Influences of the Location of Vertebral "IAR" on Cervical Spine Kinematics

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Abstract—Different spine models have placed the IAR at various locations in the spine; more commonly, the central region of the intervertebral disk, the middle region of the subjacent vertebra, and the central region of the vertebral body. A computer simulation model of the cervical spine (C2-T1) was developed to investigate sagittal plane kinematics for different placements of the vertebral axis of rotation. Stiffness of the motion segment units was modeled with rotational springs. The combined loading vector applied to the spine replicated the in vitro experimental test results generated in our laboratory. Equal stiffnesses of each vertebra were used. The difference in force magnitude amongst the different cases was less than 1% of the applied load. Although the changes in rotational magnitudes were small, the relative differences varied not only with the different models, but also amongst the different vertebral levels.

I. Introduction/Background

An important kinematic / biomechanical variable used to characterize the motion of human joints is the Instant Axis of Rotation (IAR). The IAR is a path that identifies where one body will rotate relative to another body at a given instant in time. The point of rotation will move in space when the vertebral body's motion comprises both a translational and rotational component over a given interval of time. It often serves as a standard for motion-pattern analysis, and represents the "fulcrum point" for computing moment arms in bending due to muscle and ligamentous contributions. Knee kinematics have been documented to have repeatability in identifying this parameter as well as showing variances in the IAR patterns for degenerative knee conditions [10].

Different spine models have placed the IAR at various locations in the spine; common positions are the central region of the intervertebral disk, the middle region of the subjacent vertebra, and the central region of the vertebral body [6] [8] [11]. This study examined the effects of placing the IAR at a confined point for each of these three regions in a computer simulation model used to investigate cervical spine extension mechanics.

The *in vivo* cervical spine consists of a series of interconnected spinal bodies that exhibit a complex coupled motion behavior. The human spine was simulated with a simple model in which the cervical vertebrae were rigid bodies connected with rotational springs. When set in motion, these springs stored energy and developed an internal torque proportional to the relative rotation at the corresponding spinal level.

Cervical spine kinematics is often analyzed using only one or two functional spinal units in an attempt to understand its most basic types of motion [5] [7] [9]. Simultaneous rotation and translation have been identified as the characteristic motion of a functional spinal unit during flexion and extension [11]. However, to gain a full appreciation of the cervical spine's movement, the entire region from C2 to T1 should be analyzed over its full range of motion. Rotation is typically the only value used in the literature to quantify the sagittal plane motion of the entire cervical spine. For flexion and extension the average range of motion is 35 degrees [5].

II. Analysis

We have developed a biomechanical testing protocol to study the in vitro extensional mechanics of the intact and instrumented cervical spine. In this experimental protocol, the spine was subjected to a combined loading state that consisted of an extensional moment and axial compressive force. The spine was inverted and fixed at C2-body. Motion was applied to the cervical spine via a vertically aligned actuator pinned to a shaft and linear bearing at an offset distance, as shown in fig. 1. As the actuator traveled down, the joint coupling the actuator to the shaft and linear bearing allowed free rotation and free translation leaving the spine unconstrained in the sagittal plane. This set-up allowed investigation of spinal motion due to a single degree of freedom input. The computational models which were used to validate the mechanics of this protocol were also used to investigate the placement of the spine's axis of rotation.

The cervical spine's kinematics were simulated using rigid body mechanics. For simplification each vertebra was allowed one rotational degree of freedom and assigned a stiffness value (i.e. a rotational spring for each functional spinal unit). Knowing this stiffness, k, and the angular offset at a vertebral level, theta, the torque, T, at that level was computed by:

$$T_i = k * \text{theta}_i \tag{1}$$

The torque at each of these levels was found to verify the magnitude of the loading vector found at the actuator. This was computed from the equation:

$$F = T_i / d_i \quad (2)$$

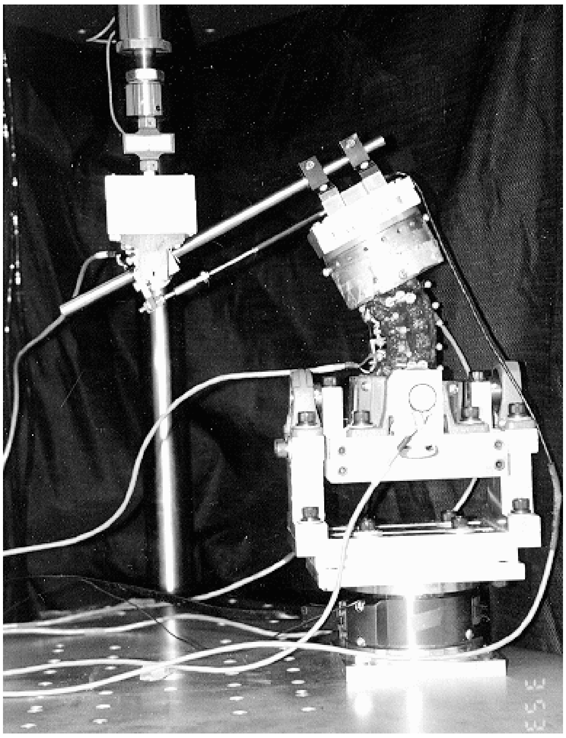

Fig. 1. Experimental setup for cervical spine extension testing

where F was the force in the actuator divided by the cosine of the global rotational offset, and d is the perpendicular distance from the line of action of F to each of the individual rotational springs.

III. MATERIALS AND METHODS

Computer simulations were developed and analyzed using the software package Working Model 2D™ (Knowledge Revolution Inc.) which utilizes animation based on Lagrangian mechanics. A simplified geometric model of the cervical spine (C2 to T1) was constructed based on digitized lateral radiographs and morphological data [3]. The stiffness of the intervertebral disk and surrounding ligamentous and musculature structure were modeled as linear rotational springs. The stiffness values used at all of these rotational springs were of the same magnitude and were determined from an earlier study by means of iteration and comparison to the experimental data. Although a true "instant axis of rotation" would undergo translations as well as rotations, the translational movement of the IAR of the cervical spine is confined to a small region. Therefore, the rotational spring was used to reduce the model's complexity and computational demand.

The joint which coupled the spine to the displacement controlled actuator was assembled so that it would allow free rotation and free translation while undergoing a vertical displacement. This was accomplished by placing kinematic constraints in the model's background which would only allow the slider mechanism to move along a vertical path, while rotating with the shaft that connected the spine to the actuator. Furthermore, the shaft was allowed to translate through the slider mechanism due to slotted constraints placed on the shaft as shown in fig. 2.

The simulations were driven by a combined loading vector similar to that of the in vitro spine tests performed on fresh human cadaveric spines in our laboratory. The load was initiated by the vertical displacement of the actuator, but transferred to the shaft via the linear bearing which could only maintain a normal surface contact. The line of action of this normal force vector also represents the line perpendicular to the moment arms which verify the torques computed at the rotational springs.

Three different spine models were constructed in which all variables remained constant, except for the placement of the rotational springs. The three locations of the axis of rotation, or spring connection, were the center of the vertebral body; the middle of the subjacent intervertebral disc; and the center of the subjacent vertebral body.

IV. RESULTS

The rotation at each vertebral level was obtained as well as the expected internal torque at these levels. The torque values were indeed equal to the rotations times the assigned stiffness value. Other values computed by the simulation were the translation occurring at the slider joint, and the force component registered at the actuator. Both the cumulative rotations, fig. 3, and the individual rotations, fig. 4, are shown for each of the three different spine models.

Greater total rotation of the cervical spine occurred when the IARs were placed at the intervertebral disc and the least

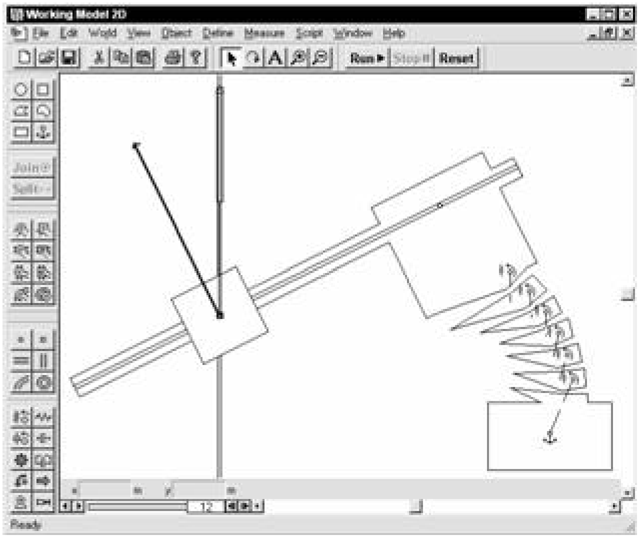

Fig. 2. Working model simulation showing the loading vector acting at the slider mechanism

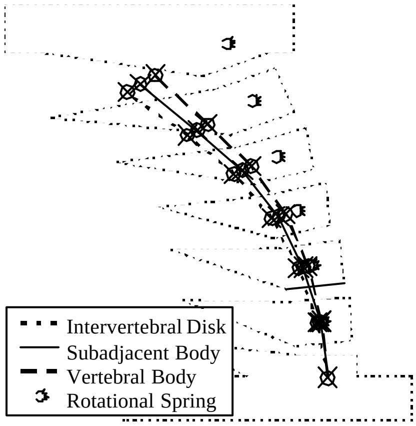

Fig. 3. Location of IAR for each of the three spine models at maximum displacement of actuator.

amount occurred for placement at the vertebral body. The applied force was greatest when the center of rotation was placed at the subjacent body. Less force resulted when the IAR was located at the intervertebral disc. Note that the difference in force magnitude amongst the different cases was less than 1% of the applied load.

V. DISCUSSION / CONCLUSION

The magnitude of rotations and reaction forces did not vary widely amongst the spine models due to the small dimensions of the vertebral bodies and the assumption of equal rotational stiffness at each spinal level. Variations among the three models in the placement of the IARs were only a few millimeters (<15mm). Although the changes in magnitudes of rotations and reaction force were small, the relative difference in rotations varied not only with the different models, but also amongst the different vertebral levels.

The results of this study show that the IAR is probably not a good diagnostic measure of degenerative spinal conditions. The size of the cervical spine, especially individual functional spinal units, is too small to identify accurate landmarks which will correctly identify the path of the IAR. The inherent errors of calculating an IAR are probably larger than the smallest resolution of an imaging system used to diagnose cervical spine instability.

The important findings of this study came from the observation of the spine under a combined loading vector at large angular rotations. In these conditions, the moment profile in the spine is shown to depend on the curvature of the spine as well as the line of action of the loading vector.

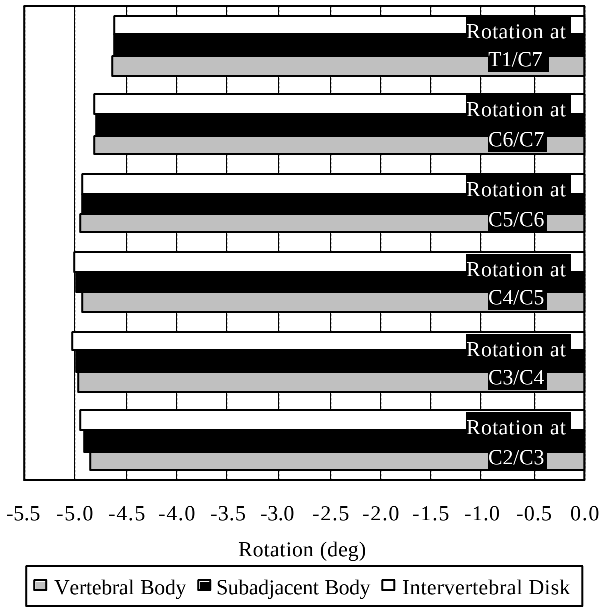

Fig 4. Comparison of relative rotation for each spinal unit among the three different spine models.

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