A SIMULATION FOR DEFINITION OF ARM AND LEG KINEMATIC STRUCTURES

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INTRODUCTION

In order to obtain a visual and quantitative verification of the appropriateness of one, two, and three degree-of-freedom models for motion, this work develops an interactive system for the independent adjustment and definition of multiple degree-of-freedom linkage systems representative of human leg and arm motion. The system is built so that, once the kinematic structure is defined, control points for interactive definition of muscle and tendon parameters may also be adjusted and defined, thus providing interactive, 3D musculoskeletal modeling and simulation.

All kinematic transformation nodes are built as linkages within an openGL hierarchical structure. The structure for independent adjustment of each axis of motion required tracking the inverse of all transformations applied to the axis during visualization and adjustment. The inverse is applied to all structures below the axis of interest so that only the axis is affected during 3D adjustment. The result is a kinematic structure definition program with which the user interactively builds the kinematic model. The program provides unlimited rotational degrees of freedom and the definition of linear and curve path models for all skeletal muscle/tendon units.

MATERIALS and METHODS

The development environment was recently converted from a Sun Unix system to Windows NT and Microsoft Developer Studio 97. We utilize 400 Mhz Pentium II Xeon systems with Visual C++ v5.0, OpenGl and the GLUT Library. Graphics drivers are the AccelEclipse II and the AccelGalaxy with Evans & Sutherland’s Realimage technology. 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)..

Structures for this kinematic model are derived from axial computerized tomography (CT) slices of fresh-frozen cadaver specimens. One-mm thick slices spaced at 1 mm are used for the joint areas that require the greatest resolution. One mm thick slices spaced 5 mm apart are used for the mid shaft areas of bones. This approach helps to maintain highest detail in critical areas and save on structure size where such detail is not needed.

Each extremity was derived from a fresh cadaver (28 yr old male) obtained through the Texas willed body program. The arm was separated from the thorax at the scapular-thoracic and the clavicular-sternum junctions. The leg was separated at the mid-line of the pelvis and included half of the sacrum. The limbs were scanned on a General Electric Computerized Tomography scanner (GE Model 9800). The images are run through a UTMB developed interactive software package that outputs stacked contours and also create triangular polygons representing each individual bone [1].

The simulation program reads in each bone polygon file and interactively creates the kinematic system, adjust (position and orientation) the linked axes of motion (up to three per diarthroidal joint), and save the defined structure and model. This is followed with the interactive definition of muscle/tendon paths.

RESULTS and DISCUSSION

Results are described for the definition of an upper and lower extremity kinematic structure. Once the geometries are created for each bone using the edge detection and solid modeling software, the program is run. The initial hierarchical structure exists with three independent rotational degrees of freedom for each diarthroidal joint arbitrarily placed at the proximal-most point of each bone. The user then enters the axis transformation section of the program. Beginning with the primary joint motion, usually flexion-extension, each axis is manipulated and placed in its proper position and orientation. An example result for the pronation-supination axis of the forearm is depicted in Figure 1. Note that for such a joint, the visual cues available through iterative control of overall structure position (using a virtual mouse trackball) while manipulating the axis (using a spaceball), followed with joint rotation (using a knob rotation widget) affords a convincing confirmation of a realistic joint axis definition. For a more complex joint, such as the carpo-metacapal joint of the thumb, one first defines the flexion-extension axis, then the abduction-adduction axis that is linked to the FE axis. A third axis for internal-external rotation (approximately parallel to the long axis of the metacarpal bone) can then be defined as a third revolute if required.

Once the kinematic model is defined, the basis for math modeling of muscles at joints is created. This is realized in the simulation through interactive adjustment of control points that serve as parameters in models for effective muscle-tendon paths. Currently, the simulation provides for the choice of three models: straight lines between points, a B-spline, and a polynomial.

The lower extremity simulation (Figure 2) consists of 31 bones made up of 84,192 triangular polygons and 30 control points for each bone (for the definition of tendon/muscle control points). It includes the following kinematic linkages:

Hip - Three degrees-of-freedom (DOF) in the hierarchical order: Flexion/Extension (FE), Abduction/Adduction (AbAd), and Internal/External (IE) rotation.
Knee - Two DOF in the hierarchical order: FE, IE.
Ankle -Two DOF in the hierarchical order: FE, DP (Dorsiflexion-plantarflexion at subtalar joint).
Digits - Metatarsal-phalangeal - FE and AbAd for each ray; Phalanges - FE axis for each PIP and DIP.

The lower extremity model thus consists of a 26 degrees-of-freedom kinematic linkage. At each joint, the first revolute is set as flexion-extension. The second, when present, is for abduction-adduction, and the third, when present, is for internal-external rotation. For some two degree-of-fredom joints the second linked revolute may be for IE or ABAD.

The upper extremity model (Figure 3) consists of 35 bones of 76,058 triangular polygons and a total of 1050 control points for tendon/muscle parameter definitions. It contains the following kinematic linkages:

Shoulder - Three DOF in the order: FE. AbAd, IE.
Elbow - one DOF for FE
Forearm - one DOF for Pronation-Supination (PS).
Wrist - two DOF for FE, and Ulnar/Radial (UR) deviation.
Thumb - two DOF for FE, AbAD at CMC joint, two DOF for FE, AbAd at MP ; one DOF for FE at DIP.
Fingers - two DOF at each MP joint for FE, and AbAd, one DOF at each PIP and DIP for FE.

The upper extremity model is therefore a 28 DOF kinematic linkage. The revolutes are set in the same manner as those for the lower extremity.

The Figures represents the current state of this simulation development. One muscle/tendon unit has been defined for a simple prototype biceps brachii. The muscle shape is a simple surface formed by rotating a Gaussian distribution about a line from a distal and proximal tendon control point. As the forearm rotates under user interaction (sliding an angle control widget on a pop-up menu), volume is maintained within the muscle surface and so the muscle bulges as angle is decreased. This muscle/tendon unit was designed to test the utility of the program and to assess the speed by which it can render while simultaneously calculating and updating surface model deformations. The result with the muscle modeled is a complete structural redraw at a flexion rate of 2-3 degrees per second in the PII 400 Mhz system with the AccelEclipse II accelerator.

The system is proving to be an efficacious research tool in the visualization and verification of kinematics models, and is targeted for new applications in medical education in musculoskeletal mechanics, and clinical applications in computer aided prosthesis design and interactive surgical planning. Plans for the immediate future include comparison of visually defined revolutes with those derived analytically in the work of Van Sint Jan [2], completion of muscle/tendon definitions for the major units in the arm and leg, and further comparison of model generated data such as moment arms with those experimentally measured.

Acknowledgements

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2. Van Sint Jan, S., D. Giurintano, D. Thompson, M. Rooze. Joint kinematics simulation from medical imaging data. *IEEE Transactions on Biomedical Engineering*, 44(12), 1175-1184, 1997.

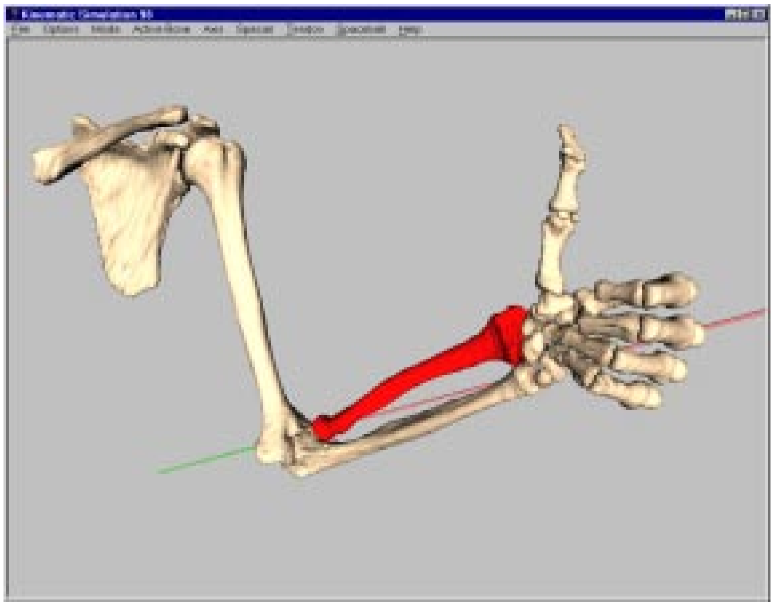

Figure 1. A view (3D with perspective) of the left upper extremity model depicted while at mid-pronation during rotation about the pronation-supination axis . Typically, the user will adjust an axis into a position and orientation, observe joint congruence during motion, make fine adjustments, and repeat until visual optimization is confirmed.

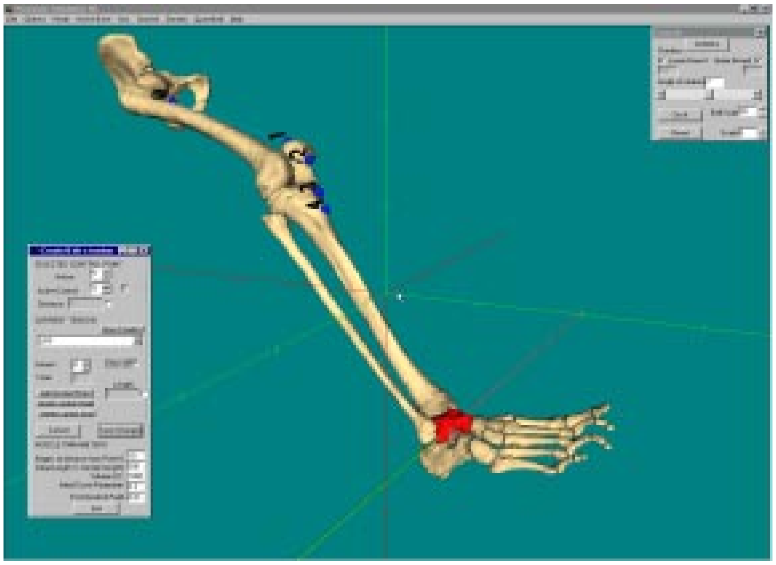

Figure 2. Anterior-lateral view of the lower extremity simulation. At this point the user has just defined four parameters for an initial definition of the vastus-intermedius muscle tendon path. At the lower left is the Create/Edit tendon dialogue box and the upper right is the Controls widget for rotation at a selectable joint axis. Flexion-extension at the ankle joint has been selected.

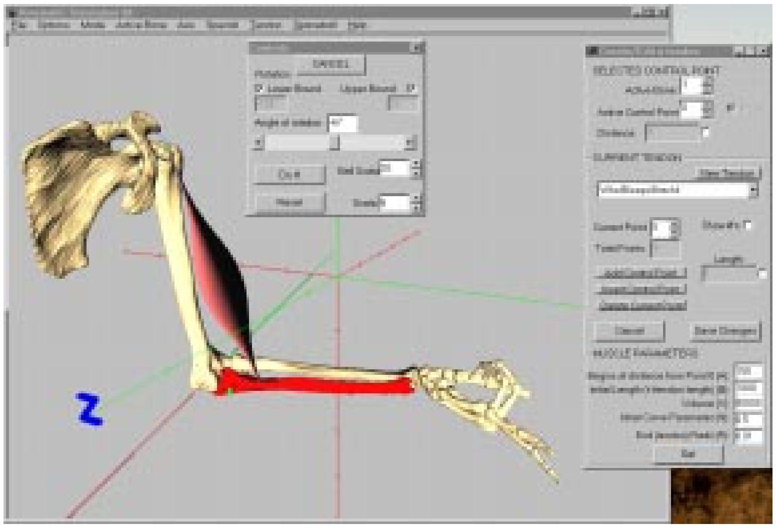

Figure 3. The upper extremity model is shown in elbow flexion with a simple path defined for a prototype biceps muscle. The muscle is a simple deformable 3D surface defined to test the speed of the system while recalculating and updating a 3D surface shape during elbow flexion-extension.