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Short communication

# A database of lumbar spinal mechanical behavior for validation of spinal analytical models

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ABSTRACT

Data from two experimental studies with eight specimens each of spinal motion segments and/or intervertebral discs are presented in a form that can be used for comparison with finite element model predictions. The data include the effect of compressive preload (0, 250 and 500 N) with quasistatic cyclic loading (0.0115 Hz) and the effect of loading frequency (1, 0.1, 0.01 and 0.001 Hz) with a physiological compressive preload (mean 642 N). Specimens were tested with displacements in each of six degrees of freedom (three translations and three rotations) about defined anatomical axes. The three forces and three moments in the corresponding axis system were recorded during each test. Linearized stiffness matrices were calculated that could be used in multi-segmental biomechanical models of the spine and these matrices were analyzed to determine whether off-diagonal terms and symmetry assumptions should be included.

These databases of lumbar spinal mechanical behavior under physiological conditions quantify behaviors that should be present in finite element model simulations. The addition of more specimens to identify sources of variability associated with physical dimensions, degeneration, and other variables would be beneficial. Supplementary data provide the recorded data and Matlab® codes for reading files. Linearized stiffness matrices derived from the tests at different preloads revealed few significant unexpected off-diagonal terms and little evidence of significant matrix asymmetry.



## 1. Introduction

Analytical models of the biomechanical function of the spine and spinal motion segments together with experimental studies provide understanding of in vivo spinal loading as well as the biomechanics of the intervertebral discs and motion segments. Finite element models have been used to gain understanding of elastic load-deformation behavior (Dreischarf et al., 2014, Weisse et al., 2012), time-dependent behavior (Castro et al., 2014; Galbusera et al., 2011a,20011b; Schmidt et al., 2010; Schroeder et al., 2010) and insights into damage accumulation (Qasim et al., 2012), degeneration and transport of nutrients and metabolites (Natarajan et al., 2004; Schmidt et al., 2013). Models are also used to predict the behavior of surgical implants (Zhang and Teo, 2008), and in multi-segmental spine models to estimate *in vivo* spinal and muscular forces with each motion segment represented by a stiffness matrix or equivalent beam (Gardner-Morse and Stokes, 2004). While motion segment and disc models are becoming increasingly sophisticated by including complex elastic formulations, creep, viscoelasticity and swelling behavior, there is a shortage of experimental data for validation of the complex nonlinear, time-dependent six-degree of freedom behavior of the spine. Although tissue properties have been extensively studied (e.g. Cloyd et al., 2007, O'Connell, Sen and Elliott, 2012, Wagnac et al., 2011), the structural behaviors of discs and motion segments including the neural arch and facet joints are not well documented.

The intervertebral disc is a complex avascular structure having nonlinear behavior in six degrees of freedom with stiffness that increases with axial compressive load (Gardner-Morse and Stokes, 2004), and with time dependent response (creep, hysteresis, etc.). The disc is commonly modeled as a biphasic tissue with fluid and solid phases, also sometimes including fixed charges responsible for swelling behavior and retention of fluid. The nonlinear elastic behavior is thought to result primarily from the cable-like nature of collagen fibers, and its time-dependent behavior resulting from both fluid-flow effects and solid phase viscoelasticity (Costi et al., 2008).

Motion segment behavior in multi-segmental analyses of spinal and trunk loading and stability can be represented efficiently by use of a continuum formulation such as a linearized stiffness matrix or 'equivalent' beam (Gardner-Morse and Stokes, 2004). Most of the available motion segment data are limited to axial

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compression stiffness and creep, and elastic behavior in the three principal angular degrees of freedom. The full linear stiffness matrix as required for equivalent structure representation comprises both diagonal and off-diagonal terms and matrix symmetry. Goel (1987) noted that certain forces or moments are associated with at least two displacements (in a flexibility experiment) and identified them as 'primary' and 'secondary'. For example, an anterior force would generally produce anterior shear (primary) as well as flexion (secondary) motion. Secondary motion is often also identified as 'coupling' behavior. Also, any misalignment of the applied force relative to structural symmetry axes of the specimen would produce additional out-of-plane motion. Here in the context of a stiffness experiment (applied displacements) we identify primary terms as the diagonal terms of the stiffness matrix, and secondary (expected) off-diagonal terms; also additional off-diagonal terms resulting from structural asymmetry or testing axis misalignment. In experimentally determined stiffness matrices, translational stiffness should be independent of the center of the axis system, but rotational stiffness terms would be axis-center dependent. (The inverse is the case for a flexibility matrix).

The purpose of this paper is to provide data for use in validation of analytical models or other analyses of the lumbar spine. Data were recorded from two sets of human lumbar motion segments (without posterior elements for the second set) in six degrees of freedom, under different axial preloads and with different loading frequencies. The data have previously been used to report stiffening by preload and representation of the motion segment as an 'equivalent' beam (Gardner-Morse and Stokes, 2004) and in a study of frequency-dependent apparent stiffness and hysteresis behavior under cyclic loading (Costi et al., 2008) with testing frequencies covering the range from quasistatic to walking.

Experimental data were also examined to identify significant off-diagonal terms in the derived linearized stiffness matrices and to determine their degree of symmetry. These matrices are symmetrical in a linear elastic structure, but experimentally have been found to be asymmetrical (Holsgrove et al., 2015) in porcine motion segments. Previously published experimentally derived stiffness matrices using this database (Gardner-Morse and Stokes, 2004) assumed symmetry.

## 2. Methods

Data for the six-degrees of freedom behavior of human cadaveric motion segments were recorded using a 'hexapod' (Stewart platform) apparatus (Stokes et al., 2002). This computer-controlled apparatus has six linear actuators, six displacement transducers and a six-degree-of freedom load cell. It was programmed to impose each of the three principal displacements and three principal rotations in the motion segment's local axis system while the three principal forces and moments were recorded. Human motion segments were dissected from available human spines (thus a sample of convenience) that had been stored at −80 °C. Each specimen was radiographed and no evidence of anatomical abnormality or gross degeneration was observed. Some osteophytes were observed on the older specimens.

In the first 'preload' test series (Gardner-Morse and Stokes, 2004), there were eight lumbar motion segments (L2-3 and L4-5 from each of four human females, aged 17, 21, 52 and 58 years). See Table 1. These specimens were tested in physiological saline at 4 °C. Each specimen was tested with axial compressive preloads of 0, 250 and 500 N (stress approximately 0, 0.15 and 0.3 MPa, comparable with the lower range of physiological values (Wilke et al., 1999)) and was allowed to equilibrate with each preload for at least three hours before each load–displacement test. The six tests (three pure translations and three pure rotations) were sequentially performed with four sawtooth-waveform (ramp-loading) cycles of 87 s ($1.15 \times 10^{-2}$ Hz) in each displacement direction. This loading rate was the slowest possible representing quasi-static conditions, compatible with an acceptable total testing time per specimen (~80 h). The applied displacements and resulting forces were recorded at 1 Hz. The displacements were cycles of +/−0.5 mm in anterior–posterior and lateral displacements, +/−0.35 mm axial displacement, +/−1.5 degrees lateral bend rotation and +/−1 degrees flexion–extension and axial rotations. After testing each intact specimen, the facets and ligaments (posterior elements) were removed and the tests were repeated.

In the second 'frequency' tests series (Costi et al., 2008), eight vertebra-disc-vertebra motion segments (posterior elements removed) from seven human lumbar spines (five males, two females, mean [SD] age: 41 [18] years, range: 16–58 years; levels: L1/L2 $n=2$, L2/L3 $n=2$, L3/L4 $n=3$, L4/L5 $n=1$; weight: 84 [19] kg) were tested. According to Thompson's criteria (Thompson et al., 1990) for disc degeneration grade modified for transverse Section, 2 discs were grade 1, 5 were grade 3, and 1 was grade 5. See Table 1. Specimens were loaded with a sine waveform at each of four frequencies (0.001, 0.01, 0.1, and 1 Hz, with displacements and forces recorded at 0.2, 2, 32 and 128 Hz respectively) after equilibration overnight under a preload based on estimated area to produce 0.4 MPa to simulate *in vivo* static loading conditions (Costi et al., 2008). The displacements amplitudes

**Table 1**
Specimen details for database of lumbar spinal mechanical behavior.

| Specimen number | Lumbar level | Disc width (mm) | Disc lateral dimension (mm) | Disc height anterior (mm) | Disc height center (mm) | Disc height posterior (mm) | Disc grade | Donor age (years) | Donor weight (kg) | Gender |
|---|---|---|---|---|---|---|---|---|---|---|
| **Preload Test Series (Specimens tested with and without posterior elements)** | | | | | | | | | | |
| 1 | L2-3 | 37.3 | 49.4 | 8.4 | 10.5 | 5.6 | | 58 | 122 | F |
| 2 | L4-5 | 37.3 | 51.3 | 11.2 | 9.0 | 4.7 | | 58 | 122 | F |
| 3 | L2-3 | 33.6 | 42.9 | 8.4 | 9.0 | 3.7 | | 17 | 52 | F |
| 4 | L4-5 | 33.4 | 44.8 | 9.4 | 10.5 | 4.7 | | 17 | 52 | F |
| 5 | L2-3 | 32.3 | 42.5 | 9.4 | 10.5 | 4.7 | | 21 | | F |
| 6 | L4-5 | 32.8 | 44.0 | 11.2 | 11.0 | 6.5 | | 21 | | F |
| 7 | L2-3 | 31.6 | 44.6 | 9.4 | 9.0 | 5.6 | | 52 | | F |
| 8 | L4-5 | 32.1 | 46.8 | 9.4 | 6.8 | 4.7 | | 52 | | F |
| Mean | | 33.8 | 45.8 | 9.6 | 9.4 | 5.0 | | 37.0 | | |
| (SD) | | (2.3) | (3.1) | (1.1) | (1.4) | (0.8) | | (19.4) | | |
| **Frequency Test Series (Posterior elements removed)** | | | | | | | | | | |
| 1 | L1-2 | 36.5 | 49.0 | | | | 3 | 39 | 115 | F |
| 2 | L3-4 | 41.7 | 53.1 | | | | 3 | 58 | | M |
| 3 | L3-4 | 44.3 | 60.9 | | | | 5 | 30 | 102 | M |
| 4 | L2-3 | 32.3 | 42.7 | | | | 1 | 19 | 57 | F |
| 5 | L2-3 | 38.2 | 44.7 | | | | 3 | 58 | 82 | M |
| 6 | L3-4 | 44.9 | 53.7 | | | | 3 | 55 | 77 | M |
| 7 | L1-2 | 43.7 | 50.6 | | | | 3 | 55 | 77 | M |
| 8 | L4-5 | | | | | | 1 | 16 | 75 | M |
| Mean | | 40.2 | 50.7 | | | | 2.8 | 41.3 | 83.6 | |
| (SD) | | (4.2) | (6.1) | | | | (1.3) | (17.7) | (19.1) | |

*Blank signifies data not available.*