Interlaboratory Mechanical Testing of Novel 3D-Printed Cervical Vertebrae

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INTRODUCTION: While composite models have become standard in assessing the fixation and stability of total joint replacements, such models for the cervical spine are notably lacking. To address this gap, we recently developed a novel additively manufactured model of a cervical vertebra, including a cancellous bone core and cortical shell.[1] The objective of this study was to evaluate the cervical vertebral body model by comparing it to cadaveric data and assessing the reproducibility of the mechanical response between two different testing configurations at different laboratories.

METHODS: A total of 20 models of the C5 vertebra were printed using an UltiMaker S5 Pro (UltiMaker; Utrecht, NL) at two different cortical thicknesses, 0.30 (N=10) and 0.15mm (N=10). Testing under pure compression loading was conducted at two different laboratories to assess reproducibility. One laboratory, lab 1, tested each model using an AMTI Vivo Simulator and a second laboratory, lab 2, used an MTS 858 Mini Bionix servohydraulic load frame (Figure 1), with both force and displacement being continuously monitored throughout testing. Destructive pure compression was applied to each model at 0.2mm/s. Additionally, each lab assessed either implant subsidence or torsional testing on each model. At lab 1, subsidence testing using a titanium alloy cage implant was performed under stepwise pure compression with 5 steps from 100N to 4000N at a rate of 0.2mm/s to assess the failure behavior of the model. At lab 2, each model initially underwent torsional testing at 0.1°/s until a maximum angle of 7.0° was achieved. This moment represents 50% of the ultimate angle at failure. The ultimate force at failure along with the model stiffness, maximum force at failure, and distance to failure were calculated for all models. Data was compared between the two participating laboratories to assess reproducibility of the model and loading setups. Statistical significance was calculated using unpaired t-tests to compare values between shell thickness.

RESULTS: Following successful completion of all testing, stiffness values were calculated from the force vs. displacement curves. The average stiffness of the 0.30mm shell models at lab 1 was 2104.9 ± 314.7N/mm and the average stiffness of the 0.15mm shell models at lab 1 was 1664.2 ± 300N/mm ($p=0.2$) (Table 1). The average stiffness of the 0.30mm shell models at lab 2 was 2515.1 ± 460N/mm and the average stiffness of the 0.15mm shell models at lab 2 was 3165.5 ± 628.3N/mm ($p=0.15$) (Table 1). There was no significant difference between the 0.30mm models ($p=0.2$) between the two laboratory testing setups. However, there was a significant difference between the 0.15mm models between the two laboratories ($p=<0.01$). However, there was no significant difference between the 0.30mm and 0.15mm shell models at either lab 1 or lab 2. The maximum force at failure for the 0.30mm models was 4312 ± 722N and the maximum force at failure for the 0.15mm models was 6446.7 ± 690N ($p<0.01$). The maximum subsidence for 0.30mm models was 3.9 ± 0.3mm and the maximum subsidence for 0.15mm models was 3.4 ± 0.2mm ($p=0.1$) (Table 1). The torsional stiffness was 71.1 ± 15.1Nm/rad for 0.30mm models and 80.7 ± 18.5Nm/rad for 0.15mm models (0.5) (Table 1).

DISCUSSION: The present study examined the reproducibility of the novel 3D-printed cervical models. Models with the 0.30 cortical shell demonstrated a consistent stiffness across different testing configurations compared to the 0.15mm models were significantly different between labs. This may be due to the precision quality of the 3D-printer resulting in markedly different prints, hindering the reproducibility between print batches. Further, the 0.15mm models in lab 2 exhibited significantly higher maximum force to failure compared to the 0.30mm models. This difference may be attributed to variations in layer height, where the 0.15mm shell's increased layer count and longer printing time possibly contributed to a greater resistance to pure compression. Therefore, the 0.30mm shell may offer more reliable results. When comparing the compressive stiffness with literature values for cadaveric cervical vertebrae, the results from the 3D-printed model were significantly stiffer. Yoganadan et al. measured the compressive stiffness of a cervical vertebral body with resected posterior elements. The average stiffness of vertebral bodies from C3 through C6 was 393.61+/- 150.64; however, the cadaveric specimens used ranged in age from 67 to 91 years of age and were all taken from female cadavers. Gozulov et al. reported the maximum failure force in pure compression with C5 specimens failing at 4,444N compared to the study by Yoganadan et al. reporting failures at 1,133N. The forces measured in the present study were more similar to Gozulov et al. which may indicate that the 0.30mm thickness PLA shell may be suitable for modeling healthy cadaveric cortical shells; whereas, a less stiff material may be needed to more accurately replicate older, weaker cortical shells.

SIGNIFICANCE/CLINICAL RELEVANCE: The present study evaluates the reproducibility of model fabrication and evaluation of structural properties between different testing setups. Suitability of the selected material and thickness for modeling a healthy cadaveric cervical vertebra was better with the 0.30mm cortical shell. The lack of conclusive evidence however indicates that future research should continue investigating alternative materials or thicknesses to better replicate osteoporotic cortical shells, thereby enhancing the clinical relevance of 3D-printed vertebral models.

REFERENCES: 1.Wahbeh, J. M., Hookasian, E., Lama, J., Alam, L., Park, S.-H., Sangiorgio, S. N., & Ebramzadeh, E. (2023). An additively manufactured model for preclinical testing of cervical devices. JOR Spine, e1285. https://doi.org/10.1002/jsp2.1285

TABLES AND FIGURES:

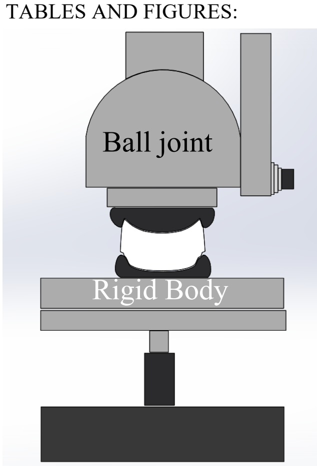

Figure 1. Testing setup of pure compression.

Table 1. Interlaboratory Results of Mechanical Properties

	Lab 1 Data		Lab 2 Data	
	15mm	30mm	15mm	30mm
Compressive Stiffness	1664.2 ± 300N/mm	2104.9 ± 314.7N/mm	3165.5 ± 628.3N/mm	2515.1 ± 460N/mm
Subsidence @ 4kN	3.4 ± 0.2mm	3.9 ± 0.3mm	N/A	N/A
Torsional Stiffness	N/A	N/A	80.7 ± 18.5Nm/rad	71.1 ± 15.1Nm/rad