	6.68 + 0.05 WT	0.700	0.46	0.0025
R. Psoas Major						L_4	0.856 + 0.117 TWXP	0.472	0.27	0.0282
						L_4	0.358 + 0.024 HT	0.411	0.28	0.0459
L. Psoas Major						L_4	1.04 + 0.1 TWTR	0.419	0.29	0.0432
						L_4	0.693 + 0.114 TWXP	0.407	0.30	0.0472
						L_4	−0.43 + 0.025 HT	0.398	0.30	0.0506
L. Quad. Lumborum	L_4	−2.148 + 0.054 HT	0.223	0.64	0.0481					
	L_4	9.99 − 6.58 TWICW	0.223	0.64	0.0478					
R. Rect. Abdominis	L_5	−1.18 + 3.75 TCIRW	0.221	0.83	0.0421	L_5	15.1 − 63.9 TWICH	0.516	0.38	0.0193
L. Rect. Abdominis						L_5	−3.08 + 0.25 BMI	0.502	0.60	0.0218
R. Psoas Major						L_5	1.15 + 0.02 HT	0.418	0.27	0.0435
						L_5	2.3 + 0.085 TWTR	0.399	0.27	0.0501
L. Psoas Major	L_5	6.3 − 1.35 TCIRW	0.209	0.31	0.0494	L_5	−0.92 + 0.2 TWIC	0.814	0.22	0.0004
						L_5	−3.31 + 0.05 HT	0.787	0.24	0.0006
						L_5	3.13 + 0.01 HTWT	0.681	0.29	0.0033

Significant sagittal plane prediction equations for females were found for the following muscles (Table 5): the right erector spinae (L_3 and L_4); the left rectus abdominis (L_4 and L_5); the right and left psoas major (L_5); and the right internal oblique (L_3) and left internal oblique (L_4). The most consistent sagittal plane moment-arm predictor across all levels was the subject height times weight (HTWT). For males in the sagittal plane, significant prediction equations were found for the following muscles: the left side at L_3 for the latissimus dorsi, erector spinae, rectus abdominis, external oblique and quadratus lumborum; the left side at L_4 for the erector spinae, rectus abdominis, external oblique, internal oblique and quadratus lumborum, as well as the right internal oblique at L_4; and at L_5, the rectus abdominis and psoas major. Generally, across all levels and muscles, different predictors consisting of the trunk depth measured at the xyphoid process were consistent predictors of the male sagittal plane moment-arms.

In the coronal plane (Table 6), many more significant regression equations predicting the moment-arms resulted as compared to the sagittal plane. For some muscles (e.g., external obliques), almost all independent variables investigated resulted in significant prediction equations. However, only the best three or four regression equations were reported, based on the magnitude of the R^2. For females, significant prediction equations for coronal plane moment-arms were found for the following muscles: the latissimus dorsi (L_3); the erector spinae, external oblique and internal oblique (all at L_3 and L_4); the left quadratus lumborum (L_4); and the right rectus abdominis and left psoas major (L_5). Generally, two or three different combinations of height and weight were consistent significant predictors of the male coronal plane moment-arms. These included the subject HTWT, subject height divided by weight (HTDWT) and subject weight divided by height (WTDHT). For males, significant prediction equations for coronal plane moment-arms were found for the following muscles: the left latissimus dorsi (L_3); the erector spinae (L_3) and the left erector spinae (L_4); the right rectus abdominis (L_5) and left rectus abdominis (L_3, L_4 and L_5); the external oblique (L_3 and L_4); the right internal oblique (L_4) and left internal oblique (L_3 and L_4), the psoas major (L_3, L_4 and L_5); and the left quadratus lumborum (L_3). Similar to the females, the HTWT and HTDWT were the most consistent significant predictors for male coronal plane moment-arms.

4. Discussion

4.1. Gender effects

It is quite apparent that the gender of an individual has an impact on the magnitude of the moment-arms.

At most levels, for most muscles, males exhibited significantly larger moment-arms in both the coronal plane (14.2% larger) and the sagittal plane (17.5% larger). These differences may not be dependent upon gross anthropometric differences alone between the genders, as the male subjects were 37.8% heavier, 6.4% taller, and had a 21.3% larger BMI than the female subjects. These findings have several implications regarding biomechanical modeling to predict spinal loading. First, using male trunk geometry, inputs into biomechanical models to estimate moment-arms of females may result in error of the relative moment contribution by the various spine loading muscles. This may underestimate the true magnitude of loading on the female spine as the male moment-arms were larger than females. Secondly, biomechanical models that use a single-muscle equivalent sagittal plane moment-arm of 5.0 cm for the erector spinae [19] may result in varying degrees of over-estimates of compression force. The right and left erector spinae for males exhibited mean sagittal plane moment-arms of 6.1 cm at L_5, and 6.2 and 6.3 cm for the right and left erector spinae at S_1, respectively. Previous studies observed moment-arms of similar magnitude between the L_4 and S_1 vertebral levels [3,8,10]. Females in the current study, on the other hand, were observed to have mean sagittal plane moment-arms for the erector spinae of 5.4 and 5.7 cm at L_5 for the right and left sides, respectively. Thus, sagittal plane moment-arms greater than 5.0 cm were observed for both males and females at L_5.

4.2. Comparison with other studies

The female moment-arms were consistent with the results of previous studies on female trunk geometry for the latissimus dorsi [2], psoas major [2,3,5], and the quadratus lumborum [2,3]. However, larger differences in moment-arms observed in this study with others were present for the erector spinae, [3] the rectus abdominis, and external and internal obliques [2,3]. These differences could have resulted from differences in the sampled female populations. The females in Chaffin et al. [2] and Kumar [3] were older (49.6 and 57.0 yr, respectively) and had larger BMIs (26.2 and 25.4 kg/m^2, respectively) than the females in the current study.

Moment-arms for the male latissimus dorsi, psoas major and quadratus lumborum were similar to those found from previous studies performed on males [3,5,8,10,11,13,14,21]. However, the rectus abdominis moment-arms in the sagittal plane were 2–3 cm shorter than those found in other studies [3,5,8,14]. Kumar [3] also found internal oblique coronal plane moment-arms 2.2 and 1.5 cm greater than in this study at the L_3 and L_5 levels, respectively.

It appears that moment-arms of certain muscles (i.e., rectus abdominis and the obliques) may be influenced by the age of the individual, as well as the body mass characteristics. The mean age of the male population studied by McGill et al. [11] (25.3 yr) was similar to those in this study (25.1 yr), with similar resulting sagittal plane moment-arms in the lower lumbar region. However, other studies on males with mean ages ranging from 40.5 to 70 yr [3,5,8] observed rectus abdominis mean sagittal plane moment-arms 2.5–3.0 cm larger than those found in the current study. The males in McGill et al. [8] were on an average 15 yr older and had a 15% greater BMI. Males were considerably older in the studies of Nemeth and Ohlsen [5] and Kumar [3], however, the BMIs were similar. This may indicate that the muscle cross-sectional areas of older males were smaller due to age-related muscle atrophy, which may then increase the distance of the muscle centroid with respect to the spine centroid. Age was not investigated as a predictor of moment-arm magnitude in this study as the subjects were in a restricted age range (20–34 yr).

The differences in coronal plane moment-arms for the external and internal obliques between males of different studies may be attributable to differences in moment-arm endpoint location methods. Kumar [3] projected a perpendicular line from the line connecting the two endpoints of the muscle into the midpoint of the muscle to locate the moment-arm endpoint. This would result in larger moment-arms than in our study, as the centroid of the crescent shaped oblique muscles was typically located medial to the medial border of the muscles.

4.3. Moment-arm regression equations

Prior studies have found very few significant predictors of sagittal plane moment-arms. For females, Kumar [3] found no significant regression equations, and Chaffin et al. [2] found only the rectus abdominis could be predicted from external anthropometric measures. Our study, however, found several more muscles could be predicted, although there was no apparent consistency across the different muscles and vertebral levels. For males, Kumar [3] found no significant regression equations, and Tracy et al. [10] found only the rectus abdominis sagittal plane moment-arm resulted in a significant prediction of the sagittal plane moment-arm from external anthropometry. Again, similar to the females in our study, we found that the males demonstrated more significant prediction equations from external anthropometry than found in previous studies [3,10], however, again there was no apparent consistency across the different muscles and vertebral levels. This lack of consistent prediction of sagittal plane moment-arms across multiple studies may indicate a natural variability across individuals.

In the coronal plane, more muscles had significant moment-arms at the L_3 and L_4 vertebral level than at L_5 for both genders. The female results were similar to those found by Chaffin et al. [2] for predictability for the latissimus dorsi, and the external and internal obliques. However, Chaffin et al. [2] found significant regression equations for the rectus abdominis whereas our study only found the right rectus abdominis at L_5. Our study found significant erector spinae moment-arms at L_3 and L_4, whereas Chaffin et al. [2] found no relationship between the erector spinae and the investigated external anthropometric measures. Thus, our study was consistent with the prediction of coronal plane moment-arm regression equations with previous findings [2], with additional relationships found. These additional relationships were found with the use of a smaller data set, as Chaffin et al. [2] used 96 females whereas we had 20 females in our dataset. Thus, our investigation yielded stronger significant predictors with a smaller dataset.

Similar to the findings from our study on the prediction of the physiological cross-sectional areas [1], measures consisting of individual height and weight (e.g., product of height and weight, height divided by weight, weight divided by height) were more consistent predictors of moment-arms across all muscles investigated for females than relationships previously used for estimates of moment-arms (e.g., measures about the iliac crest) [17]. Regression on male moment-arms from external anthropometric measures indicated that measures about the xyphoid process were consistent predictors of sagittal plane moment-arms (e.g., trunk depth measured at the xyphoid process, trunk depth at xyphoid process divided by either height or weight) and measures of height and weight (e.g., product of height and weight, height divided by weight) were consistent predictors of coronal plane moment arms across all muscles and levels. While both the L_3 and L_4 levels resulted in many muscles with significant moment-arm prediction equations, only the rectus abdominis and psoas major muscles had significant predictors of the sagittal plane and coronal plane moment-arms at the L_5 level. Thus, we did not find a significant predictor for the major extensor muscle of the male trunk (erector spinae) in either the sagittal or coronal plane, which may be indicative of too few subjects or the appropriate combination of predictors was not investigated. Other investigators have found significant predictors of erector spinae moment-arms using unconventional measures. Wood et al. [14] found a significant relationship between sitting height and the erector spinae moment-arm at L_5/S_1 from 26 subjects. Reid et al. [12] found a regression equation with six independent variables on 20 subjects, and Moga et al. [4] found regression equations with five independent variables to be significant predictors of the sagittal plane moment-arm of the male erector spinae using 19 subjects. Thus, it appears that near the levels which many biomechanical models estimate spinal loading and bending moments, difficulty exists in the prediction of the major trunk extensor's moment-arms in both the sagittal and coronal plane. This point may need further investigation as it has been shown that variation in the moment-arm in biomechanical models results in highly sensitive estimates of spinal loading, especially for single-equivalent muscle models [22].

4.4. Moment-arms in biomechanical models

In biomechanical models of the trunk, moment-arm data can serve at least two functions. First, these data can be used to estimate the internal moments generated by the trunk muscles about an axis of rotation. Biomechanical models have generally assumed this rotation axis to lie between L_3 and L_5/S_1 [17–20]. Secondly, moment-arm data across multiple levels can be used to estimate the muscle force vector or muscle force line-of-action. However, the centroid approach for identification of the muscle force vector may not be appropriate for all trunk muscles and may need to be augmented using muscle fiber orientation data. The method of centroids to identify the line-of-action of a muscle was investigated by Jensen and Davy [23]. They assumed that the force transmitted by a skeletal muscle could be defined by the locus of the centroid of its transverse cross-sectional area, and if the resultant force at any transverse section acts at the centroid of the section, it was necessary that either the muscle fiber forces are parallel and uniformly distributed over the section, or that other distributions exist which produce zero net lateral moments about the centroid. Rab [6] indicated that the assumption that the centroid line of a muscle determined by connecting the centroids of multiple muscle cross-sections is valid if all fibers of a muscle are symmetrically loaded.

Muscles for which the path of the centroids (moment-arm distances) may be consistent with the muscle fiber orientations include the latissimus dorsi [7,24] and the rectus abdominis [7,25]. However, other muscles such as the erector spinae, external oblique and the internal oblique, the orientation of the centroid path and fiber orientation in the lumbar region are different.

In the coronal plane, the erector spinae muscle vector based on centroids from L_1 to L_5 runs in a caudal/medial direction. However, Macintosh and Bogduk [26] indicated that the muscle fibers of the iliocostalis lumborum and the longissimus thoracis in the lumbar region run in a caudal/lateral direction. The sagittal plane moment-arms indicate the erector spinae vector gradually increases in the posterior direction, however, Macintosh and Bogduk [26] indicated a much greater caudal/posterior angle of the erector spinae fibers in the lumbar region. Thus, the fiber orientation of the muscles of the erector spinae need to be accounted for when determining the direction of the force.

The centroid path for the external oblique in the sagittal plane runs caudal/posterior in the upper lumbar region, to a caudal/anterior direction in the lower lumbar region. The coronal plane centroid path indicates a caudal/lateral orientation. Dumas et al. [7] found a slight variation in muscle fiber bundle orientation dependent upon the location within the muscle. In the sagittal plane, the anterior and posterior fiber bundles at the L_3/L_4 and L_4/L_5 levels all demonstrated a caudal/anterior direction. In the coronal plane, the anterior portions ran in the caudal/medial direction, which tapered to almost vertical for the posterior portion of the muscle. Thus, the differences in fiber bundle orientation and the centroid path necessitate the use of the fiber bundle directions for the estimation of the muscle force line-of-action.

The position of the centroid in the sagittal plane for the internal oblique muscle, similar to that of the external oblique, lied anterior to the vertebral body for all levels where the muscle was present. The moment-arm decreased from L_2 to L_4, and then increased again at L_5. Basing the muscle vector on the results of the centroid method indicates that the internal oblique muscle may act as a flexor of the trunk, with the centroid at all levels lying anterior to the spine. However, Dumas et al. [7] indicated a wide variation of muscle fiber bundle orientation at the L_3/L_4 and L_4/L_5 levels, where the lateral and posterior fiber bundles were considered trunk extensors. This is consistent with trunk muscle activity studies when muscle activity was sampled from the posterior aspect of the internal oblique [27]. Thus, muscle fiber orientation in the lower lumbar region should be used for the internal oblique muscle vector, which indicates the internal oblique can be modeled as a trunk extensor.

The results of this study need to be interpreted in light of several methodological considerations. First, the moment-arms in this study were observed from subjects lying supine. The moment-arms of several muscles would be expected to change as a function of standing upright [28], as a function of twisting [15], or from sagittal bending [29]. Second, as discussed above, the centroid method was used to determine the endpoints of the moment-arms. This approach may not be reflective of the true muscle force direction for muscles with oblique fiber angles such as the external oblique and internal oblique, and should be supplemented with fiber orientation data.

5. Conclusions

Moment-arms in the sagittal and coronal plane of most trunk muscles investigated in this study exhibited differences in length as a function of gender, with males having, on an average, 15.9% larger moment-arms than females. These gender differences indicate that female specific moment-arms may need to be used to improve the accuracy of biomechanical models investigating female spinal loading. Inspection of resulting moment-arms as compared to previous studies indicates that the age and body mass characteristics of the population sampled may have an impact on the moment-arm distances for certain muscles, including the obliques and rectus abdominis. Finally, for both genders, this study resulted in better predictions of sagittal plane and coronal plane moment-arms as compared to prior studies.

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