Effect of Axial Compression on the Kinetic and Kinematic Responses of Adult Male Human Lumbar Spine in Lateral Bending

Kalle Chastain, Michael R. Burns, Bronislaw Gepner, Jason Forman, Jason Hallman, Jason R. Kerrigan

I. INTRODUCTION

The musculature of the spine has been found to provide around 1000 N of compression for standing and walking, with loads estimated to reach several thousand Newtons during lifting activities [1-3]. Similarly, previous biomechanical characterisation studies have found the biomechanical response of lumbar functional spinal units subjected to bending is affected by the presence and magnitude of axial compressive load [4-5]. While loads and motion of the lumbar spine have been found in the literature, previous whole-spine tests have shown the lumbar spine to buckle under relatively low (~88 N) axial compression loads [6]. Since buckling occurs at significantly lower forces than those the spine has been found to carry, Patwardhan *et al.* developed the follower load technique to investigate spinal biomechanics at higher compressive loads which was found to increase load-carrying capacity [7-8]. This technique was employed to evaluate the effect of axial compression on the lumbar spine response in lateral bending. The objective of this study was to measure the kinetic (stiffness) and kinematic (deformation) responses of the lumbar spine and to develop response corridors for human body model (HBM) and anthropomorphic test device (ATD) applications.

II. METHODS

The lumbar spines (T10–S1) of seven fresh-frozen, adult male post-mortem human surrogates (PMHS) were tested in lateral bending to a sub-injurious level in the same testing matrix as Chastain et al. 2023, where additional details are found [9]. All PMHS handling and testing procedures were performed in accordance with the ethical guidelines of the National Highway Traffic Safety Administration (NHTSA). The specimens were free from any injuries, deformities, significant ossification, or degeneration and were isolated from musculature, but ligamentous structures were intact. The iliolumbar ligaments, which have been found to restrict vertebral motion in lateral bending, were removed [10]. Collars were fixed to the L1-L4 vertebrae by four screws at the approximate midline of the vertebral height and four different locations along the perimeter for follower load guiding and 3D motion tracking. L5 motion was tracked by markers connected to the antero-lateral aspects. The sacrum was potted with the S1 superior endplate parallel to the surface of the potting material and the L5-S1 joint unconstrained by material. Potting material was also applied from T10 to the midline of T12, with the T12 inferior endplate parallel to the potting material surface and the T12-L1 joint unconstrained. A six-degrees-of-freedom (6DOF) serial robot, with force/torque and position control, was used for lateral bending loading. In combination linear actuators and the robot applied the axial compressive follower load to two wires at 0 N, 900 N, or 1800 N (combined), which passed through vertebral collar housings with optimised positions for relative vertebral rotation (<3 deg) and joint moments (<2.5Nm). A 10-camera optoelectronic stereo-photogrammetric system recorded 3-D vertebral motion. The robot applied motions and loads to the superior end of the specimen while the inferior end was connected via a 6DOF load cell to the laboratory floor. The specimen joint coordinate system (JCS) was defined by anatomical landmark vertebra coordinate systems on L4 and L5 [11]. Neutral position was determined as the centre of its laxity region [9]. During each test the force-controlled follower load was applied first to the desired magnitude and held, the robot applied uni-directional lateral bending to non-injurious limits, then returned to a neutral position before the compressive load was removed. The robot's load-control capability found a lateral bending motion path that maintained 0 N of anterior-posterior and lateral shear. Kinetic and kinematic response corridors were created following previously developed techniques.

M. R. Burns (michael.r.burns@virginia.edu) is a PhD student in Mechanical Engineering, B. D. Gepner is a Research Scientist, J. L. Forman is a Principal Scientist, J. R. Kerrigan is the Director and Associate Professor in Mechanical Engineering, all at the University of Virginia's Center for Applied Biomechanics, USA. K. C. Chastain is a Research Engineer at Hospital for Special Surgery, New York USA. J. Hallman is a Senior Manager for the Collaborative Safety Research Center at Toyota Motor North America Research & Development, Michigan USA.

III. INITIAL FINDINGS

All tests were completed without specimen structural or material failure, as observed by inspection and a small loading regime compared to failure. The kinematic measurement was right lateral rotation angle and the kinetic was the left lateral moment (negative moment oriented right). Without axial compression, the lumbar spine exhibited a nonlinear response (Fig. 1). With 900 N and 1800 N of axial compression the lateral bending response remained nonlinear, with an initially stiffer response (to ~10 Nm), followed by a similar stiffness to the 0 N case with comparatively high linearity. A negligible response difference was found between the 900 and 1800 N cases. The response corridors suggest the variation from application of axial compression was greater than inter-specimen variation in response. The spine's kinematic response to this loading was analysed by computing the rotation angle at each intervertebral level as a percentage of the whole spine total bending angle at peak deformation (Fig. 1). The kinematic data without axial compression show non-uniform rotation across vertebral levels, with rotation concentrated in the four inferior joints. Axial compression resulted in deformation increases at the superior (T12-L1) level and reductions at the inferior (L4-L5&L5-S1) joints.

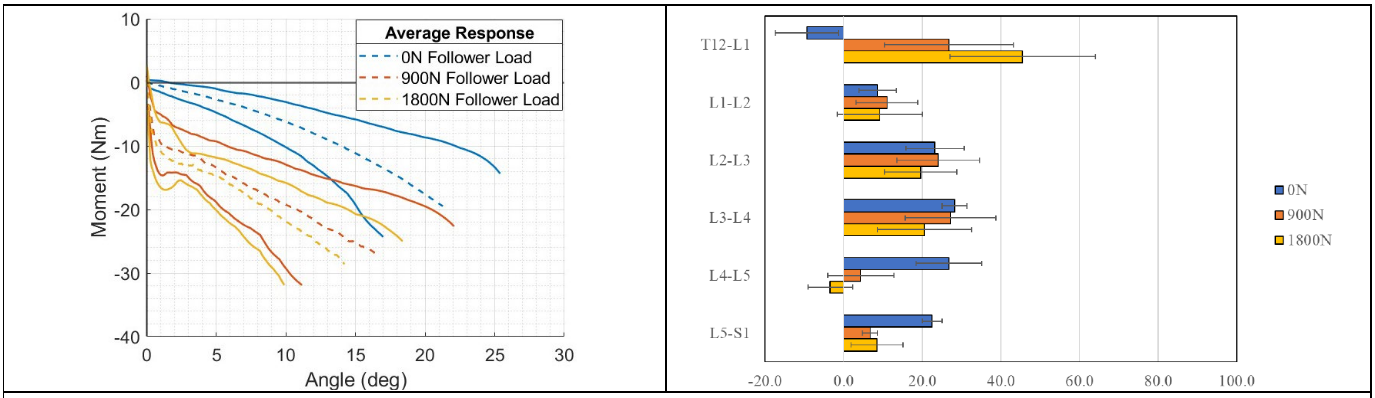

Fig. 1. Left: moment vs. angle averaged responses (dashed lines) and upper/lower corridor bounds (solid lines) for each axial compressive load in lateral bending. Right: bar plot of the average (std dev) of the percentage of joint lateral rotation angle to the maximum lateral rotation angle of the spine.

IV. DISCUSSION

The novel methodology using 6DOF position and force/torque-controlled loading combined with a force-controlled linear-actuator to apply follower load axial compression provides the ability to isolate responses of the full spine in individual directions. The methodology allowed loads and motions to be applied in one direction while maintaining zero-load in other directions, which created easily replicable boundary conditions for computational simulation. These results highlight the substantial effect axial compression has on the response of the lumbar spine in lateral bending. Moment vs. angle response corridor differences suggest a change in the stiffness response profile to be more linear with follower load application. Vertebral rotation angle corridors identify a difference in rotation angle with and without follower load. These corridors are valuable for sub-injurious HBM and ATD applications in lateral bending. The kinematic response data captured show the spine does not equally distribute deformations among the individual joints when pure moments are applied, which indicates stiffness differences of the individual joints which may be relevant when the body is subjected to complex loading likely in vehicle crashes. The shift of rotation angle contribution among vertebra with axial compression may highlight its relevance. Since axial compression has been shown here and in our previous work to affect lumbar response [9], and the lumbar spine is unlikely to be in a fully unloaded state due to passive tension in the lumbar musculature, response data collected with superimposed axial compressive loading would be advantageous in the evaluation of human surrogates like ATDs and HBMs.

V. REFERENCES

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