Multidimensional Mechanical Changes of the Human Cervical Spine

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INTRODUCTION: *In vivo* mechanical testing of the human spine is integral to characterization of complex spinal biomechanical behavior that guides diagnosis and treatment of spinal injuries and development of spinal implants. Yet protocols for mechanical testing vary widely, particularly for specimen preconditioning and characterization of biomechanical creep, and are reported only for pure moment, uniplanar loading protocols, which do not factor in the multidimensional nature of *in situ* spinal behavior. This study explores: 1) if the gain tuning process for stabilizing robotic control for mechanical testing can also serve as a biomechanical preconditioning phase and 2) describing the multidimensional creep properties of post-mortem human cadaveric specimens.

METHODS: Two post-mortem lower cervical spine specimens (C2-C7 and C2-T1, female only available) were each exposed to 16 hours of loading over two days each. Loads were applied by a six degree-of-freedom robot (KUKA) and the specimens' moment-displacement behavior were recorded with an load cell (ATI), optical tracking sensors (NDI), and biomechanical testing software (simVITRO/Cleveland Clinic BioRobotics). Specimens were subjected to system gain tuning and two distinct loading trajectories combining Flexion-Extension (FE) and Lateral Bending (LB) loading over an eight-hour period on two consecutive days each and were refrigerated and wrapped in saline-hydrated gauze between testing days. The first loading trajectory captures the subject-specific boundary of the spine's range of motion (ROM) under an applied combined FE and LB loading of 1-2 Nm and was applied five times consecutively at the beginning of each testing day and then at regular intervals (every 60-90 minutes) throughout the experimental day. The kinematic response of the specimen to this boundary loading was used to crop the boundary of a custom, combined FE and LB bending protocol which approximates pure moment bending along planes defined by steps of 5 degrees about the craniocaudal axis, where the zero degree axis is at pure right LB. This trajectory (called "Rays"), was applied three times consecutively, followed by another round of boundary capture, repeating this process until the testing day was complete. Key outcomes included specimen kinematics and kinetics for the full segment and individual functional spinal units (FSU) in response to the trajectories and changes across the testing days. Visualization of these metrics was performed in MATLAB (Mathworks). ARCMap (Arcus, Analytica) was utilized to parameterize the data and to perform statistical operations on the continuum biomechanical data through Statistical Parametric Mapping[1].

RESULTS: Overall segmental ROM for both specimens had a non-statistically significant increase an average of 10% across five initial cycles of boundary capture at the start of each test day ($p > 0.1$). Specimens experienced an additional increase in ROM over the course of each testing day (Average across both days: Specimen 1 - 6.67%, Specimen 2 - 20.5%), with mostly uniform increases in all bending planes around the boundary excepting a statistically significant increase occurring around only at Flexion-dominant loading ($p=0.038$). Both specimens had a 25% reduction in ROM between the end of the first day and beginning of the second day of testing. In addition to this decrease in overall ROM, both specimens experienced an increase in neutral zone area between the first and second days of testing, increasing the overall ROM (Specimen 1 – 10%, Specimen 2 – 20%) falling within lower loads (under 0.5 Nm) for identical kinematic poses within the Rays trajectory loading. Notably, a decrease in the proportion of ROM with low stiffness (under 0.1 Nm/deg), with an increase in the proportion of ROM with higher stiffness, was observed for both specimens between testing days. The hysteresis effect between loading and unloading behaviors of the segment became more pronounced in the elastic zone than the neutral zone on the second day compared to the first day, but changes in hysteresis were less pronounced within a day on the second day than the first. FSU ROM typically followed similar changes to those of the segmental ROM, load, and stiffness.

DISCUSSION: The non-statistically significant increase in ROM in the first five boundary capture cycles suggests that the loading involved in gain tuning a robotic testing system for cadaveric testing may be sufficient to precondition a specimen. The changes to ROM across individual days of testing, though statistically significant, were not retained between days of testing, suggesting that any increase laxity may not be due to damage of bony anatomy or microtears of soft tissue, but instead viscoelastic adaptation, else this increased ROM would have been maintained. The changes between days of testing, particularly to the neutral zone area, may be linked to intervertebral disc dehydration, as prior work has demonstrated that the observed neutral zone increase can be a more sensitive parameter to mechanical changes in the spine than the overall ROM[2].

SIGNIFICANCE/CLINICAL RELEVANCE: This study produced previously undocumented multidimensional mechanical changes of the spine during *in vivo* testing, enhancing understanding particularly of creep of the spinal joints during experimental testing. These characterizations are crucial in designing robust protocols to validate spinal devices and design for potential failure mechanisms due to multiplanar loading. Devices that are mechanically robust in multiple dimensions will ideally lead to improved patient outcomes and reduced adverse effects.

REFERENCES: [1] Pataky, T. C. (2012). *Computer Methods in Biomechanics and Biomedical Engineering*, *15*(3), 295–301. (DOI: 10.1080/10255842.2010.527837) [2] Oxland, T. R., & Panjabi, M. M. (1992). *Journal of Biomechanics, 25*(10), 1165–1172. (DOI: 10.1016/0021-9290(92)90072-9)

IMAGES AND TABLES:

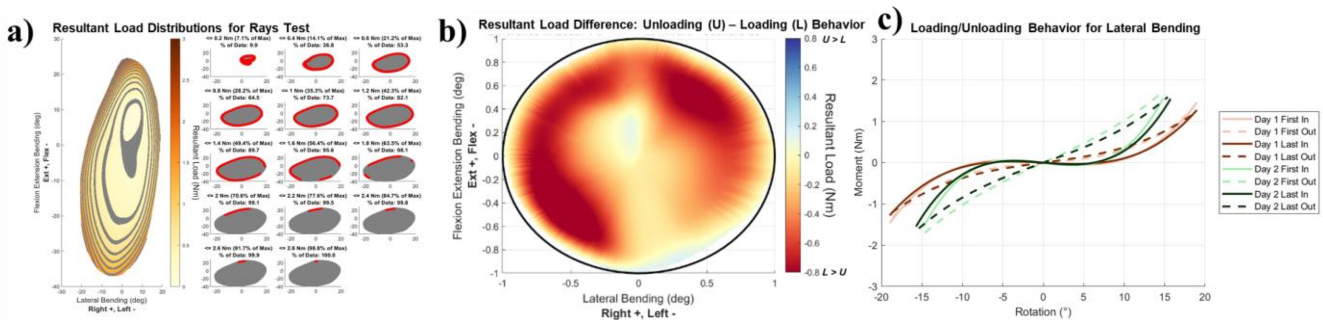

Figure 1: (a) Distribution of resultant load across the multiplanar ROM, (b) normalized difference in resultant load for unloading vs loading behaviors, (c) hysteresis behavior for lateral bending for first and last tests of day 1 (pink) vs day 2 (green).