Development and in Vitro validation of Goat Specimen-specific Finite Element Models of Functional Cervical Spine Units for Biomechanical Research

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INTRODUCTION: Finite Element (FE) models validated against cadaveric experiments in conjunction with *in vivo* data have been widely used in biomechanical studies to understand the underlying reasons for various spine-related disorders and assess the efficacy of associated treatments. However, cadaveric studies using the human spine are associated with certain limitations, such as difficulty in acquiring fresh specimens, old age, and poor quality of donor specimens [1]. Similarly, clinical studies using imaging are limited to low-quality image data and lack of histology data, which make building credible computational models with high fidelity challenging or even impossible [2]. Considering such limitations, large animal models imitating the human spine have been shown to be a suitable alternative for use in mechanobiology and biomechanical research, where the micro-mechanics of tissue are studied [3,4]. Among animal models, the goat spine is a suitable specimen for spinal research and investigation of the efficacy of instrumentation due to its resemblance to humans in bone microstructure, content, and remodeling [5, 6]. Many similarities exist between the vertebrae of goats and humans, although there are considerable differences in certain dimensions [1]. Due to the differences in the macrostructure of the goat and human spines, constructing an animal model requires a thorough understanding of the goat's biomechanical data, notably the range of motion (ROM). Limited data exist on the biomechanics of goat cervical spine, and the existing models are for ovine spines based on a single anatomy, which is validated against a set of cadaveric data. The purpose of this study was to develop a workflow for the construction and validation of the specimen-specific finite element (FE) models of a set of mechanically tested goat cervical functional spine units (FSU) so they can be used for the simulation of various treatment settings.

METHODS: *In vitro* studies: 3 fresh adult (3-5 year-old) goat cervical spine specimens (C1–C7) were obtained. The specimens were in healthy condition and free of any noticeable abnormality or disease. The muscle and soft tissue of the specimens were carefully removed, keeping the ligaments, capsules of facet joints and bony structures intact. The specimens were preserved at a temperature of −20 °C. The specimens were thawed at room temperature, dissected to isolate C4-5 segments. The specimens were CT-scanned then potted cranially and caudally in resin blocks. Each specimen was mounted on a universal test frame (TA Instruments 5500) with the lower block fixed and the upper block attached to the actuator of the machine using a universal joint attachment. A six-camera system (Optitrack) was used to track 3D motion clusters attached to actuator blocks. Compressive loads of 300 N were applied for 100 cycles at 1 Hz and the corresponding axial displacement of the actuator was recorded (**Figure 1**). Each of the three specimens was tested in healthy and following complete nucletotomy (injured) states.

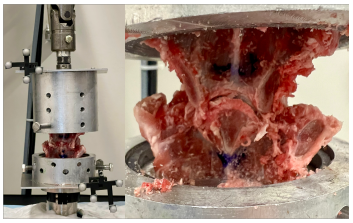

Figure 1. in Vitro experiment setup for compression testing of Goat FSUs.

FE Modeling: Specimen-specific CT images of the goat cervical FSUs used in the experiment were segmented and converted to 3D anatomical geometries using Dicom-to-Print (D2P, Oqton Inc.). The 3D models of the vertebra were imported into Simplware (Synopsys Inc.) to create volumetric meshes for Finite Element (FE) analysis. The meshed geometries were then imported into Abaqus (Simulia Inc.) for the creation of three FE models of C4-C5 functional spine units (FSU) with connecting tissues and material details (**Figure 2A-D**). The segmented images were meshed with linear tetrahedral elements about 1 mm in size for the bone and 0.55 mm for the cartilage, and 0.5 mm for the disc tissues. The bone mesh size was based on a previous convergence study [7]. A similar mesh size was used for the soft tissues since the parameters of interest were displacements rather than localized stress fields. Hybrid linear element integration was used for cartilage, nucleus pulposus, and annulus fibrosus when modeled as isotropic. The FE models were then modified to simulate the two states of the injured state (nucleotomy). Each model was then validated against the average actuator displacements for 300N compression loading for both states. The validated models were then used to simulate the anatomical loadings of flexion/extension, left and right bending, and left and right axial rotation under 1.5 Nm bending load, and the corresponding segmental motion was compared against a previous study by Dong et al. for further validation [1].

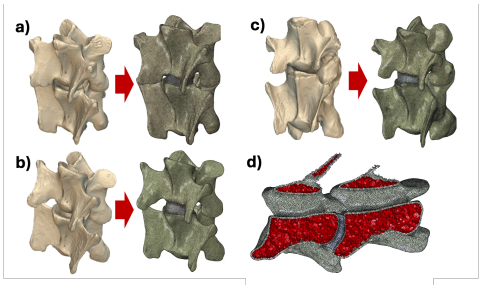

Figure 2. A) FE FSU model I, B) FE FSU model II, C) FE FSU model III and D) section view of FE FSU showing the cortical and cancellous bone segments.

RESULTS: The average displacement motions of the three FE FSUs in both healthy and injured states were slightly lower than the cadaver data but still close to one STD range of the in vitro data (**Figure 3**). Removal of the nucleus did not result in a noticeable change in the compression displacement of the cadaveric specimens unlike the FE FSUs where the displacement increased slightly in the injured models. When comparing the anatomic ROM of the FSUs at 1.5 Nm load against the data reported in the literature for the Goat C-spine, the data were close to average and were within one SD of the data in all loading conditions except in right rotation [1].

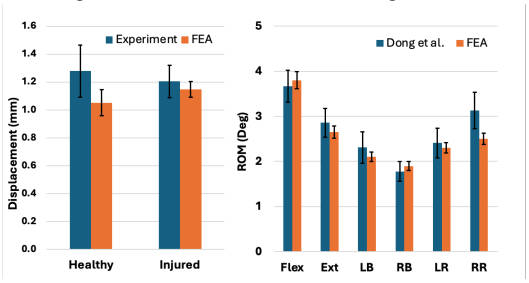

Figure 3. Left: Compression disp. of FE models versus in house cadaver data. Right: Comparison of anatomical ROM of FE models vs. literature at1.5 Nm bending load.

DISCUSSION: A major challenge in developing validated FE models for spine biomechanics research is the availability of good-quality human spine specimens. Data obtained from testing of large animal spine specimens such as the goat can be a better alternative due to the abundance of healthy specimens, availability of high-resolution CT data, and histology data. The developed workflow discussed in this study for creating finite element models from CT images of functional spinal units (FSUs) can be applied to investigate various parameters of interest related to spine biomechanics. This research marked the initial verification of a set of FSU models, offering a novel validation of the intricacy needed to replicate an in-vitro axial compression and anatomical loading procedure. The devised FSU models and techniques can be employed to evaluate the immediate mechanical impacts of medical interventions like spinal fixation, disc replacement, minimally invasive procedures etc. and quantify the biomechanical parameters such as load sharing, stress and strain distribution on the hard and soft tissue and joints such facet joints which are not practical to monitor in *in vitro* or *in vivo* settings.

SIGNIFICANCE: The use *in vitro* experiment data can help to develop specimen-specific *in silico* models with high fidelity, which can be used for the simulation of variety of spinal conditions and disorders and be used to evaluate and optimize the biomechanical efficacy of existing and emerging surgical treatments.

REFERENCES: [1] Dong+*JOSR*, 2023; [2] Sainoh+SPINE, 2014; [3] Newell+SPINE, 2014; [4] Dong+CLINICS, 2015; [5] Lao+JORS, 2014; [6] Pearce+ECM, 2007; [7] Jones+JBIOMECH, 2007.

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