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

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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

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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

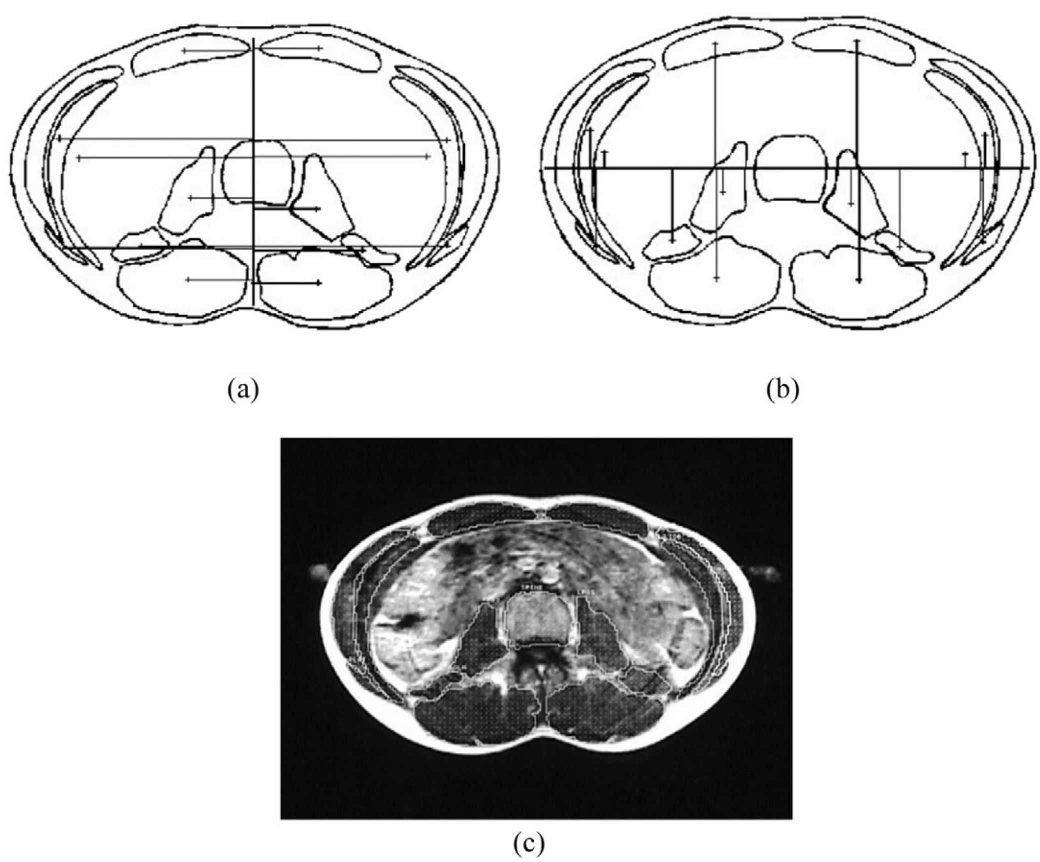

Fig. 1. Measurements of coronal plane moment-arms (a), and sagittal plane moment-arms (b) taken from each of trunk muscle centroids at the L3 level (Jorgensen et al., 2001); and cross-sectional areas (c) of a female subject at the L3 level (Marras et al., 2001).