INTRODUCTION
Spinal motion segment stiffness (together with muscle stiffness and forces) stabilizes the spinal column. There are several limitations of the existing experimental stiffness data. Most reported data do not include all six degrees of freedom, were obtained by inverting flexibility data, were obtained without physiological levels of axial compression and were not performed with the discs in a physiological saline bath. Axial compression preload increases stiffness by a factor of two or more (1,3) and may reduce the amount of load-displacement nonlinearity (3). Discs in a physiological saline bath have greater hydration than discs that are just exposed to saline spray and wrap (4). This increased hydration presumably affects the disc biomechanics.

This study tested hypotheses that axial compression preload increases motion segment stiffness, increases hysteresis and load-displacement behavior is more linear. These effects were tested in both intact motion segments and in isolated intervertebral discs.

METHODS
The stiffness matrix of each of four female human (ages 17, 21, 52 and 58 years) L2-L3 motion segments was measured directly in six degrees of freedom (6-DOF) by a ‘Steward platform’ or ‘hexapod’ robot (5). Specimens were immersed in an isotonic saline bath cooled to ~4°C.

In each test, a sequence of axial compression preloads of 0 N, 250 N and 500 N was applied, and the specimen was allowed to equilibrate with these preloads for at least three hours before any stiffness measurements. Six pure displacement tests (4 sawtooth cycles of 87 s each) were then sequentially imposed, and the applied displacements and resulting forces were recorded at 1 Hz. The displacements were ±0.5 mm in the AP and lateral directions, ±0.35 mm in the axial direction, ±1.5 degrees in lateral bending rotation and ±1 degree in flexion/extension and torsional rotations. After testing the intact specimen, the facets and ligaments were removed and the tests repeated.

Forces at the vertebral body center were assumed to be related to independent coefficients due to the assumption of symmetry). The 21 independent coefficients were estimated using a least squares fit to experimental data (5). The hysteresis (damping) was evaluated as the enclosed area in the load-displacement recording for the second and third cycles. The nonlinearity of the displacement-load relationships were measured by subtracting the coefficient of determination (R²) for linear regression and the pure error estimate from unity.

Changes in diagonal and primary off-diagonal (2) stiffness coefficients, linearity and hysteresis area with axial compression preload were analyzed using repeated-measures ANOVA. Significant preload effects were further analyzed with linear and quadratic contrasts.

RESULTS
Increased axial compression preloads produced progressively increased stiffness (Figure 1). The mean values of the diagonal and primary off-diagonal stiffness coefficients for intact motion segments increased significantly by an average factor of 1.49 and 1.81 with 250 N and 500 N compression respectively (all eight tests F²;0.74, p=0.024) (Figure 2). Removal of the facets and ligaments decreased the motion segment stiffness an average 66%. Stiffness of isolated discs increased significantly by an average factor of 2.27 and 3.26 with 250 N and 500 N compression preload respectively (all eight F²;0.58, p=0.029). The linear trend of increasing stiffness with preload was highly significant for both intact motion segments and isolated discs (F²;13.4, p=0.011). A quadratic trend was only significant for AP shear stiffness in intact motion segments. Compression preload had the greatest effect on axial stiffness. Axial stiffness (average intact and isolated discs) increased by 3.64 and 5.41 with 250 N and 500 N compression preloads.

The hysteresis was very consistent from cycle to cycle (Figure 1). Mean hysteresis areas for intact motion segments increased by 1.38 and 1.75 with compression. This was significant for all degrees of freedoms except for the diagonal flexion/extension and one-off-diagonal relationship. The mean hysteresis area for isolated discs increased significantly by 2.12 and 2.94 with compression (F²;11.8, p=0.008).

The linearity of load-displacement relationships was characterized by R² values in the range 0.853-0.998. The mean R² increased with axial compression in intact motion segments (mean R² = 0.942, 0.956 and 0.959 at 0 N, 250 N and 500 N compression respectively) and isolated discs (mean R² = 0.927, 0.978 and 0.986 at 0 N, 250 N and 500 N compression respectively). The increase was only significant for one off-diagonal load-displacement relationship in the isolated discs.

DISCUSSION
These findings indicate that motion segment stiffness measured without compression underestimate the in vivo values in all degrees of freedom. These effects were present in both intact motion segments and in isolated intervertebral discs. The large increase in stiffness and hysteresis with preload in the isolated discs suggests that disk biomechanics may be important. Load-displacement behavior was surprisingly linear and became more linear with axial compression preload. The stiffness values and changes with axial compression preload found in this study were similar to previous studies (1,3). Biomechanical analyses of the spine that simulate in vivo loading should include preload effects.

REFERENCES

ACKNOWLEDGEMENTS
Supported by NIH R01 AR44119. Motion segments supplied by the Anatomical Board of the State of Texas and National Disease Research Interchange (NDRI).