

A New Device for Multi-Axial Tissue Testing: Application to Combined Bending and Shear Loading of the Spine

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ABSTRACT

A multi-axial test device was designed to obtain the material properties of the lumbar spine in combined loading modes. The custom designed tester consists of a rigid platen driven by three DC powered geared motors. Two motors, each connected to parallel linear actuators control the angular displacement (for flexion and extension) and vertical motion (for tension and compression), while a third DC motor connected to a threaded rod was employed to control the horizontal displacement (for anterior and posterior shear) of the rigid platen. The testing machine is driven in displacement-control mode by a feedback system based on data from three rotary potentiometers.

Six entire lumbar spine segments (T12-S1) were potted in aluminum cups with DynaCast and tested within failure limits to compression, tension, anterior shear, posterior shear, flexion, extension, anterior shear-flexion, posterior shear-extension and finally in combined anterior shear-flexion loading. The specimens were hydrated throughout the tests with 0.1 % saline solution and positioned in their natural lordosis curvature. All data was processed as per SAE J211 convention. This unique multi-axis tester can be used for testing spines and other tissue in combined loading modes that are not common to commercially available material testing systems.

INTRODUCTION

Knee airbags, deployable knee bolsters, and seat mounted anti-submarining airbags have been introduced to control the lower torso kinematics and reduce the likelihood of posterior cruciate ligament (PCL) injury. Though these devices function against the "balanced restraint" concept of simultaneously restraining the upper and lower occupant kinematics, they engage the lower torso early in a crash and may prevent submarining.

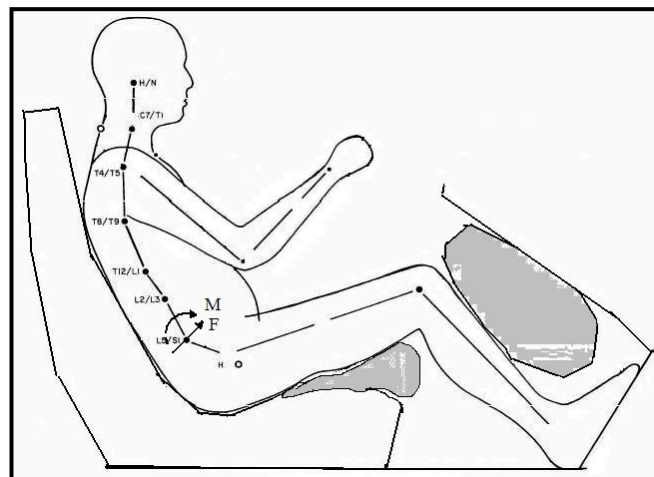


Figure 1: Combined anterior shear-flexion loading on the lumbar spine in the event of a frontal crash with knee airbags and anti-submarining airbags

During a frontal crash, the knee airbag or deployable knee bolsters works in concert with the main airbag to reduce the risk of injury. While the knee airbag or

deployable knee bolster may greatly reduce the lower torso movement, causing the upper torso to move and rotate considerably, causing a **combined anterior shear with flexion load to the lumbar spine in adult occupants** not seen prior to the introduction of knee airbag and deployable knee bolster (Figure 1).

Commonly used material testing systems are designed to conduct single-axis tensile or compressive loading. There are also bi-axial testing machines that are designed for applying tensile or compressive loading in conjunction with axial rotation. To the best of our knowledge, there is no commercially available material testing system that is capable of applying flexion-extension, compression-extension, and anterior- or posterior-shear loading needed to determine the force-deflection and moment-angle characteristics of human spine. The purposes of this study were to design and fabricate a multi-axis testing machine for testing spines and to obtain biomechanical responses of whole lumbar spines subjected to single and multiple modes of loading.

MULTI-AXIS TESTING MACHINE

Conventional material testing machines (MTS, AMTI and INSTRON) can predominantly perform uni-axial loading (such as compression, tension, shear and rotation) and combined tension/compression with axial rotational loading. They can also perform bi-axial testing with some additional fixtures and can turn out to be expensive to build and maintain. Researchers who have attempted to perform combined loading on the spine have in the past resorted to using complicated paths to transfer loads in multiple axes. Osvalder et al. (1990) used a pendulum based fixture whose rate could not be controlled while Demetropoulos et al. (1998) used a pulley-string attachment to perform flexion of spine on a high speed INSTRON tester. Stokes et al. (2002) built a hexapod like apparatus with six actuators (6 degrees-of-freedom, DOF) with closed-loop position control system to test the compressive stiffness of the thoracic spine. The system proved to be too complicated with a lot of cross talk and posed difficulties in accurate control.

TEST FRAME

A custom designed multi-axis testing machine, shown in Figure 2, was designed and built to perform combined shear and bending of the lumbar spine.

The tester comprised of two Duff Norton Linear actuators (Duff-Norton, Charlotte, NC) with a load capacity of 4.45 kN (1000 lbs) each driven by a DC motor. Each of these motors has an electromagnetic brake built into it to provide accurate control by enabling quick stopping of the shafts. A third DC motor was employed to drive an Acme threaded rod to move the platen in and out thus proving the third axis of the tester. Figure 3 shows the sub-assembly of the loading platen.

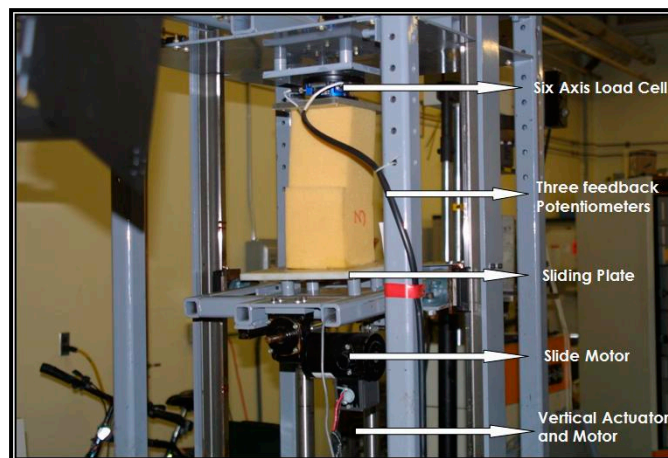


Figure 2: Multi-axis material testing machine

The linear actuators when driven in unison can provide compression or tension and when driven independently in opposite directions can provide flexion or extension, while the slide motor can provide anterior/posterior shear to the specimen mounted on it.

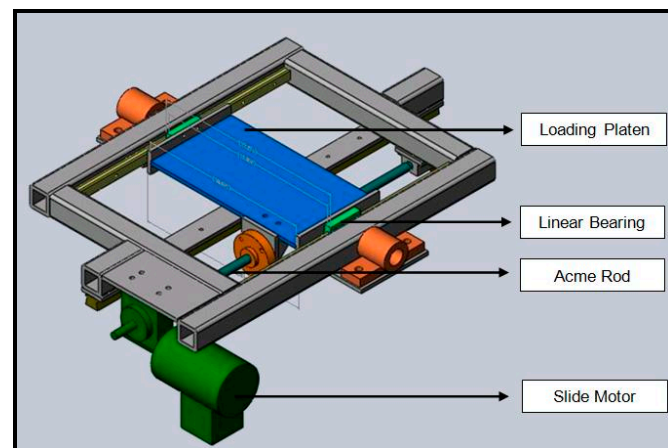


Figure 3: Loading platen sub-assembly with slide motor, Acme Rod and linear bearings

The linear shafts connected to the platen via sliding bearings provided easy transfer of load while allowing flexion/extension of the platen (Figure 4). The slide motor was connected to the Acme threaded rod through a flexible coupling which allowed for some offset of the two shafts during loading (Figure 5). Sliding Teflon bearings were employed between the loading platen to reduce friction during shear loading (Figure 6). Figure 7 shows the final assembly of the multi-axis tester.

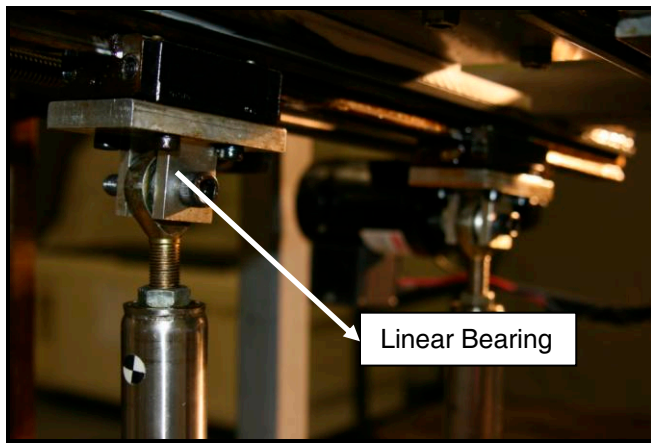


Figure 4: Bearings on the linear shafts

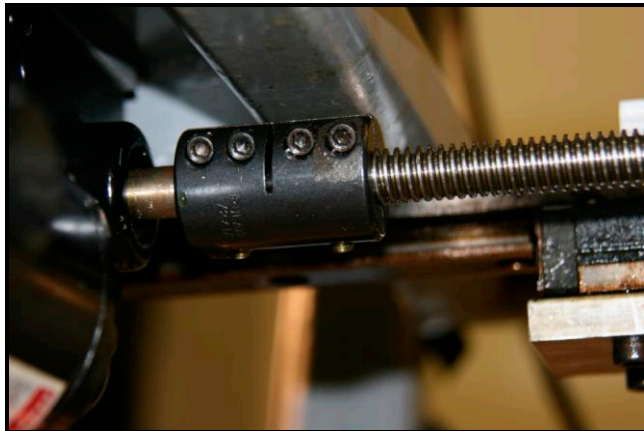


Figure 5: Flexible coupling

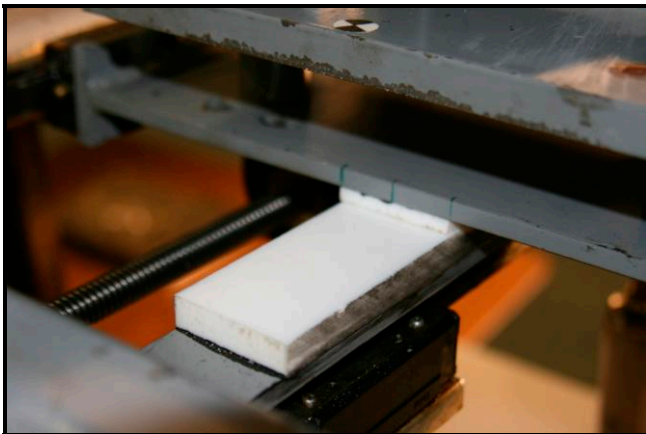


Figure 6: Sliding Teflon bearings to reduce friction

All tests were conducted at fixed actuator speeds of 8 mm/s for the vertical actuators and 4 mm/s for the horizontal axis. Because the distance between the two actuators was fixed at 254 mm, the machine is capable of rotational deformation rate of $3.5^\circ/\text{s}$ (0.061 rad/s). Rotary potentiometers attached to each motor provided data for feedback control and determination of the displacement and angle of the platen.

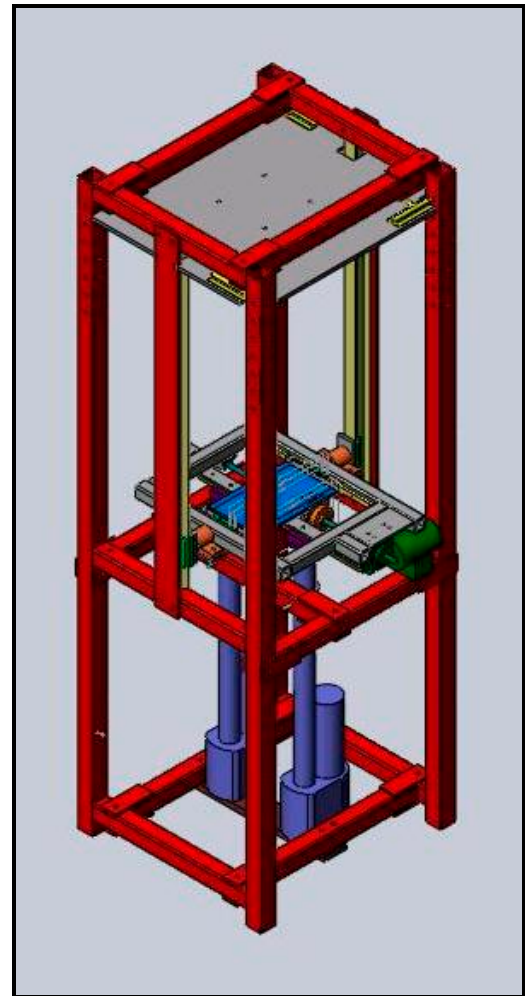


Figure 7: Schematic diagram of the final assembly of the multi-axis tester

CONTROL SYSTEM

There have been two variations of the control system that have been developed for operating the tester. The hardware on the tester remained the same but the design approach changed for each control method.

Variation 1: The first variation of the control system used a National Instruments NI 6034E DAQ board. This board is a PCI bus based board with 16 single ended or 8 differential input analog input channels that provide 16 bits of resolution at a sampling speed of 200ks/s. The board also had 8 Digital I/O channels (Figure 8). The board does the following:

- 1) Provide digital outputs to turn on and off the three actuators
- 2) Digitize the potentiometers devices on the three actuators that indicate actuator position
- 3) Digitize and Store the load cell channel values

Additionally there was a custom relay board that was designed and built to complete the hardware portion of the data acquisition and control system. This relay board used the digital outputs from the board and switched the voltage onto the actuators to allow for the high-current required by the actuators.