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Computational model of the lumbar spine musculature: Implications of spinal surgery

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ABSTRACT

Background: The development of a comprehensive and detailed model of the musculature of the lumbar region is required if biomechanical models are to accurately predict the forces and moments experienced by the lumbar spine.

Methods: A new anatomical model representing the nine major muscles of the lumbar spine and the thoracolumbar fascia is presented. These nine muscles are modeled as numerous fascicles, each with its own force producing potential based on size and line of action. The simulated spine is fully deformable, allowing rotation in any direction, while respecting the physical constraints imposed by the skeletal structure. Maximal moments were predicted by implementing the model using a pseudo force distribution algorithm. Three types of surgery that affect the spinal musculature were simulated: posterior spinal surgery, anterior surgery, and total hip replacement.

Findings: Predicted moments matched published data from maximum isometric exertions in male volunteers. The biomechanical changes for the three different types of surgery demonstrated several common features: decreased spinal compression and production of asymmetric moments during symmetric tasks.

Interpretation: This type of analysis provides new opportunities to explore the effect of different patterns of muscle activity including muscle injury on the biomechanics of the spine.

1. Introduction

The complexity of the spine makes a complete understanding of its mechanical function difficult, particularly since the stresses and strains cannot be measured directly with non-invasive techniques. To describe the behaviour of the spine and its various components, biomechanical models are used where in-vivo studies are impractical.

All biomechanical models of the spine share one common feature; each must consist of an anatomical model of the spine and a means of distributing force to the components in this anatomical model.

There is little consistency between previous anatomical models with authors incorporating different numbers of muscles, using different measures of muscle area (physiological cross-sectional area (PCSA) or cross-sectional area (CSA)), grouping muscles differently with respect to activation and using values between 30 N cm^{-2} and 100 N cm^{-2} for the maximum muscle force intensity. Most of these differences stem from a lack of detailed anatomical information for the muscles of the lumbar spine. Without a 'correct' anatomical model that reflects the complex anatomy of the region, the model will be deficient in some aspect irrespective of the force allocation technique used. For instance, incorporating the detailed anatomy of the erector spinae muscle has the effect of reducing predicted spinal compression and shear, and also changing the direction of the shear (McGill and Norman, 1987). Predictions of spinal shear and compression are sensitive to changes in muscle lines of action, particularly during asymmetric loading (Nussbaum et al., 1995) and flexion (McGill et al., 2000). It has also been suggested that better correlations between model predictions and EMG data can be obtained from models incorporating accurate and detailed anatomy (McGill, 1996; van Dieën, 1997).

This paper describes a three dimensional anatomical model of the muscles of the lumbar spine. It incorporates the muscles reviewed by Hansen et al. (2006) as well as the detailed structure of the internal and external oblique muscles and the thoracolumbar fascia (TLF) thereby addressing some of the issues noted previously. To validate the proposed model, a pseudo force distribution technique is applied. This same technique is employed to explore biomechanical changes resulting from surgical injuries.

2. Methods

2.1. Anatomical model

A quasi-static 3D anatomical model of the lumbar spine was created. The model incorporates nine muscles; the multifidus, erector spinae, quadratus lumborum, psoas major, latissimus dorsi, rectus abdominis, internal oblique, external oblique and transverse abdominis.

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The model assumes that, 1) the nine muscles included are responsible for all of the moments produced across the lumbar spine and that each muscle is composed of fascicles; 2) any length change within a muscle/tendon complex is attributable to changes in the length of the muscle belly; 3) the orientation of muscle fibres within a fascicle is parallel to the direction of the fascicle; and 4) the thorax is rigid.

The model uses a local coordinate system for each vertebra from L_1 to S_1 (Fig. 1). Each is an orthogonal basis set with the *jk* plane parallel to the superior endplate of the vertebra. Flexion/extension moments act around *k*, lateral bend moments about *j*, and axial twist moments about *i*.

Geometry and size of the muscle fascicles were obtained from a variety of sources (Table 1). Some of these data are summarized in a review by Hansen et al. (2006). Where detailed anatomical descriptions of the bony attachment points were available, the corresponding 3D coordinates were determined by locating the anatomically described point on a rendered 3D reconstruction of the Visible Man (Visible Human Project®, National Library of Medicine, Bethesda, MD). For muscles where such detailed information was not available, the coordinates were derived by scaling and rotating the values reported by Stokes and Gardner-Morse (1999) by 1.1295 and 0.0345°, respectively, such that the points fitted the skeleton of the Visible Man. A description of each fascicle included in the model, and the corresponding attachment data are given in Tables A and B in the Supplementary material available online. The most posterior component of the internal oblique muscle (Int6) was assumed to contribute to the TLF, and as such, is not considered independently in the model.

Most muscle fascicles have an almost linear path between attachment points so a simple line of action was assumed. For the longissimus thoracis pars thoracis, iliocostalis lumborum pars thoracis, psoas major and internal and external oblique muscles, which do not have a linear path between attachment points, separate techniques were used to determine the lines of action.

The fascicles of longissimus thoracis pars thoracis that attach rostrally to the thoracic spine follow the contour of the spine. The model represents these fascicles using two linear segments; one from the thoracic attachment to T_{12} and the second from T_{12} to the lumbar/sacral attachment. Since the model assumes that the thoracic spine is rigid, the length of the first segment is constant. As each fascicle of the longissimus thoracis pars thoracis must pass posterior to T_{12}, an artificial origin was established at the T_{12} level by maintaining the original alignment of the fascicle in the *ik* orientation but changing the *j* value to force the fascicle to pass directly posterior to T_{12}. Steps were also implemented to ensure that in flexed postures the muscle fascicles remained posterior to the lumbar vertebrae.

Fascicles of the iliocostalis lumborum pars thoracis and some fascicles of the longissimus thoracis pars thoracis attach to the surface of the ribs. The model identified those fascicles that would pass in front of the ribs assuming a straight line of action between attachment points, and adjusted the line of action appropriately so that the fascicle remained posterior to the rib cage.

Table 1
Data sources for each of the muscles crossing the lumbar spine.

Muscle	Data source	Type of data
Multifidus	Macintosh et al. (1986)	Anatomical
	Bogduk et al. (1992a)	Anatomical
Erector spinae[a]	Macintosh and Bogduk (1987)	Anatomical
	Bogduk et al. (1992a)	Anatomical
Psoas major	Bogduk et al. (1992b)	Anatomical
Latissimus dorsi	Bogduk et al. (1998)	Anatomical
Rectus abdominis	Stokes and Gardner-Morse (1999)	Coordinate
Quadratus lumborum	Stokes and Gardner-Morse (1999)	Coordinate
Internal obliques	Stokes and Gardner-Morse (1999)	Coordinate
External obliques	Stokes and Gardner-Morse (1999)	Coordinate

[a] The erector spinae consists of the longissimus thoracis and the iliocostalis lumborum.

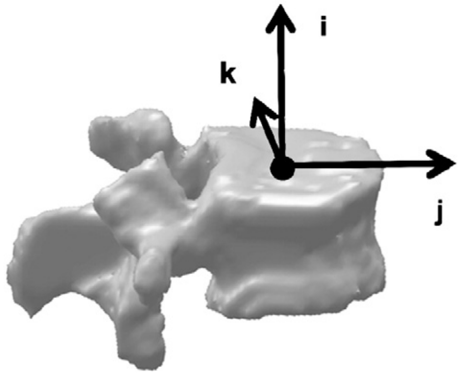

Fig. 1. The coordinate basis system used for each vertebra.

The psoas major muscle attaches the lumbar vertebrae and intervertebral discs (IVDs) to the lesser trochanter of the femur (Bogduk et al., 1992b). To achieve this distal insertion, the muscle (or its tendon) passes over the anterior surface of the ilium and hip capsule which, in the standing posture, is positioned anterior to the head of the femur. Thus, the line of action for the force generated by the psoas major muscle is along the vector from the spinal attachment to the anterior of the hip capsule.

The internal and external oblique muscles attach to the pelvis and the rib cage and wrap around the torso between these attachment points. The method described by Gatton et al. (2001) was used to determine the lines of action for these muscles. Four of the six components of the external oblique muscle (Ext1–4) exert their force caudally through the aponeurosis, which is continuous with the linea abla and Poupart's ligament. Assuming the linea alba is fixed (since it is firmly attached at both ends), the point of application of any forces generated by fascicles Ext1–4 is either the linea alba or Poupart's ligament, dependent on where the aponeurotic fibres continuous with the fascicles end. Assuming these aponeurotic fibres act in the same *ik* orientation as the fibres of Ext1–4, and that the linea alba ends 35 mm below the centre of the S_1 vertebral body, the method described by Gatton et al. (2001) was used to determine that Ext1 and Ext2 exert their force on the linea alba, while Ext3 and Ext4 apply their force to Poupart's ligament (Table B in supplementary material online).

The TLF is a structure that provides a means of attachment to the spine for the transverse abdominis muscle and parts of the latissimus dorsi and internal oblique muscles. The 3D model of the TLF reported by Gatton et al. (in press) was used to calculate the line of action for these muscles.

2.2. Estimation of forces and moments

Since the model is an anatomical representation of the lumbar spine, it does not contain a force distribution algorithm. To allow force and moment predictions to be made, a pseudo force distribution algorithm which involved applying published muscle activation data for specific tasks was used (Table 2). This approach was used rather than an optimization strategy as used by de Zee et al. (2007) because it reflects muscle activations as measured in life which an optimization strategy may not do. To apply this algorithm, it was assumed that, 1) muscles achieve their maximum active force in the upright posture; 2) 100% of the maximum active force is able to be voluntarily neurally activated by an individual; 3) several muscles are able to be activated at the same time to give a simultaneous contraction; and 4) muscle activation patterns do not change with posture.

Since the vertebral bodies were assumed to be rigid, movement occurred around the instantaneous centres of rotation (ICRs) (Pearcy and Bogduk, 1988). Although not included in the model, the dynamics