A Three-Dimensional Nonlinear Kinematic Finite Element Model of the Human Cervical Spine Under Dynamic Inertial Loading

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INTRODUCTION

State-of-the-art finite element models were developed, calibrated, validated, and exercised to realistically simulate the kinematic response of the human head and neck during any general three-dimensional acceleration. A specific case was exercised, with the exclusion of musculature, of our general hypothesis that an in vitro model can be used to test the feasibility of an in vivo finitie element model and to provide motion input data for individual motion segments for the said in vivo model. The models were developed based on motion analysis of ligamentous cervical spines, cadaveric motion analysis at the Medical College of Wisconsin (MCW), and from human research volunteer (HRV) data acquired at the National Biodynamics Laboratory (NBDL) in New Orleans.

The models exhibit biofidelic motion on the individual motion segment level, as validated by cadaveric data. Previously reported models have been validated for head motion only. Our model was validated for head motion as well as individual vertebral motion with cadaveric data for extension, flexion, and lateral inertial loads.

METHODS

Complete kinematic data sets from cadaveric studies performed at the Medical College of Wisconsin's Biomechanics Research Laboratory were obtained. Four unembalmed cadaveric human head and neck specimens, were mounted on a specially designed mini-sled pendulum. A low pulse acceleration profile with a peak of 8 g and duration of 15 milliseconds (ms) at T1, with the pendulum having an impact velocity of 5 mph and a high pulse acceleration with a peak of 14 g and duration of 15ms at T1, with a pendulum impact velocity of 7.5 mph were selected. This information was used as a standard in the calibration of the model. Data obtained included accelerations for the head and T1, angular rotational rates for the head, and displacements in three orthogonal directions for the head and C2 through C7.

Using data compiled by Williams and Belytschko (Williams and Belytschko, 1981) based on the work of Liu, et al., Francis and Lanier anatomic points representing "key points" of the vertebral bodies were used to develop the structural geometry utilizing TrueGrid® (XYZ Scientific Applications, Inc., Livermore, CA) mesh generating software.

Material properties were taken from the literature, when available, and modified based on the quasi-static mechanical testing using an in-house MTS servo-hydraulic system.

A masked prediction study was done to ensure that the model's properties were accurately described. Acceleration profiles from the NBDL, different from those of

MCW, were utilized so that numerical results would be accurate when compared to the experimental data from HRVs. The acceleration profiles utilized in the validation process were chosen specifically to match that used by Wismans (Wismans, et al., 1986) and de Jager (de Jager, et al., 1994). In addition to providing external validity, it allowed for direct comparison of this model to other previously developed models.

RESULTS AND DISCUSSION

A perfect agreement between the measured and calculated values would result in a correlation coefficient of 1.0. The correlation of the x displacement for frontal impact simulations had a minimum coefficient of 0.94. This exceeded the values of current and previous researchers of 0.7. In comparison of a low pulse 45° orientation run, the correlation of the x and y displacement for the oblique impact simulation was 0.9.

The model was also exhibited physiological phenomenon. The phenomenon of coupling was demonstrated because the model is novel in its use of accurate anatomic structures, such as the facets, and contact analysis.

In the external validation phase, the correlation value was exceeded for eighty-nine percent of the NBDL test subjects for the x-displacement at all acceleration levels in flexion runs. The correlation coefficient for the overall response for all test subjects for each acceleration profile exceeded 0.9 for the oblique runs.

SUMMARY/CONCLUSIONS

The model developed can satisfactorily represent the dynamic displacement and, therefore, dynamic acceleration behavior of the head and neck in frontal (minus x), lateral (plus y) as well as oblique (minus x plus y). This is the first finite element head neck model to be validated for frontal, lateral, and oblique impact simulations by comparisions with experimental results. Previous researchers have validated their models in a plane that corresponds to a single orthogonal axis. Oblique validation is a more severe validation test because of the three-dimensional motion involved. Multi-planar motion exists due to the direction of the load, as well as the coupling phenomenon. The agreement obtained with the oblique test is comparable to the test with single-plane motion. This agreement is an example of the robustness of the model.

This model can be further developed for the investigation of injury mechanisms. It is capable of calculating stresses within materials. It would be possible to compare calculated disc loads with experimentally known structural failure loads, and the likelihood of injury.

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