INJURY BIOMECHANICS RESEARCH
Proceedings of the Thirty-Third International Workshop

PROBABILISTIC RESPONSE OF A VALIDATED AND VERIFIED PARAMETRIC CERVICAL SPINE FINITE ELEMENT MODEL

W. L. Francis, A.R. Bonivtch, D.E. Moravits, G.R. Paskoff, B.S. Shender,
C.R. Bass, S.R. Lucas, F.A. Pintar, N. Yoganandan, M.H. Koebbe,
B.H. Thacker, and D.P. Nicolella

ABSTRACT

Biological systems are often modeled using computational methods such as finite element modeling because of the complex nature of system being analyzed. However, most computational analyzes fail to account for the variability and uncertainty of the model inputs and boundary conditions, which leads to an inability to predict a probability of injury in the given biological system. The goal of this study is to calculate the probabilistic response of a cervical spine finite element model by incorporating variability into the model inputs such as soft tissue properties and geometry. The geometry of the finite element model was created by using a set of geometry parameters that can be measured from Computed Tomography (CT) scans. The parameters were measured from CT scans both male and female volunteers. Material properties for the soft tissues of the cervical spine were determined from literature and experimental data. Once the data was collected, random distributions were fit to both the geometry and material data. The software package NESSUS was used to calculate the probabilistic response of the cervical spine model. This methodology can be used to predict the probability of injury not only in the cervical spine but many other biological systems.

INTRODUCTION

Computational analysis methods such as the finite element method (FEM) are widely accepted in computational biomechanics as an important tool used in the prediction and analysis of biological structures subjected to injurious loading conditions. These methods are ideally suited to simulate the behavior of complex biological structures that often include complicated geometry, non-linear material behavior, and time dependent phenomenon. Predicting the probability of injury is a major goal of computational biomechanics. However, the actual probability of injury is not computed per se; only quantities such as the stresses and strains in the hard or soft tissues are computed and compared to a measure of the bone or tissue strength in order to estimate the risk of injury. A major limitation of the application of computational methods in injury research is their inability to account for variability and uncertainty in important system parameters such as loading, material properties, and anatomy and the effect of this variability on the computed model response. Thus, the usefulness of conventional FEA is severely limited in predicting actual probabilities of injury.

Biological systems have a large amount of variations in both material properties and geometries and incorporation of measures of this variability and uncertainty is required in a numerical analysis in order to compute a probability of injury (Thacker et al 2006). Our goal is to capture the probabilistic response of the cervical spine by incorporating distributions and standard deviations for both the tissue material properties and the geometry as shown in the schematic in Figure 1.

The geometry of the cervical spine finite element model was built using a discrete set of geometric parameters that can be measured from Computed Tomography (CT) scans. These parameters were measured from CT scans of 100 volunteers, 50 males and 50 females. The material properties of the soft tissues of the cervical spine were determined from both the literature and experimental data. Random variable distributions were fit to the geometric and material data. The probabilistic response of the cervical spine model was determined using the probabilistic software package NESSUS® to run the simulations and calculate the responses given the statistical properties for the model variables. The resulting probabilistic spine model gives us the ability to determine the probability of a particular response that would result in injury. By having the ability to predict the probability of injury, the model has many applications in the field of biomechanics.

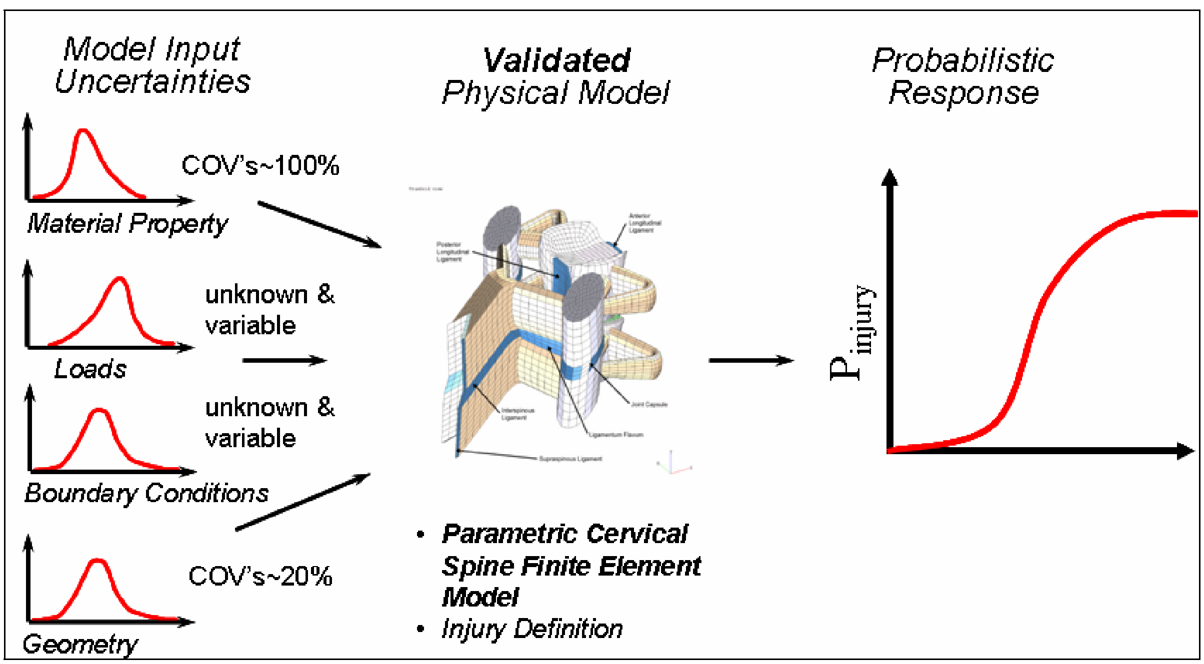

Figure 1. Schematic showing the process of propagating model input variability into a finite element model to determine a probabilistic response

METHODS

A verified and validated parametric finite element model of the C5/C6 motion segment was used to determine the probabilistic response. The FEM was created by using the Truegrid® preprocessing software to build a mesh based on a set of geometry parameters that define the surface geometry of each vertebra. A total of 35 geometry parameters define each vertebral level.

The mesh consists of a combination of brick, shell and spring elements. Boundary conditions were applied such that they recreated the constraints of the experiments being modeled. For this analysis, the FEM of the C5/C6 motion segment was subjected to a 2 N-m moment in both flexion and extension. During the quasi-static loading the degree of rotation of the C5 vertebra with respect to the C6 vertebra was recorded.

During the validation and verification process, deterministic values were used for both the geometry and material properties of the FEM of the C5/C6 motion segment. For the probabilistic analysis those deterministic values were used as mean values and a lognormal distribution was assumed for each variable. As shown in Table 1, all variables except for the cross section areas of the anterior longitudinal ligament (A.L.L.) and the posterior longitudinal ligaments (P.L.L.) were assumed to have a coefficient of variation (C.O.V.) of 10%.

Table 1. Random variable inputs to the probabilistic FEM

	Mean	StDev	C.O.V.
Bulk Modulus A.L.L. (psi)	3000000	300000	10.0%
Bulk Modulus P.L.L. (psi)	4200000	420000	10.0%
I.S.L. Stiffness (N/mm)	0.125	0.0125	10.0%
L.F. Stiffness (N/mm)	0.25	0.025	10.0%
J.C. Stiffness (N/mm)	0.089	0.0089	10.0%
Bulk Modulus Annulus (psi)	2783000	278300	10.0%
Cross Section A.L.L. (mm^2)	12.4853	0.8551	6.8%
Cross Section P.L.L. (mm^2)	15.0556	0.995	6.6%

With both material properties and geometry random variables defined the NESSUS® probabilistic engineering analysis software was used to perform the probabilistic analysis. The problem is set up in NESSUS® so that both the geometry and the material properties considered random, Figure 2. NESSUS® will first perturb the geometry by running the TrueGrid software to build the mesh and then that mesh is used in the LS-Dyna model where the material properties are perturbed. For this analysis, a Mean Value (MV) response using forward difference was used to look at the probabilistic response of the C5/C6 motion segment. With the two geometry variables and the six material property variables, NESSUS® initiated a total of 9 finite element runs.

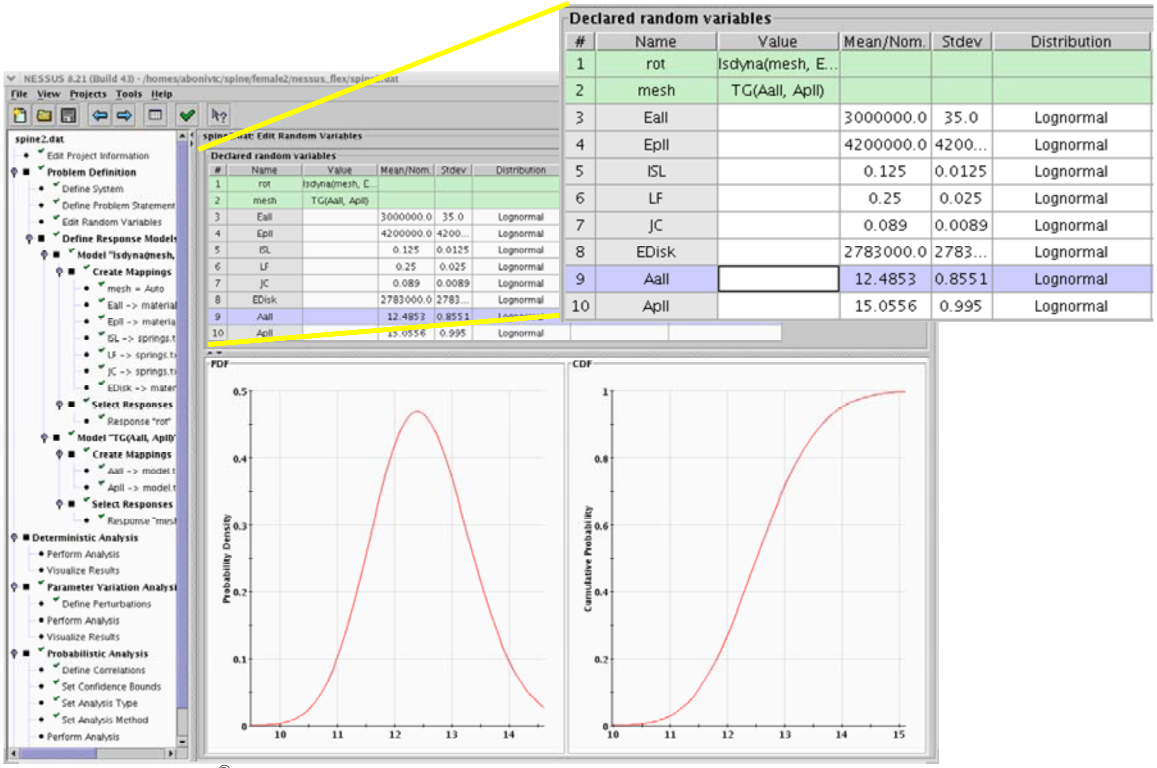

Figure 2. NESSUS® allows for random variables to be defined with a mean, standard deviation and distribution type.

RESULTS

The results of the forward difference mean value analysis were compared to experimental results obtained by Wheeldon et al. (2006). Figure 3 shows the experimental results with one standard deviation corridors along with the probabilistic response of the FEM. The results show that even when assuming a relatively small C.O.V. of 10% there can be large variations in the response, particularly in flexion.

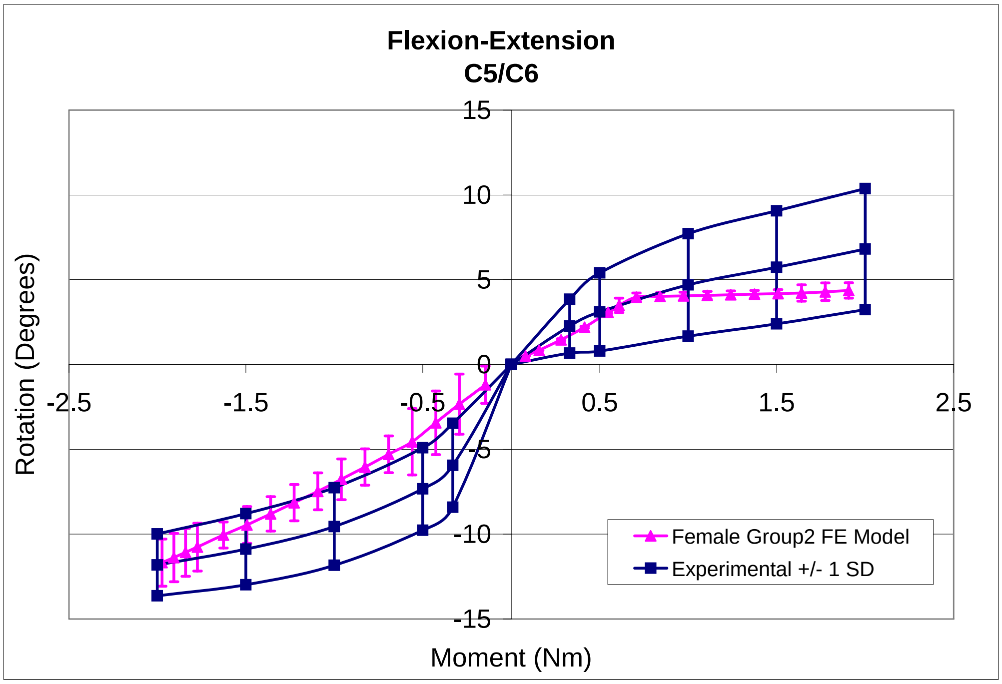

Figure 3. Probabilistic response of a C5/C6 motion segment in flexion and extension shown with C5/C6 experimental data +/- 1 SD

The NESSUS® software also has the capability to return importance values for the random variables at each point in the loading curve. Figure 4 shows how the importance values of the variables change throughout the range of motion. When the applied moment is low thie disk modulus has low importance but at higher moments the importance is increased. This added information can help focus the researcher's efforts towards variables that most influence the response.

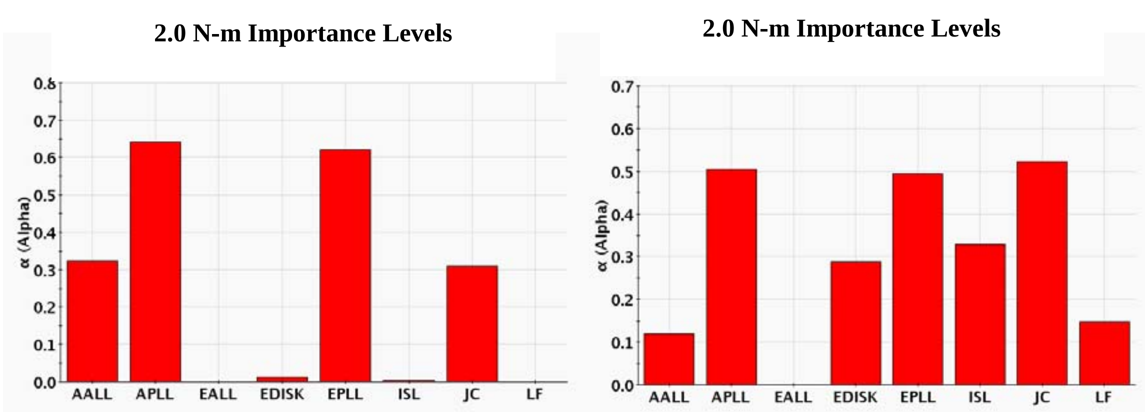

Figure 4. Importance levels for flexion at 0.5 N-m (right) and at 2.0 N-m (left)

CONCLUSIONS

A probabilistic finite element model of the C5/C6 motion segment has been created and run in order to determine a probabilistic response for flexion and extension. The results of the probabilistic analysis were compared to experimental data and show that variability in both geometry and material properties needs to be accounted when using a numerical model to make predictions of biological responses

ACKNOWLEDGEMENTS

We would like to thank the Naval Air Warfare Center Aircraft Division (NAWCAD) for their continuing support of this project. We would also like to acknowledge Frank Pintar and Narayan Yoganandan at the Medical College of Wisconsin and Dale Bass and Scott Lucas at the University of Virginia for sharing their results from the PMHS specimen tests.

REFERENCES

THACKER, B.H., RIHA, D.S., FITCH, S.H.K., HUYSE, L.J. AND PLEMING, J.B., (2006), “Probabilistic engineering analysis using the NESSUS® software,” Stuctural Safety, 28, pp. 83-107.

WHEELDON, J.A., PINTAR, F.A., KNOWLES AND S., YOGANANDAN, (2006), “Experimental flexion/extension data corridors for validation of finite element models of the young, normal cervical spine,” J Biomechics, 39, pp. 375-380.

W. Loren Francis
Reliability and Engineering Mechanics Section
Mechanical and Materials Engineering Division
6220 Culebra Rd, San Antonio, TX 78238-5166
Phone: (210) 522-6647 Fax: (210) 522-6965
Email: loren.francis@swri.org

Amber R. Bonivtch
Reliability and Engineering Mechanics Section
Mechanical and Materials Engineering Division
6220 Culebra Rd, San Antonio, TX 78238-5166
Phone: (210) 522-2129 Fax: (210) 522-6965
Email: amber.bonivtch@swri.org

Donald E. Moravits
Reliability and Engineering Mechanics Section
Mechanical and Materials Engineering Division
6220 Culebra Rd, San Antonio, TX 78238-5166
Phone: (210) 522-2891 Fax: (210) 522-6965
Email: donald.moravits@swri.org

Glenn R. Paskoff
Code 4621
MS 5, Bldg. 2187
48110 Shaw Road
Patuxent River, MD 20670-5304
Phone: (301) 342-8469 Fax: (301) 342-8503
Email: PaskoffGR@navair.navy.mil

Barry S. Shender
Bldg. 2187, Lab 1A92
48110 Shaw Road, Unit 5
Patuxent River, MD 20670-1906
Phone: (301) 342-8881 Fax: (301) 342-8876
Email: barry.shender@navy.mil

C.R. Dale Bass
Center for Applied Biomechanics
University of Virginia
1011 Linden Ave
Charlottesville, VA 22902
Phone: (434)-296-7288 Fax:
Email: bass@virginia.edu

Scott R. Lucas
Center for Applied Biomechanics
University of Virginia
1011 Linden Ave
Charlottesville, VA 22902
Phone: (434)-296-7288 Fax:
Email: slucas@virginia.edu

Frank Pintar
Department of Neurosurgery
Neuroscience Research Labs 151
VA Medical Center
5000 W. National Ave
Milwaukee, WI 53226
Phone: (414) 384-2000 Fax: (414) 384-3493
Email: fpintar@mcw.edu

Narayan Yoganandan
Department of Neurosurgery
Neuroscience Research Labs 151
VA Medical Center
5000 W. National Ave
Milwaukee, WI 53226
Phone: (414) 384-3453 Fax: (414) 384-3493
Email: yoga@mcw.edu

Matthew Koebbe
GADAB Engineering
#123
1406 East Main Street, Suite 200
Fredericksburg, TX 78624
Phone: (830) 456-3879
Email: matthew@koebbe.net

Ben H. Thacker
Reliability and Engineering Mechanics Section
Mechanical and Materials Engineering Division
6220 Culebra Rd, San Antonio, TX 78238-5166
Phone: (210) 522-3896 Fax: (210) 522-6965
Email: ben.thacker@swri.org

Daniel P. Nicolella
Reliability and Engineering Mechanics Section
Mechanical and Materials Engineering Division
6220 Culebra Rd, San Antonio, TX 78238-5166
Phone: (210) 522-3222 Fax: (210) 522-6220
Email: daniel.nicolella@swri.org