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Development of a Parametric Finite Element Model of Lower Cervical Spine in Sagital Plane

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Abstract— **A parametric 2D finite element model was developed for lower cervical spine (C3-C7) in sagital plane in this research. Being parametric, this model facilitates making changes in the geometrical sizes as well as omitting or modifying some parts of it in order to build a new model with special purposes. Application of geometrical parameters, the values of which differ from one vertebra to the other one due to each one's morphology, utilizes deriving equations which define geometrical shape of the model of both soft tissue and hard tissue. Then a Macro is programmed with Ansys Parametric Design Language (APDL), which runs under FEA software, ANSYS9.0. As the result, a good fit was observed when validated the model with existed experimental results in sagital plane. The comparison shows more reliable results out of this 2D model than cited 3D complex models in flexion and extension.**

I. INTRODUCTION

CERVICAL spine injuries could have life threatening consequences. This has made biomechanical studies on this region to be essentially needed. Different approaches have been established in biomechanical spine modeling due to each one's purpose. Among finite element models, parametric ones facilitate much easier reconstruction of different vertebrae of different levels rather than CT scan derived models. Making different models with various parts for different patients is so easy using a parametric model. The parametric model developed in this research is programmed in APDL which utilizes the application of desired geometrical parameters, material properties and the type of elements used (for ligaments especially) in a simple way. In this research using a non-complex 2D model was studied in sagital plane in comparison with 3D models.

II. MODELING METHOD

The first step of this research approach is to define 15 geometrical parameters for each vertebra available in the literature based on anatomical and morphological specifications as shown in Fig. 1 [1], [2]. These parameters could be defined in this region due to the anatomical similarities of the 3rd to 7th vertebra of human cervical spine. Thus, parametric equations which describe the geometry of the model are derived. This model is made up of hard tissue (vertebral body, cortical and posterior elements bone) and soft tissue (inter-vertebral disks including nucleus, annulus and fibers, Ligaments with two interchangeably selectable options of linear cable and nonlinear springs, and articular facets) which in spite of their integrity and continuity they preserve their independency to each other and to the changes in the size of parameters.

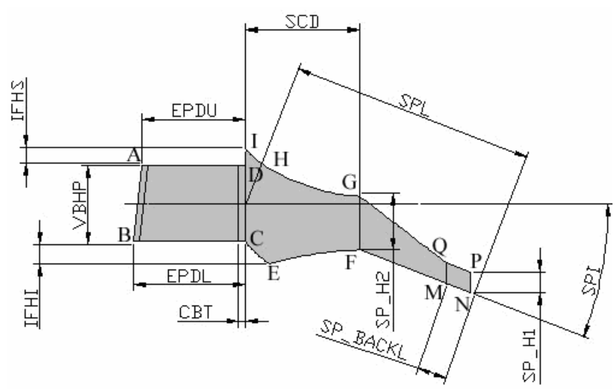

Fig. 1. Parameter definition

A. Hard Tissue

Firstly the hard tissue consisting of the following parts are modeled in sagital plane.

Vertebral body intersection with sagital plane
Reflect of posterior arc on sagital plane
Spinal process intersection with sagital plane

The equations describe the geometry of aforementioned parts when value of each parameter is assigned for each set of fifteen parameters per vertebra. The used material properties for hard tissue are shown in Table I [2].

Then, in order to develop a desired motion segment of the cervical spine, the hard tissue of adjacent vertebrae should be assembled. The inferior facet of the upper vertebra was assumed to be positioned on the superior facet of the lower vertebra and the intervertebral angle was calculated. Therefore rotation and displacement of a vertebra is

TABLE I
HARD TISSUE MATERIAL PROPERTY

Material	E(MPA)	ν
Vertebral Body Cortical Shell	1e4	0.29
Vertebral Body Cancellous Core	1e3	0.29
Posterior Elements	3.5e3	0.29

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calculated with respect to the upper one. Then a 0.3 mm gap was considered for interfacet distance in the assembling process.

B. Soft Tissue

Soft tissue is consisted of the following parts which will be added to the model by the program after bones are modeled.

- Intervertebral Disks (Nucleus, Annulus and endplates)
- Ligaments (ALL, PLL, CL, LF and ISL)[1]
- Facets

Intervertebral disks are positioned between vertebrae. Annulus is modeled as fibers (cable elements) embedded into a matrix of collagen. Used material properties and geometrical specifications are shown in Table II [3].

In modeling ligaments, a new approach was envisaged in the macro program which makes it easy for the user to study the behavior of the model in two different modes of modeling. The first mode is modeling ligaments with elastic linear cables with three options for elastic module shown in Table III [4].

TABLE II
INTERVERTEVRAL DISK MATERIAL PROPERTIES AND GEOMETRICAL SPECIFICATIONS

Material	E(MPa)	ν	Area
Nucleus	1e6	0.499	50% Disk
Annulus Matrix	4.2e6	0.455	50% Disk
Annulus Fibers	4.5e8	0.3	20% Matrix
Endplate	5e8	0.4	----

TABLE III
YOUNG'S MODULUS OF ELASTICITY OF CERVICAL SPINE LIGAMENTS

Ligaments	E1 (Mpa)	E2 (MPa)	ε_{12} *	Eavg (MPa)
C2-C5				
ALL	43.8	26.3	12.9	35.05
PLL	40.9	22.2	11.1	31.55
LF	3.1	2.1	40.7	2.6
ISL	4.9	3.1	26.1	4
C5-C6				
ALL	28.2	28.4	14.8	28.3
PLL	23	24.6	11.2	3.45
LF	3.5	3.4	35.3	4.15
ISL	5	3.3	27	28.3

*Denotes the strain transition between the two bilinear moduli (E1 and E2).

The second mode is modeling ligaments as non-linear springs using force-deflection data in Table IV [2], [4]. Used data for Length and cross-sectional area of cervical spine ligaments are shown in the Table V [4] which will be modified by *R* ratio explained later.

An initial 0.3 mm gap and line-to-line low friction contact represents the soft tissue of interfacet joint when supported by capsular ligaments in this model.

TABLE IV
LIGAMENTS' FORCE-DEFLECTION DATA

ALL		PLL		LF		ISL		CL	
F	ΔL	F	ΔL	F	ΔL	F	ΔL	F	ΔL
0	0	0	0	0	0	0	0	0	0
32	1.2	28	1.2	30	1.8	8.5	1.3	1.5	1.7
60	2.5	50	2.2	55	3.5	10	2.8	29	3.6
81	3.7	66	3.2	71	5.1	23	4.1	52	5
100	4.8	79	3.4	95	6.9	28	5.5	86	7.5
115	6	88	5	105	8	32	7	104	9.5
								108	9.5

F: Force (N), L: Deflection (mm)

Every time the programmed macro is run, hard tissue is modeled and desired user-assigned segment is assembled, then keypoints are defined which locate the position of two-node elements (ligaments and annulus fibers) attachment points, and then mesh network is generated. Available nodes' data at the keypoints are then written in files and are reread at the time of creating the sort of elements. This helps the flexible model to preserve its continuity against any changes in size of parameters, used parts of the model and mesh generation in various motion segments.

TABLE V
LENGTH AND CROSS-SECTIONAL AREA OF CERVICAL SPINE LIGAMENTS

Ligaments	Area (mm²)	Length (mm)
C2-C5		
ALL	11.1	18.8
PLL	11.3	19.0
LF	46.0	8.5
ISL	13.0	10.4
C5-C6		
ALL	12.1	18.3
PLL	14.7	17.9
LF	48.9	10.6
ISL	13.4	9.9

Modeled C5-C6 motion segment is shown in Fig. 2.

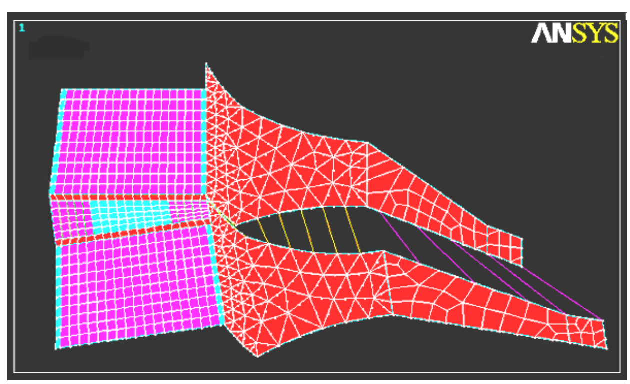

Fig. 2. C5-C6 motion segment of the model

III. RESULTS AND VALIDATION

In order to validate this 2D model, an *R* ratio was calculated, which is the ratio of the 2D model area (considering the virtual thickness) and 3D models' area. Areas of the ligaments and fibers sections as well as the load values were multiplied by *R* in this model.

[1] ALL: Anterior Longitudinal Ligament, PLL: Posterior Longitudinal Ligament, CL: Capsular Ligament, LF: Ligamentum Flavum, ISL: Interspinous Ligament

The validation was performed by comparison of kinematical behavior of C5-C6 motion segment under two load cases of flexion and extension on the upper endplate of C5. Each loading was studied under three normal preloading conditions set at 0, 50 and 100 N to the upper endplate of C5. Thus, 6 different load cases were studied for each motion segment per ligament mode (24 cases per motion segment). Table VI [5] includes average results of the current model in comparison with cited literature. The

TABLE VI
COMPARISON OF A PARAMETRIC MODELED C5-C6 MOTION SEGMENT WITH EXPERIMENTAL DATA (DEGREE FOR 1.8 NM)

	Current*	Lopez*	Moroney	Goel	Maurel*	Voo
FLE	5.26	3.7	5.55	5.7	7.8	4.28
EXT	-3.18	-2.9	-3.52	-3.69	-8.7	-3.5

* Parametric models

results stand for the study of the behavior in the E1 mode of ligaments as it was in its strain zone and the results appear most fitting in this range of loading. Fig. 3 illustrates the comparison. It is recognized that the results of the current model are in a better fit with the experimental data in sagital plane rather than complex 3D models.

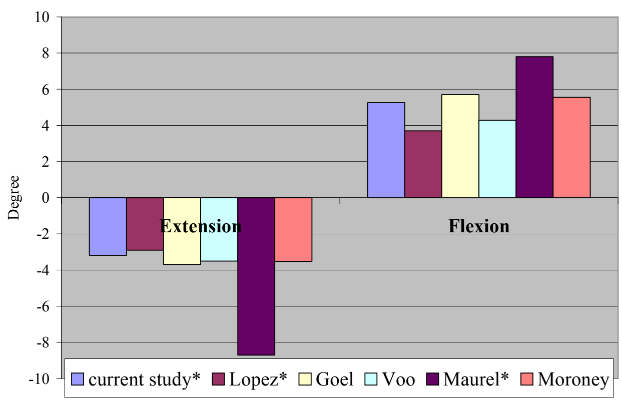

Fig. 3. Comparison of a C5-C6 motion segment deflection with experimental data (Degree for 1.8 Nm), * Parametric models

Fig. 4 shows the results of C5-C6 motion segment step-loading from 0.2 to 1.8 Nm, using both modeling modes for ligaments as elastic cables and non-linear springs.

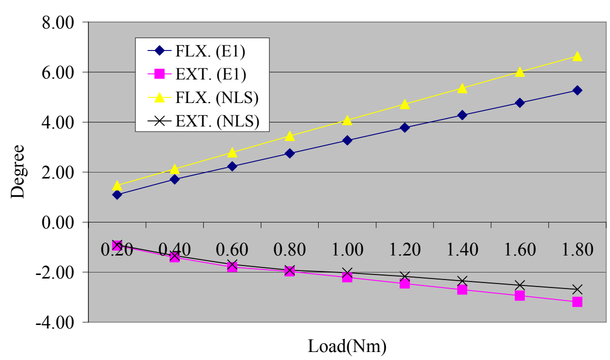

Fig. 4. C5-C6 Flexion-Extension Step-Loading Results.
E1: Elastic cable ligaments, NLS: Non-linear spring ligaments

The meshed assembled model of cervical spine (C3-C7) is shown in Fig. 5. The results of different levels' deflection in degree for the same loading and preloading conditions are illustrated in Fig. 6.

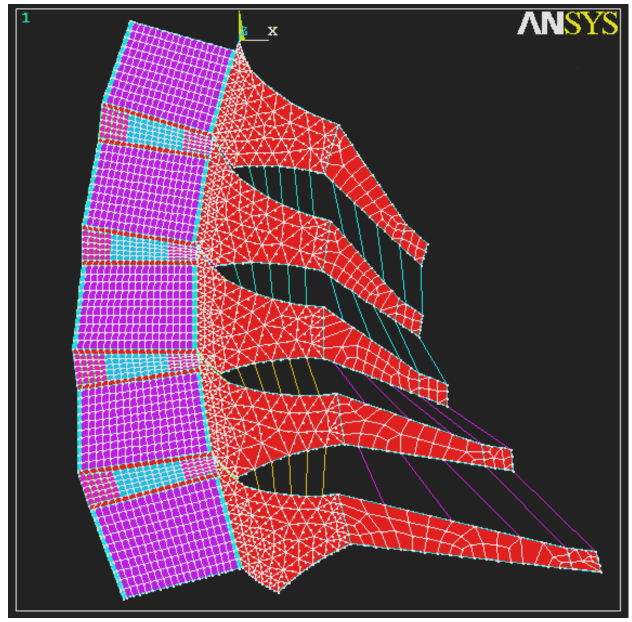

Fig. 5. C3-C7 Assembled Model

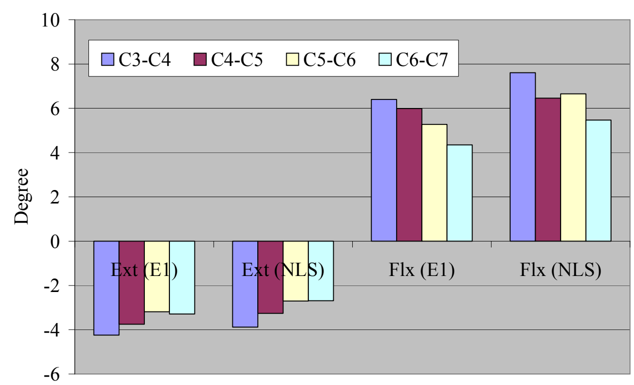

Fig. 6. C3-C7 Flexion-Extension Results in Degree (1.8 Nm)

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