Exploration of the Full-Field Biomechanics of the Lumbar Spine

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ABSTRACT INTRODUCTION: The widely accepted method for evaluating spinal biomechanics developed by Panjabi et al has been adopted into standards such as ASTM F2077-22 to validate spinal implants. This method involves applying a pure Cartesian moment to a spinal segment or a functional spinal unit in each physiologic plane, then measuring the resulting range of motion, loading and unloading stiffness, hysteresis, and neutral zone behavior. While planar moment testing is a standardized and powerful tool, it leaves the spinal motion-loading space in-between planes untested and unknown. Adding more simultaneous dimensions of loading in a full-field multi-planar methodology will lead to deeper insight into the complex physiological behavior of the spine in various surgical interventions. To address this gap, we propose a novel testing protocol that uses six-degree-of-freedom trajectories to produce complex motion paths which map the spine's multi-planar behavior. This exploration enables multidimensional visualization of the spine's bending stiffness in all directions within its physiological limits. The objective of this study was to debut complex multi-planar spinal testing, explore visualization strategies, and identify spinal behavior insights gained relative to traditional testing.

METHODS: One L3-L4 lumbar surrogate from Sawbones® with a previously surgically implanted Anterior Lumbar Interbody Fusion (ALIF) cage was mounted to custom fixtures on a 6 DOF KUKA KR 300 R2500 Ultra Robot. The specimen's moment-displacement behavior was captured by an ATI Delta IP68 SI-330-30 load cell, NDI Optotrak sensors, and SimVITRO software. Testing was performed in a moment-control scheme with maximum planar loads in Flexion-Extension (FE) and Lateral Bending (LB) of 2.5 Nm. The trajectory studied in this report was a 360° circles of increasing radii up to 2.5 Nm around the neutral axis of the surrogate in both clockwise and counterclockwise directions. After testing, the measured Lateral Bending, Flexion-Extension, and Axial Rotation angles of the spine were transformed from the anatomical joint coordinate system, combined into a resultant range of motion measure, and used for calculation of a resultant stiffness value of the spine across a subset of points throughout the inputted loading trajectory. The data were then sliced as shown in Figure 1 to visualize the corresponding two planar and two 45° off-axis behaviors.

RESULTS SECTION: The spinal surrogate stiffness, when viewed in a slice through the 3D surface, follows a roughly V-shaped path reaching its maxima at the extrema of the elastic zone and minima at the neutral zone. When viewed in the planar directions of FE and LB, the specimen experienced a peak stiffness of 1.55 Nm/deg in Flexion and 1.83 Nm/deg in Extension (Figure 1a) and asymmetric peak stiffness between right LB, 1.00 Nm/deg, and left LB, 2.00 Nm/deg (Figure 1b). This testing is unique in that it enables assessment of stiffness of the spine as it passes from combined full Flexion and right LB through the neutral zone (Figure 1c) to full Extension and left LB (negative 45° approach), during which it sees a peak stiffnesses of 1.13 Nm/deg and 0.9 Nm/deg at the extrema, respectively (Figure 1d). The complementary path from full Flexion and left LB through the neutral zone to full Extension and right LB (positive 45° approach), saw different peaks in stiffness values of 1.20 Nm/deg and 2.11 Nm/deg. By contrast, the average stiffness of planar LB and FE across the same range of load values was calculated to be 1.0 Nm/deg and 2.13 Nm/deg. Differences in behavior between the two 45° off-axis slices as well as between these slices from the average planar stiffness suggest that spinal stiffness in all directions cannot be inferred exclusively from planar testing.

DISCUSSION: The interpretation of this data is in and of itself, a part of the objective of this study. Mapping the changes in stiffness of the spine across its physiologic spaces enables improved visualization of spinal disease and injury. This in turn, informs more nuanced diagnosis, assessment of treatment modalities, and differentiation between injurious movement patterns which may otherwise not be visible in planar-only testing. Future work will explore the spine in its intact state, in disease states, and with implants such that this protocol may be used to inform treatment predictions for patients based on pre-surgical and desired post-surgical biomechanics of the spine.

SIGNIFICANCE/CLINICAL RELEVANCE: A multi-planar loading scheme for testing spine biomechanics offers holistic assessment of spinal behavior throughout the spine's physiologic workspace. To the knowledge of the authors, this study is the first report of the multi-planar bending stiffness in the full field of the FE and LB space of the human lumbar spine.

Figure 1. Slices through 3D stiffness surface for specimen. a) Planar Flexion-Extension, b) Planar Lateral-Bending, c) Negative 45°, d) Positive 45°.