Clinical Biomechanics 37 (2016) 60–64

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Prediction of magnetic resonance imaging-derived trunk muscle geometry with application to spine biomechanical modeling

Jaejin Hwang, Jonathan S. Dufour, Gregory G. Knapik, Thomas M. Best [1], Safdar N. Khan [2], Ehud Mendel [3], William S. Marras *

Biodynamics Laboratory, Spine Research Institute, Department of Integrated Systems Engineering, The Ohio State University, 210 Baker Systems Engineering, 1971 Neil Avenue, Columbus, OH 43210, USA

ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form 20 May 2016
Accepted 3 June 2016

Keywords:
Muscle geometry
Moment-arm
Cross-sectional area
Biomechanical model
Regression model
Spine

ABSTRACT

Background: Accurate geometry of the trunk musculature is essential for reliably estimating spinal loads in biomechanical models. Currently, many models employ straight muscle path assumptions that yield far less accurate tissue loads, particularly in extreme postures. Precise muscle moment-arms and physiological cross-sectional areas are important when incorporating curved muscle geometry in biomechanical models. The objective of this study was to develop a predictive model of moment arms and physiological cross-sectional areas of trunk musculature at multiple levels in the thoracic/lumbar spine as a function of anthropometric measures.
Methods: Based on magnetic resonance imaging data from thirty subjects (10 male and 20 female) reported in a previous study, a polynomial regression analysis was conducted to estimate the muscle moment-arms and physiological cross-sectional areas of trunk muscles through thoracic/lumbar spine as a function of vertebral level, gender, age, height, and body mass.
Findings: Gender, body mass, and height were the best predictors of muscle moment-arms and physiological cross-sectional areas. The predictability of muscle parameters tended to be higher for erector spinae than other muscles. Most muscles showed a curved muscle path along the thoracic/lumbar spine.
Interpretation: The polynomial regression model of the muscle geometry in this study generally showed good predictability compared to previous reports. The predictive model in this study will be useful to develop personalized biomechanical models that incorporate curved trunk muscle geometries.

1. Introduction

Accurate trunk muscle geometry including muscle moment-arms and physiological cross-sectional areas (PCSAs) is essential for estimating reliable muscle-generated moments, muscle forces, and spinal loads in biomechanical models of the spine (Jorgensen et al., 2001; Marras et al., 2001). Within biomechanical models, muscle moment-arms influence the calculation of muscle-generated internal moments at specific levels of the lumbar spine (Chaffin, 1969; Marras and Granata, 1997; McGill, 1992; Schultz and Andersson, 1981) and the direction of reaction forces on different tissues based on muscle force lines of action (Jorgensen et al., 2001), whereas PCSAs affect maximum physiological muscle force capability (Gungor et al., 2015; Marras et al., 2001).

Historically, most biomechanical spine models have represented muscle lines of action as straight-lines (Chaffin, 1969; Granata and Marras, 1993; Marras and Sommerich, 1991; McGill and Norman, 1986; Schultz and Andersson, 1981). Straight muscle lines of action have worked reasonably well in upright posture or during relatively small lumbar range of motions. However, straight-line muscle paths could be less reliable at the extreme range of complex lumbar motions such as deep bending or asymmetric postures as a result of under-representing the realistic curved path of the tissues (Arjmand et al., 2006; Garner and Pandy, 2000). Subsequently, these muscle path definitions could result in inaccurate muscle force lines of action, ineffective muscle moment-arms (Jorgensen et al., 2001), and unreliable distribution of compression and shear reaction forces on the intervertebral discs. In order to minimize these issues, some have explored a curved muscle path technique that coordinates muscle lines of action with spine movements during highly asymmetric postures and complex

* Corresponding author.
E-mail addresses: hwang.285@osu.edu (J. Hwang), dufour.8@osu.edu (J.S. Dufour), knapik.1@osu.edu (G.G. Knapik), Tom.Best@osumc.edu (T.M. Best), Safdar.Khan@osumc.edu (S.N. Khan), Ehud.Mendel@osumc.edu (E. Mendel), marras.1@osu.edu (W.S. Marras).
[1] Department of Family Medicine, The Ohio State University, Martha Moorehouse Medical Plaza, 2050 Kenny Dr., Columbus, OH, USA 43210.
[2] Department of Orthopaedics, College of Medicine, The Ohio State University, Columbus, OH, USA 43210.
[3] Department of Neurological Surgery, The Ohio State University, Columbus, OH, USA 43210.

http://dx.doi.org/10.1016/j.clinbiomech.2016.06.001
0268-0033/

motions (Arjmand et al., 2006; Delp et al., 1990; Garner and Pandy, 2000; Ghezelbash et al., 2015; Jensen and Davy, 1975; Kruidhof and Pandy, 2006; Vasavada et al., 2008).

Curved muscle path techniques often require that the centroid positions of muscles across multiple vertebral levels of the spine be defined in order to develop a curved muscle path (Cholewicki and McGill, 1996; Jaeger et al., 2012; Kruidhof and Pandy, 2006; Santaguida and McGill, 1995; Suderman and Vasavada, 2012). Therefore, an accurate understanding of muscle centroid positions for each level of the spine is essential. In addition, maximum PCSA for each muscle is required to estimate the maximum muscle force generation capability within biomechanical models (Gungor et al., 2015; Marras et al., 2001). This maximum muscle force capability could alter the magnitude of spinal loads in biomechanical models (Marras and Granata, 1997; McGill and Norman, 1986; Schultz and Andersson, 1981), therefore accurate estimation of PCSA for each muscle is important.

Muscle moment-arm and PCSA values used in most biomechanical models are based on a limited population of subjects, such as only young or an older age group or a single gender population (Chaffin et al., 1990; McGill et al., 1993; Reid et al., 1987; Tracy et al., 1989). In addition, most models use non-personalized muscle geometries, which ignore the individual variability of muscle moment-arms and PCSAs across individuals. In order to overcome this concern, predictive models for muscle moment-arms and PCSAs estimated as a function of anthropometric measures might be a good alternative to account for the variability of muscle geometry between individuals including the effects of age, gender, and body size.

To date, only one study has systematically provided the muscle moment-arms and PCSAs of several major power producing trunk muscles through multiple levels of the thoracic/lumbar spine for use in biomechanical models (Anderson et al., 2012). They predicted muscle parameters at each vertebral level, respectively, and reported that a large number of regression models generally showed low R^2 values. Moreover, given the variability of different measurements, varied definitions of muscle parameters, and diverse subject populations across studies, putting variable data sources into a single biomechanical model requires careful evaluation and potentially introduces additional variability to the model.

Thus, the objective of this study was to develop a predictive model of personalized muscle geometry including muscle moment-arms and PCSAs for major trunk muscles through multiple levels of the thoracic/lumbar spine as a function of anthropometric measures.

2. Methods

2.1. Approach

Subjects signed a consent form approved by the University's Institutional Review Board (IRB). The present study used MRI-derived values of the muscle geometry of thirty subjects (10 males and 20 females) from previous studies (Jorgensen et al., 2001; Marras et al., 2001). Fig. 1 shows an example of measurements taken including muscle moment-arms and CSAs. Muscle moment-arms were calculated between the muscle centroid and the vertebral body centroid for sagittal and coronal planes at multiple vertebral levels. CSAs were obtained by measuring the area of the enclosed region of trunk muscles at a transverse scan plane, respectively. Then, muscle fiber corrections of each muscle were applied to derive PCSAs, which were perpendicular to their fibers. More detailed information of measurements and adjustments can be found elsewhere (Jorgensen et al., 2001; Marras et al., 2001).

The sagittal and coronal plane six trunk muscles' (pair of lattisimus dorsi, erector spinae, and rectus abdominis) moment-arms were considered. The available vertebral levels of the lattisimus dorsi were

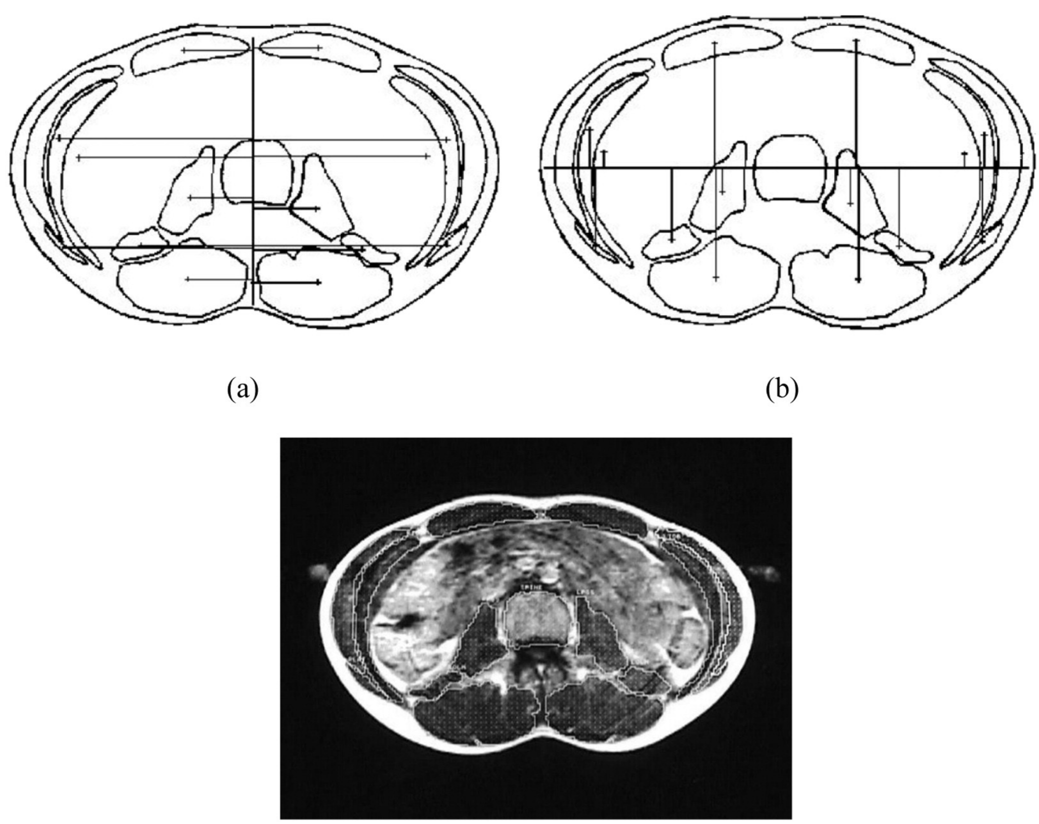

Fig. 1. Measurements of coronal plane moment-arms (a), and sagittal plane moment-arms (b) taken from each of trunk muscle centroids at the L3 level (Jorgensen et al., 2001); and cross-sectional areas (c) of a female subject at the L3 level (Marras et al., 2001).

from T12 through L3, whereas erector spinae and rectus abdominis were from T12 through S1.

Our initial goal was to estimate muscle force lines of action to implement within biomechanical models of the spine. The muscle force through muscle centroid path was considered reasonable when muscle fibers were parallel and uniformly distributed (Jensen and Davy, 1975; Rab et al., 1977). Muscle centroid paths of the latissimus dorsi and rectus abdominis were well aligned with their fiber orientations (Bogduk et al., 1998; Dumas et al., 1991; Stokes and Gardner-Morse, 1999). The muscle centroid path was also found reasonable to identify resultant force line of actions of the erector spinae group including both the erector spinae and transversospinalis (An et al., 1981; Nussbaum and Chaffin, 1996; Takashima et al., 1979). However, for the external and internal obliques, fiber orientations were highly different from the muscle centroid path (Dumas et al., 1991; Jorgensen et al., 2001), so MRI-derived centroid path vales of these muscles from previous studies were not considered here.

Ten trunk muscles' (pair of lattisimus dorsi, erector spinae, rectus abdominis, external oblique, and internal oblique) PCSAs were used. The available vertebral levels of the lattisimus dorsi were from T8 through L3; the erector spinae were from T12 through L5; the rectus abdominis were from T12 through S1; the external oblique were from T12 through L4; and the internal oblique were from L2 through L4.

A polynomial regression analysis was conducted to estimate sagittal and coronal plane trunk muscle moment-arms and PCSAs through multiple thoracic/lumbar levels (from T8 to S1) using individual anthropometric data from 30 subjects (10 males, 20 females).

2.2. Muscle geometry

2.2.1. Participants

MRI-based measured muscle moment-arms and PCSAs from T8 to S1 levels of thirty subjects (10 male and 20 female) were used from previous studies to derive regression models (Jorgensen et al., 2001; Marras et al., 2001). All subjects had no prior history of low back pain symptoms that caused them to seek medical attention. Mean vales and standard deviations of age, body mass, and height were 26.4 (5.5) years, 79.8 (13.3) kg, and 175.9 (9.1) cm, respectively for male subjects, and 25.0 (7.2) years, 57.9 (6.4) kg, and 165.5 (5.9) cm, respectively for female subjects.

2.2.2. Data analysis

Two adjustments of the muscle moment-arms and PCSAs were performed in order to incorporate the information into a biomechanical model of the lumbar spine. First, the sagittal plane moment-arms of the rectus abdominis were increased by 30% to adjust for differences between upright and supine postures during MRI data collection (Jorgensen et al., 2005; McGill et al., 1996; Theado et al., 2007). Next, the PCSA of the lattisimus dorsi was reduced to 43% of the original PCSA in order to adjust for the contribution of lumbar spine extension (specifically) in the biomechanical model (Bogduk et al., 1998; Theado et al., 2007).

2.2.3. Statistical analysis

The list of independent variables and descriptions are shown in Table 1. Height and body mass variables were chosen as potential predictors because of their high predictability of muscle geometry in previous studies (Anderson et al., 2012; Chaffin et al., 1990; Gungor et al., 2015; Moga et al., 1993; Seo et al., 2003). Since height and body mass are easily and commonly measured, the height and body mass based predictive model could be widely used while minimizing the potential additional measurement error of complex anthropometric measurements (Anderson et al., 2012).

Gender (sex), age, trunk depth, and trunk width measures were also considered as potential predictors of muscle geometry based on previous findings (Anderson et al., 2012; Chaffin et al., 1990; Gungor et al., 2015; Jorgensen et al., 2001; Marras et al., 2001; Moga et al., 1993; Reid et al., 1987; Tracy et al., 1989). The vertebral levels of the thoracic/lumbar spine were used as potential predictors to estimate the linear or nonlinear pattern of muscle moment-arms and PCSAs through multiple levels of the spine. Left and right side muscle geometries were predicted separately because of the significant difference in muscle size as a function of side reported in previous studies for several trunk muscles (Jorgensen et al., 2001; Marras et al., 2001; McGill et al., 1993).

Table 1
Independent variables and descriptions of polynomial regression model.

Independent variable	Description
Level	Vertebral level from S1 through T8 (S1 = 1 through T8 = 11)
$Level^2$	Level squared
$Level^3$	Level cubic
Gender	Male = 0; Female = 1
Age (years)	Subject age (years)
Height (cm)	Subject height (cm)
Body mass (kg)	Subject body mass (kg)
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)

A stepwise linear regression analysis was initially conducted to find suitable predictors for each muscle moment-arm and PCSA. After carefully choosing variables based on the statistical significance and the robustness of anthropometric measures that potentially minimize measurement error, the best polynomial regression models (from first to third degree) were selected to estimate the pattern of muscle moment-arms for the sagittal and coronal planes, and PCSAs through multiple levels of the thoracic/lumbar spine. All statistical analysis was performed using JMP statistical software (SAS Institute, Inc., Cary, NC) with a significance level of $P < 0.05$.

3. Results

Tables 2 and 3 show the polynomial regression coefficients and model performance for predicting the pattern of sagittal and coronal plane muscle moment-arms and PCSAs across the thoracic/lumbar spine.

All polynomial regression models (n = 22) of muscle moment-arms and PCSAs were statistically significant (P-value < 0.05) (Tables 2 and 3). The adjusted coefficients of determination (R^2 adj.) of sagittal plane moment-arms ranged between 0.11 and 0.76, whereas coronal plane moment-arms varied between 0.12 and 0.79. The root-mean-square-error (RMSE) of sagittal plane moment-arms ranged between 0.48 cm and 1.52 cm, whereas coronal-plane moment-arms ranged between 0.33 cm and 0.82 cm. The adjusted R^2 of PCSA varied between 0.45 and 0.84, and RMSE ranged between 1.40 cm^2 and 2.86 cm^2.

For sagittal plane muscle moment-arms, gender was the most significant predictor for the erector spinae (average 0.37 cm decrease for female) and rectus abdominis (average 2.07 cm decrease for female), whereas height was the most significant predictor for the lattisimus dorsi (average 0.02 cm increase per 1 cm). For coronal plane muscle moment-arms, body mass was the most significant predictor for the lattisimus dorsi (average 0.08 cm increase per 1 kg), whereas gender was the most significant predictor for the erector spinae (average 0.27 cm decrease for female), and right rectus abdominis (0.49 cm decrease for female). In the case of PCSAs, gender was the most significant predictor for the latissimus dorsi (average 1.70 cm^2 decrease for female), erector spinae (average 3.26 cm^2 decrease for female), and external oblique (average 2.40 cm^2 decrease for female). Body mass was the most significant predictor for the rectus abdominis (average 0.15 cm^2 increase per 1 kg), whereas height was the most significant predictor for the internal oblique (average 0.12 cm^2 increase per 1 cm).

Table 2
Polynomial regression coefficients, adjusted R^2, *P*-values, and RMSE (cm) for the prediction of the muscle moment-arms (cm) in the sagittal and coronal plane.

Plane	Muscle	Intercept	Level	$Level^2$	$Level^3$	Gender	Age	Height	Body mass	R^2 Adj.	RMSE (cm)	*P*-value
Sagittal	Right Latissimus Dorsi	0.51	0.23					−0.03		0.107	0.982	0.0006
	Left Latissimus Dorsi	−4.32	0.54					−0.01		0.241	1.062	<.0001
	Right Erector Spinae	−2.92	0.18			0.52	−0.03	−0.01		0.508	0.484	<.0001
	Left Erector Spinae	−1.77	0.23			0.22	−0.03	−0.02		0.518	0.516	<.0001
	Right Rectus Abdominis	6.28	−5.06	1.39	−0.09	−1.93		0.05		0.740	1.468	<.0001
	Left Rectus Abdominis	6.80	−5.31	1.49	−0.10	−2.21		0.05		0.757	1.520	<.0001
Coronal	Right Latissimus Dorsi	−9.37	−0.52					0.04	−0.08	0.644	0.772	<.0001
	Left Latissimus Dorsi	8.73	0.45					−0.04	0.08	0.600	0.817	<.0001
	Right Erector Spinae	1.66	−1.55	0.23	−0.01	0.22		−0.01		0.756	0.364	<.0001
	Left Erector Spinae	−1.64	1.53	−0.23	0.01	−0.31		0.02		0.789	0.333	<.0001
	Right Rectus Abdominis	−2.22	−0.71	0.09		0.49			−0.01	0.290	0.783	<.0001
	Left Rectus Abdominis	1.13	0.24	−0.02		0.35			0.02	0.122	0.731	<.0001

Note: Available levels (Latissimus dorsi = T12 to L3; Erector Spinae = T12 to S1; Rectus Abdominis = T12 to S1); RMSE = root-mean-square-error of moment-arms (cm); Positive values of sagittal plane moment arms = anterior direction; positive values of coronal plane moment arms = left side.

4. Discussion

This study used a novel approach (the polynomial regression model) to estimate the linear and nonlinear patterns of muscle moment-arms and PCSAs of major trunk muscles along the thoracic/lumbar spine. All regression models showed statistical and biological significance for the muscle moment-arms and PCSAs. Gender, height, and body mass were the most significant predictors of muscle moment-arms and PCSAs. In general, muscle moment-arms and PCSAs of trunk muscles showed nonlinear patterns across vertebral levels.

In general, all predictive models ($n = 22$) of muscle geometry showed statistical significance for all muscles (*P*-values < 0.05). Adjusted R^2 values of sagittal plane moment-arms were between 0.11 and 0.76, coronal plane moment-arms between 0.12 and 0.79, and PCSAs varied from 0.45 to 0.84. PCSA predictabilities were generally higher than the predictability of muscle moment-arms, especially in the erector spinae. This result suggests that erector spinae muscle size might be more associated with anthropometric measures than muscle moment-arms, as noted previously (Anderson et al., 2012; Seo et al., 2003).

Gender, height, and body mass were the most significant predictors to estimate personalized muscle moment-arms and PCSAs, similar to other studies (Anderson et al., 2012; Gungor et al., 2015; Jorgensen et al., 2001; Marras et al., 2001). However, age was only included to predict the sagittal plane moment-arms of the erector spinae (average 0.03 cm increase per one year). Given the limited range of subject age within our test group (from 20 to 34 years), it might be a reasonable expectation that the age variable did not reflect significant predictability. This finding was similar to previous studies (Anderson et al., 2012; Gungor et al., 2015).

With regard to the comparison with previous studies, only one study systematically provided a regression model for multiple trunk muscles with a wide range of vertebrae levels of the thoracic/lumbar spine (Anderson et al., 2012). For the sagittal plane moment-arms, the present study generally demonstrated higher R^2 values than other studies (Anderson et al., 2012; Chaffin et al., 1990; Moga et al., 1993; Seo et al., 2003), especially in the rectus abdominis (0.76 vs. 0.60). In the case of coronal plane moment-arms, the present study generally showed higher R^2 values compared with previous studies (Anderson et al., 2012; Moga et al., 1993), especially in the erector spinae (0.78 vs. 0.39). For the PCSAs, the present study showed significantly higher R^2 in erector spinae than other studies (0.84 vs. 0.43) (Anderson et al., 2012; Chaffin et al., 1990; Gungor et al., 2015; Reid et al., 1987; Seo et al., 2003), whereas other muscles generally showed comparable predictability. In general, this higher predictability for the current study could be partially related to the polynomial regression approach through levels rather than the linear regression approach at individual levels from other studies. In our study, vertebral levels significantly helped to explain the variability of linear or nonlinear patterns of muscle geometry along the spine, and increased the overall predictability of the models.

A unique feature of this study was the inclusion of vertebral level as a predictor to estimate from first to third order polynomial lines for muscle moment-arms and PCSAs along the spine curvature. As seen in Tables 2 and 3, muscle moment-arms and PCSAs varied as a function of vertebral level. In a separate pilot study, linear regression models for muscle geometry were initially developed for each vertebral level, respectively. Since the model's predictability was highly variable across levels, it often resulted in a highly nonlinear pattern of some muscle moment-arms across levels, which was different from the actual pattern of measure values. These unstable muscle moment-arms through vertebral levels could significantly hinder the accuracy of muscle force line of actions, disc forces, and disc moments in biomechanical models. Therefore, the polynomial regression approach was introduced, and it was able to predict smoother, more realistic and accurate linear and nonlinear patterns of muscle geometry across multiple levels.

The current study evaluated the pattern of moment-arms for six trunk muscles and PCSAs for ten trunk muscles in the thoracic/lumbar

Table 3
Polynomial regression coefficients, adjusted R^2, *P*-values, and RMSE (cm^2) for the prediction of the PCSA (cm^2).

Muscle	Intercept	Level	$Level^2$	Gender	Height	Body mass	R^2 Adj.	RMSE	*P*-value
Right Latissimus Dorsi	−7.03	0.85		−1.86	0.03		0.627	1.696	<.0001
Left Latissimus Dorsi	−8.23	0.75		−1.53	0.04		0.569	1.703	<.0001
Right Erector Spinae	−12.04	16.60	−1.66	−3.38	−0.15	0.27	0.838	2.861	<.0001
Left Erector Spinae	−17.56	16.47	−1.64	−3.13	−0.11	0.26	0.837	2.851	<.0001
Right Rectus Abdominis	11.77	−0.36			−0.08	0.14	0.572	1.404	<.0001
Left Rectus Abdominis	11.93	−0.33			−0.09	0.15	0.545	1.510	<.0001
Right External Oblique	5.11	−0.50		−2.42	0.03		0.512	1.420	<.0001
Left External Oblique	1.95	−0.56		−2.37	0.05		0.536	1.464	<.0001
Right Internal Oblique	6.59	−8.49	0.81		0.11		0.453	2.006	<.0001
Left Internal Oblique	10.43	−11.46	1.17		0.12		0.506	1.984	<.0001

Note: Available levels (Latissimus dorsi = T8 to L3; Erector Spinae = T12 to L5; Rectus Abdominis = T12 to S1; External Oblique = T12 to L4; Internal Oblique = L2 to L4); RMSE = root-mean-square-error of PCSA (cm^2).

spine. Variances of muscle moment-arms and PCSAs along the spine curvature indicate changes in mechanical moment-arm advantages and the maximum physiological force capability of different muscles. Such information could improve our understanding of how different mechanical and physiological advantages of muscles would affect muscle force, disc moments, and spinal loads in biomechanical models of the entire lumbar spine.

For muscle moment-arms, the six trunk muscles showed a different range of patterns (from first to third degree polynomial) along the spine curvature by each plane. The muscle moment-arms were measured as the distance of the muscle centroid relative to the vertebral bodies. For example, the linear pattern of sagittal plane moment-arms of the erector spinae indicated that this muscle's line of action was curved well along with the spine curvature in the sagittal plane. In sum, most muscles were curved in sagittal and coronal planes to wrap around the spine. This finding highlights the potential importance of incorporating curved muscle geometries in models of the spine.

When estimating PCSAs, the ten trunk muscles showed a variety of patterns (from first to second degree of polynomial) of muscle size at different levels of the spine. The erector spinae and internal oblique both showed a nonlinear pattern (quadratic) of PCSAs along the spine, whereas other muscles showed a linear pattern of PCSAs. Given the various patterns, the maximum PCSA for the latissimus dorsi, erector spinae, rectus abdominis, external oblique, and internal oblique were found to be at different levels (T8, L2, S1, L4, and L4, respectively). This information is useful for estimating the different contribution of maximum force capability of each muscle along the spine in biomechanical models.

There were several limitations of this study. First, the regression model was developed based on a sample of 30 young, healthy subjects (Jorgensen et al., 2001; Marras et al., 2001). The regression model generated from this cohort was then applied to a group of 12 subjects with comparable body size and age. Therefore, variables such as age remain to be investigated as possible confounding variables in the determination of subject specific muscle parameters. Second, the MRI-derived muscle moment-arms and PCSAs were collected from a static supine position of subjects, thus the muscle geometry data in non-neutral postures such as sagittal flexion/extension, lateral bending and axial twisting was not included. Third, direct validation of the regression model was not performed in this study. Based on the regression models derived from a historical dataset, the comparison between predicted values and measured values of the same subject group (validation dataset) would enhance the reliability of the model.

5. Conclusions

This study introduced a unique approach to predict the pattern of moment-arms and PCSAs of multiple trunk muscles along the thoracic/lumbar spine. The polynomial regression model developed herein resulted in good model predictability, and generally showed higher predictability than previous studies. This predictive model incorporating personalized muscle geometry could yield improved estimations of muscle forces and spinal loads on a highly individualized basis that can be incorporated into biomechanical models of high fidelity. In turn, this should improve our efforts to understand more about complex loading tasks and their effects on individual spinal structures, and may lead to a better understanding to the development of low back pain.

Conflict of interest statement

No potential conflict of interest was reported by the authors.

References

An, K.N., Hui, F.C., Morrey, B.F., Linscheid, R.L., Chao, E.Y., 1981. Muscles across the elbow joint: a biomechanical analysis. J. Biomech. 14, 659–669.
Anderson, D.E., D'Agostino, J.M., Bruno, A.G., Manoharan, R.K., Bouxsein, M.L., 2012. Regressions for estimating muscle parameters in the thoracic and lumbar trunk for use in musculoskeletal modeling. J. Biomech. 45, 66–75.
Arjmand, N., Shirazi-Adl, A., Bazrgari, B., 2006. Wrapping of trunk thoracic extensor muscles influences muscle forces and spinal loads in lifting tasks. Clin. Biomech. 21, 668–675.
Bogduk, N., Johnson, G., Spalding, D., 1998. The morphology and biomechanics of latissimus dorsi. Clin. Biomech. 13, 377–385.
Chaffin, D.B., 1969. A computerized biomechanical model—development of and use in studying gross body actions. J. Biomech. 2, 429–441.
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.
Cholewicki, J., McGill, S.M., 1996. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. Clin. Biomech. 11, 1–15.
Delp, S.L., Loan, J.P., Hoy, M.G., Zajac, F.E., Topp, E.L., Rosen, J.M., 1990. An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. Biomed. Eng. IEEE Trans. On 37, 757–767.
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.
Garner, B.A., Pandy, M.G., 2000. The obstacle-set method for representing muscle paths in musculoskeletal models. Comput. Methods Biomech. Biomed. Engin. 3, 1–30.
Ghezelbash, F., Arjmand, N., Shirazi-Adl, A., 2015. Effect of intervertebral translational flexibilities on estimations of trunk muscle forces, kinematics, loads, and stability. Comput. Methods Biomech. Biomed. Engin. 18, 1760–1767.
Granata, K.P., Marras, W.S., 1993. An EMG-assisted model of loads on the lumbar spine during asymmetric trunk extensions. J. Biomech. 26, 1429–1438.
Gungor, C., Tang, R., Sesek, R.F., Foreman, K.B., Gallagher, S., Davis, G.A., 2015. Prediction models for the erector spinae muscle cross-sectional area. J. Biomech. Eng. 137.
Jaeger, R., Mauch, F., Markert, B., 2012. The muscle line of action in current models of the human cervical spine: a comparison with in vivo MRI data. Comput. Methods Biomech. Biomed. Engin. 15, 953–961.
Jensen, R.H., Davy, D.T., 1975. An investigation of muscle lines of action about the hip: a centroid line approach vs the straight line approach. J. Biomech. 8, 103–110.
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.
Jorgensen, M.J., Marras, W.S., Smith, F.W., Pope, M.H., 2005. Sagittal plane moment arms of the female lumbar region rectus abdominis in an upright neutral torso posture. Clin. Biomech. 20, 242–246.
Kruidhof, J., Pandy, M.G., 2006. Effect of muscle wrapping on model estimates of neck muscle strength. Comput. Methods Biomech. Biomed. Engin. 9, 343–352.
Marras, W.S., Granata, K.P., 1997. Spine loading during trunk lateral bending motions. J. Biomech. 30, 697–703.
Marras, W.S., Sommerich, C.M., 1991. A three-dimensional motion model of loads on the lumbar spine: I. Model structure. Hum. Factors J. Hum. Factors Ergon. Soc. 33, 123–137.
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., 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., Norman, R.W., 1986. Partitioning of the L4-L5 dynamic moment into disc, ligamentous, and muscular components during lifting. Spine 11, 666–678.
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.
Moga, P.J., Erig, M., Chaffin, D.B., Nussbaum, M.A., 1993. Torso muscle moment arms at intervertebral levels T10 through L5 from CT scans on eleven male and eight female subjects. Spine 18, 2305–2309.
Nussbaum, M., Chaffin, D., 1996. Development and evaluation of a scalable and deformable geometric model of the human torso. Clin. Biomech. 11, 25–34.
Rab, G.T., Chao, E.Y., Stauffer, R.N., 1977. Muscle force analysis of the lumbar spine. Orthop. Clin. North Am. 8, 193–199.
Reid, J.G., Costigan, P.A., Comrie, W., 1987. Prediction of trunk muscle areas and moment arms by use of anthropometric measures. Spine 12, 273–275.
Santaguida, P.L., McGill, S.M., 1995. The psoas major muscle: a three-dimensional geometric study. J. Biomech. 28, 339–345.
Schultz, A.B., Andersson, G.B., 1981. Analysis of loads on the lumbar spine. Spine 6, 76–82.
Seo, A., Lee, J.-H., Kusaka, Y., 2003. Estimation of trunk muscle parameters for a biomechanical model by age, height and weight. J. Occup. Health 45, 197–201.
Stokes, I.A., Gardner-Morse, M., 1999. Quantitative anatomy of the lumbar musculature. J. Biomech. 32, 311–316.
Suderman, B.L., Vasavada, A.N., 2012. Moving muscle points provide accurate curved muscle paths in a model of the cervical spine. J. Biomech. 45, 400–404.
Takashima, S.T., Singh, S.P., Haderspeck, K.A., Schultz, A.B., 1979. A model for semi-quantitative studies of muscle actions. J. Biomech. 12, 929–939.
Theado, E.W., Knapik, G.G., Marras, W.S., 2007. Modification of an EMG-assisted biomechanical model for pushing and pulling. Int. J. Ind. Ergon. 37, 825–831 (Musculoskeletal Load of Push–Pull Tasks).
Tracy, M.F., Gibson, M.J., Szypryt, E.P., Rutherford, A., Corlett, E.N., 1989. The geometry of the muscles of the lumbar spine determined by magnetic resonance imaging. Spine 14, 186–193.
Vasavada, A.N., Lasher, R.A., Meyer, T.E., Lin, D.C., 2008. Defining and evaluating wrapping surfaces for MRI-derived spinal muscle paths. J. Biomech. 41, 1450–1457.