ELUCIDATION OF SPINE MUSCLE FUNCTION USING A 3D SIMULATION OF SPINAL KINEMATICS

William L. Buford, Jr., Clark R. Andersen, Anthony J. Muffoletto, Kim J.Garges, James W. Simmons

Orthopaedic Biomechanics Lab, Department of Orthopaedics and Rehabilitation, University of Texas Medical Branch, Galveston, TX

INTRODUCTION

Most descriptions of spinal muscle function are limited to qualitative descriptions relating at most the action in terms of extension, lateral bending and rotation (twist about a vertical axis). Compared with muscles of the extremities, for which extensive mechanical advantage (or moment arm) data is available, very little quantitative descriptions of spine muscles exist. This study develops a 3D kinematic structure of the thorax, defines the effective rotational axes of motion for intersegmental motion and constructs spline path models for muscles and ligaments of the back. Then the simulation is used to predict the most likely mechanical advantage for each muscle about the axes, the strain in ligaments and the excursion of muscle-tendon units.

MATERIAL AND METHODS

Development System

The simulation development environment is a dual 1.2GHz Pentium Xeon with Windows 2000 using Visual C++ v5.0, and OpenGl with the GLUT Library. The graphics driver is the Nvidia Quadro4 900XGL 128Mb graphics processor. In addition to mouse and keyboard interactive methods, this system utilizes pop-up menus with control widgets and 6 DOF control using a Spaceball (Spaceball model 2003, Spacetec IMC Corp., Lowell, MA). Programs developed in C++ and openGL are transferable between NT and Unix systems with minor program modification. Use of the system for simulation of the extremities is described in [1].

Structures for the spine kinematic model are derived from axial computerized tomography (CT) slices of the NLM Visible Human (male). The frozen CT structure is used because the slices are spaced at one-mm (maximum vertical resolution). Also, because the data set was built to maximize planar resolution, the in-plane pixel size varies from .53 to .94 mm/pixel. The images are run through the MIMICS interactive software package that creates triangular polygons representing each bone. MAGICS software (MIMICS and MAGICS are from Materialise, Inc) is used where required to edit and combine the polygonal files. Files (in .stl format) for each bone then serve as the base level structures in the openGL kinematic hierarchy.

Definition of Effective Axes

The ability to manually adjust and dynamically alter (with 6 DOF) effective axes of motion is provided within the kinematic structure. Up to three axes were defined at each articulation using interactive control with the Spaceball. **Figure 1** depicts the axes defined for each spinal segment. Initial placement of axes is based upon generalized knowledge from the literature. Limitations in range-of-motion were set first based upon the work of White and Panjabi [2], then through iterative monitoring of subsequent motion corrected based upon joint congruence and bone segment interaction.

Definition of Muscle-tendon Paths

The prior work in our lab [1] developed muscle-tendon path models for the extremities using B-Splines with several possible blending functions and three types of control points (bone relative, tendon relative, or floating). Most control points were of the bone relative type, representing a rigid constraint or soft tissue pulley point. The floating type provided for sliding along the surface of a bone when within a certain region of a bone surface. Tendon relative allowed for the origination or connection of one tendon/muscle to another tendon or otherwise dynamically altering surface. Using this same procedure, the major muscles of

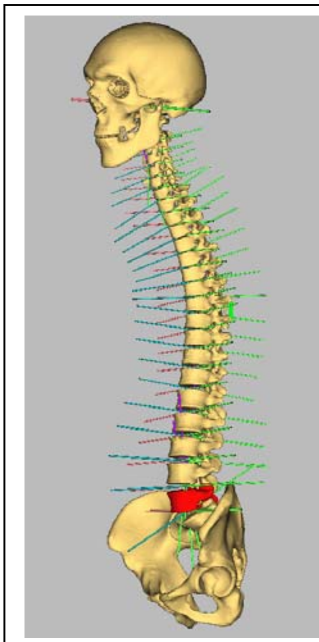

Figure1. Spinal structure: Occ-C1 and C1-C2 have 2 DOF, remainder have 3 DOF.

the back and spine were defined.

RESULTS

Figure 2 is three positions of the spine simulation data structure including preliminary defined axes of motion (3DOF for all but atlanto-occipital with 2 and atlanto-axial with 1). The entire structure is nearly 900,000 triangular polygons (ranging from 6000 [C6] to 130,000 [pelvis]. Twenty-eight bones and 73 axes are linked in the hierarchical kinematic structure. B-Spline curve paths are included to represent some of the spine muscle models. The left and right images represents linked rotation of all spinal segments in full twisting motion or longitudinal rotation. Spinal motions for each primary function (flexion-extension, lateral bending, and twist[rotation about vertical axes]) are linked in the simulation so that resultant muscle-tendon models are viewed and studied in real-time.

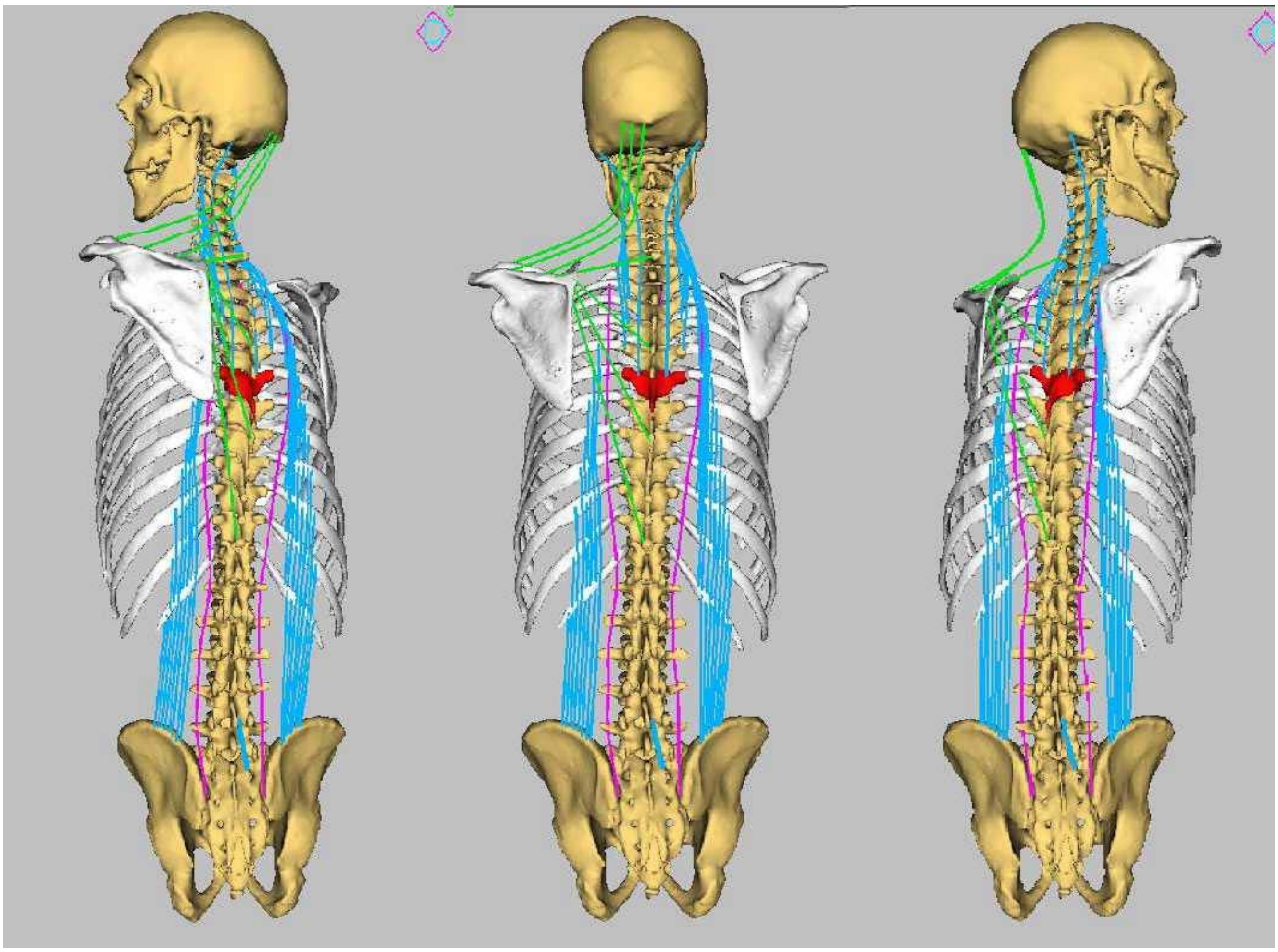

Figure 2. Kinematic structure of the spine with B-spline curve models depicted for some of the muscles – the iliocostalis, longissimus, one of the rotatores, and the left trapezius. These are perspective views representing full twist from left to right.

Functional results include the elucidation of rotatore muscle function. For the S1-L4 Rotatore Longus, for example, the effective moment arm for rotation (CCW) about the vertical axis averaged just under one cm through less than 3 degrees ROM, 5 cm for rotation about the extension axis through about 16 degrees ROM and less than 0.5 cm for right lateral bending through about 4 degrees ROM. Other quantitative results include predicted strain in ligaments and the total excursion of a muscle unit through all possible combinations of motion.

CONCLUSIONS

The 3D-simulation system developed for simulation of the extremities has been used to successfully define an interactive, 3D simulation of the spine. With the definition of kinematic structure and muscle/tendon/ligament models, essential parameters such as moment arms and strain can be predicted and studied in a real-time, interactive environment. Clarification of primary function (such as the mechanical advantage of the Rotatore Longus reported here) is one example of the simulation effectiveness. Otherwise, the simulation is proving to be a valuable research tool in the rapid generation of hypotheses through interactive, real-time 3D visualization.

REFERENCES

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2. White, AA, Panjabi, MM, "The Basic Kinematics of the Human Spine - A Review of Past and Current Knowledge," *Spine*. 3(1):12-20, 1978.

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