ELSEVIER

Journal of Biomechanics 41 (2008) 1450–1457

JOURNAL OF BIOMECHANICS

www.elsevier.com/locate/jbiomech
www.JBiomech.com

# Defining and evaluating wrapping surfaces for MRI-derived spinal muscle paths

Anita N. Vasavada[a,b,*], Richard A. Lasher[a], Travis E. Meyer[a], David C. Lin[a,b]

[a]*School of Chemical Engineering and Bioengineering, Washington State University, Pullman, WA, USA*
[b]*Department of Veterinary and Comparative Anatomy, Pharmacology and Physiology, Washington State University, P.O. Box 646520, Pullman, WA 99164-6520, USA*

Accepted 18 February 2008

**Abstract**

Muscle paths can be approximated in biomechanical models by wrapping the path around geometric objects; however, the process for selecting and evaluating wrapping surface parameters is not well defined, especially for spinal muscles. In this study, we defined objective methods to select the shape, orientation, size and location of wrapping surfaces and evaluated the wrapping surfaces using an error metric based on the distance between the modeled muscle path and the centroid path from magnetic resonance imaging (MRI). We applied these methods and the error metric to a model of the neck musculature, where our specific goals were (1) to optimize the vertebral level at which to place a single wrapping surface per muscle; and (2) to define wrapping surface parameters in the neutral posture and evaluate them in other postures. Detailed results are provided for the sternocleidomastoid and the semispinalis capitis muscles. For the sternocleidomastoid, the level where the wrapping surface was placed did not significantly affect the error between the modeled path and the centroid path; use of wrapping surfaces defined from the neutral posture improved the representation of the muscle path compared to a straight line in all postures except contralateral rotation. For the semispinalis capitis, wrapping surfaces placed at C3 or C4 resulted in lower error compared to other levels; and the use of wrapping surfaces significantly improved the muscle path representation in all postures. These methods will be used to improve the estimates of muscle length, moment arm and moment-generating capacity in biomechanical models.


*Keywords:* Modeling; Neck muscles; MRI; Wrapping surfaces

## 1. Introduction

Realistic definition of muscle paths in biomechanical models is necessary for accurately estimating muscle lengths and moment arms, which determine the force- and moment-generating capacities of a muscle. Muscle paths are most often represented in biomechanical models by straight lines, but modifications for more realistic paths include using "via" points connecting straight line segments (e.g., Delp and Loan, 1995; Kruidhof and Pandy, 2006) or modeling underlying constraints as geometric surfaces over which line segments must wrap (e.g., Arnold et al., 2000; Garner and Pandy, 2000). "Wrapping surface" or "obstacle-set" methods have been used in upper limb (Garner and Pandy, 2000) and lower limb models (Arnold et al., 2000) and result in muscle lengths and moment arms which are comparable to experimental measurements.

The implementation of geometric wrapping surfaces for muscle paths has not been evaluated in musculoskeletal models of the spine, which present many challenges for modeling and validating muscle paths. For many spinal muscles, the paths are not dominated by specific anatomical structures (e.g., underlying bone geometry, joint capsule or retinacula as in some limb joints). Because spinal muscles cross several intervertebral joints, there are many options for placement of wrapping surfaces. Further,

*Corresponding author at: Department of Veterinary and Comparative Anatomy, Pharmacology and Physiology, Washington State University, P.O. Box 646520, Pullman, WA 99164-6520, USA. Tel.: +1 509 335 7533; fax: +1 509 335 4650.
*E-mail address:* vasavada@wsu.edu (A.N. Vasavada).

0021-9290/$ - see front matter 
doi:10.1016/j.jbiomech.2008.02.027

experimental measures of muscle lengths and moment arms over the range of motion are usually not available to validate the modeled spinal muscle paths. More generally, the process for selecting parameters and evaluating the wrapping surfaces is not well defined for musculoskeletal models.

The general goal of this study was to develop objective methods to select and evaluate wrapping surface parameters (shape, orientation, size and location) for muscle paths that best approximate the centroid paths of muscles. These methods were applied to a model of the neck musculature, where our specific goals were (1) to optimize the vertebral level at which to place a single wrapping surface per muscle; and (2) to define wrapping surface parameters in the neutral posture and evaluate them in other postures. Neck muscle geometry was characterized from magnetic resonance imaging (MRI) data in seven head and neck postures. The neutral posture MRI centroid path data were used to define a wrapping surface (shape, orientation, size and location relative to the vertebral body center) for each vertebral level. The wrapping surfaces for the different vertebral levels were applied separately in all postures and evaluated by calculating the error between the modeled path and the centroid path. This metric quantified the improvement in the muscle path representation with wrapping surfaces compared to a straight line and was used to select the best vertebral level, if one existed, for wrapping surface placement.

## 2. Methods

### *2.1. MRI data acquisition and processing*

Axial proton density-weighted MR images (TR = 2500 ms; TE = 18 ms; slice thickness 5.0 mm; gap 1.0 mm) were obtained from the base of the skull to the second thoracic vertebra in one male subject with a 55th percentile neck circumference (Gordon et al., 1989) to identify muscle boundaries. T1-weighted images (TR = 400 ms; TE = 20 ms; slice thickness 3.0 mm; gap 0.5 mm) were obtained in the sagittal and coronal planes to define vertebral position and orientation. A wooden jig was used to hold the subject's head and neck in seven postures: neutral, 30° flexion, 30° extension, 30° axial rotation, 20° lateral bending, 6 cm protraction and 5 cm retraction (protraction and retraction are anterior and posterior translations of the head in the sagittal plane without any flexion or extension rotation). The protocol was approved by the Institutional Review Board of the Washington State University, and the subject provided informed consent.

Eighteen neck muscles were outlined bilaterally using image analysis software (3D-DOCTOR, Able Software, Lexington, MA), and the centroid on each slice was calculated (Fig. 1). The identification of individual muscles was validated by photographic cross-sectional data from the National Library of Medicine's Visible Human Project (Zheng et al., 2007), anatomical dissection and textbooks (Agur and Lee, 1991; Cahill et al., 1995; Dean and Herbener, 2000). The muscle centroid path was defined by lines connecting consecutive centroids. The first and last identifiable centroid points were considered to be the effective origin and insertion for the muscle.

The location of muscle paths and wrapping surfaces (described below) was defined relative to the vertebral body centers. Vertebral body centers were chosen as a reference point because they are more easily identified on MRI scans, rather than the joint centers between vertebrae, for which there are few quantitative descriptions in the literature. Vertebral body centers were calculated as the centroid of the four corners formed by the ends of the superior and inferior vertebral endplates on a midsagittal or coronal scan. For the neutral, flexed, extended, protracted and retracted postures, midsagittal scans were used to identify the anterior–posterior and superior–inferior coordinates of the vertebral body centers, and the medial–lateral coordinates were obtained from axial scans. For the lateral bent posture, a coronal scan was used to identify the medial–lateral and superior–inferior vertebral center coordinates, and the anterior–posterior coordinates were obtained from the axial scan. For the axially rotated posture, the endplate points were not always clearly identifiable on the sagittal or frontal scans due to the associated coupled rotations. The anterior–posterior and medial–lateral coordinates of the vertebral body center were obtained from axial scans, and the superior–inferior coordinates were interpolated between the two axial slices closest to the middle of the vertebra.

### *2.2. Wrapping surface parameters*

The model was implemented in Software for Interactive Musculoskeletal Modeling (SIMM; Motion Analysis, Santa Rosa, CA). Graphical

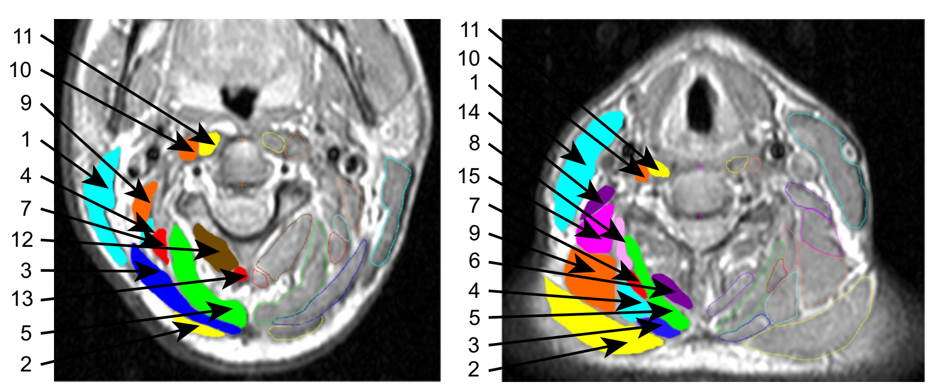


Fig. 1. Axial proton density-weighted MRI scan at the level of C2 (A) and C5 (B) of the subject in the neutral posture. Neck muscles are outlined and identified by number: 1 = Sternocleidomastoid, 2 = Trapezius, 3 = Splenius Capitis, 4 = Splenius Cervicis, 5 = Semispinalis Capitis, 6 = Semispinalis Cervicis, 7 = Longissimus Capitis, 8 = Longissimus Cervicis, 9 = Levator Scapulae, 10 = Longus Capitis, 11 = Longus Colli, 12 = Obliquus Capitis Inferior, 13 = Rectus Capitis Posterior Major, 14 = Scalenus Anterior, 15 = Scalenus Posterior. Sternocleidomastoid was defined by two segments below the level where it splits into two tendons attaching to the sternum and clavicle and one segment above that level. Trapezius was separated throughout its length into two subvolumes, one inserting on the clavicle and the other on the scapula. The scalene muscles were separated into anterior and posterior volumes, but the middle scalene could not be distinctly identified.