ELSEVIER

Journal of Orthopaedic Research 21 (2003) 547–552

Journal of Orthopaedic Research

www.elsevier.com/locate/orthres

Physiological axial compressive preloads increase motion segment stiffness, linearity and hysteresis in all six degrees of freedom for small displacements about the neutral posture

Mack G. Gardner-Morse *, Ian A. Stokes

Department of Orthopaedics and Rehabilitation, University of Vermont, Stafford Hall, Burlington, VT 05405-0084, USA

Received 26 September 2002

Abstract

The stiffness of motion segments, together with muscle actions, stabilizes the spinal column. The objective of this study was to compare the experimentally measured load–displacement behavior of porcine lumbar motion segments in vitro with physiological axial compressive preloads of 0, 200 and 400 N equilibrated in a physiological fluid environment, for small displacements about the neutral posture. These preloads are hypothesized to increase stiffness, hysteresis and linearity of the load–displacement behavior.

At each preload, displacements in each of six degrees of freedom (±0.3 mm AP and lateral translations, ±0.2 mm axial translation, ±1° lateral bending and ±0.8° flexion/extension and torsional rotations) were imposed. The resulting forces and moments were recorded. Tests were repeated after removal of posterior elements. Using least squares, the forces at the vertebral body center were related to the displacements by a symmetric 6×6 stiffness matrix. Six diagonal and two off-diagonal load–displacement relationships were examined for differences in stiffness, linearity and hysteresis in each testing condition.

Mean values of the diagonal terms of the stiffness matrix for intact porcine motion segments increased significantly by an average factor of 2.2 and 2.9 with 200 and 400 N axial compression respectively ($p < 0.001$). Increases for isolated disc specimens averaged 4.6 and 6.9 times with 200 and 400 N preload ($p < 0.001$). Changes in hysteresis correlated with the changes in stiffness. The load–displacement relationships were progressively more linear with increasing preload ($R^2 = 0.82$, 0.97 and 0.98 at 0, 200 and 400 N axial compression respectively). Motion segment and disc load–displacement behaviors were stiffer, more linear and had greater hysteresis with axial compressive preloads.

Keywords: Biomechanics; Lumbar spine; Stiffness; Axial compressive preload; Hysteresis; Linearity

Introduction

The spinal column is stabilized by motion segment stiffness together with muscle forces and stiffness [1]. In dynamic situations, the absorption of energy associated with hysteresis also contributes to stability. Accurate analyses of spinal stability and force equilibrium therefore require accurate load–displacement properties of the motion segments. There are several limitations of the existing experimental load–displacement data. Most reported data do not include all six degrees of freedom, stiffness values were obtained by inverting flexibility data, and were obtained without physiological levels of axial compressive force. Physiological axial compression has been observed to increase motion segment stiffness by a factor of two or more [5,10]. This stiffening effect was predicted analytically in a model of the disc that includes the geometrical effects of disc compression and bulging [2]. Other than the axial direction, the effect of preload on hysteresis and linearity of the motion segment load–displacement behavior have not been reported. Additionally, the fluid and ionic environment may influence the mechanical behavior, since discs tested in a physiological saline bath have greater hydration than discs that are just exposed to saline spray and wrap [17].

This study was designed to investigate how the load–displacement behavior of motion segments for small displacements about the neutral posture varies with

* Corresponding author. Tel.: +1-802-656-2250; fax: +1-802-656-4247.

E-mail address: mack.gardner-morse@uvm.edu (M.G. Gardner-Morse).

0736-0266/03/$ - see front matter © 2002 Orthopaedic Research Society. Published by Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0736-0266(02)00199-7

axial compressive preloads under conditions that aimed to simulate the in vivo loading and fluid environment. Specifically we tested the hypotheses that motion segment stiffness increases, load–displacement behavior is more linear and hysteresis increases with axial compressive preloads. Also, we tested whether these effects are present in isolated intervertebral discs as well as in intact motion segments.

Methods

Each of six porcine lumbar segments (all animals over 16 weeks old) was embedded in dental PMMA (Zahn Acraweld, Henry Schein, Inc., Melville, NY) and attached to end-fittings. Biplanar radiographs were used to align the specimen's local axis system (based on the vertebral body centers) with the centers of the end-fittings. AP and lateral dimensions (i.e. minimum and maximum diameters) of each disc were measured from the X-rays.

The load–displacement behavior was measured directly in six degrees of freedom (6-DOF) by the method described in detail by Stokes et al. [19]. In this method a 'Steward platform' or 'hexapod' robot with six linear actuators displaces the upper end of the motion segment to any specified 6-DOF position relative to the immobilized lower vertebra. A 6-DOF loadcell measures the forces transmitted to the upper end of the specimen. Here, all rotational displacements occurred about the center of the upper vertebral body, as measured from the radiographs. Forces recorded by the loadcell were transformed to this same point. During these tests the specimens were immersed in an isotonic saline bath cooled to approximately 4 °C to slow the biological degradation of the specimens over the 76 h duration of testing of each specimen.

In each test, a sequence of axial compressive preloads of 0, 200 and 400 N was applied. There are six permutations of possible preload loading sequences and each was used once for each of the six specimens. The specimen was allowed to equilibrate with these preloads for at least 3 h before any stiffness measurements were gathered. The compressive preload was generated by applying vertical displacements with subsequent horizontal displacements to zero the shear forces. The axial preload values of 200 and 400 N were selected because they are typical of active in vivo loading in similar sized sheep [8]. At 400 N, the compressive stress was approximately 0.5 MPa. Six pure displacement tests (four sawtooth cycles each of three translations and three rotations) were then sequentially imposed (each cycle took 87 s), and the applied forces and moments were recorded every second. The displacements were ±0.3 mm in the AP and lateral translations, ±0.2 mm in axial translation, and ±1° in lateral bending and ±0.8° in flexion/extension and torsional rotations. After testing the intact motion segment, the posterior elements (facets and ligaments) were removed and the tests were repeated on the isolated disc.

The recorded data were analyzed to obtain measures of the stiffness, linearity and hysteresis of the load–displacement behavior in each of the 6-DOF. The tests provided initially 36 recordings (three forces and three torques for each of the three rotations and three translations). For the stiffness properties, forces were assumed to be linearly related to the displacements by a 6 × 6 stiffness matrix. In general there are 36 independent coefficients in this matrix, but this can be reduced to 21 coefficients by imposing matrix symmetry based on conservation of energy and assuming linear load–displacement properties [18,20]. These 21 independent coefficients were estimated using a least squares fit to experimental data [19]. Considerations of the sagittal plane symmetry and beam-like behavior of the motion segment permitted further reduction of the number of coefficients to six diagonal terms and two "primary" off-diagonal terms as defined by Goel [7]. The six diagonal terms are those stiffness terms that relate forces or moments to the collinear displacements or rotations (e.g. flexion moment associated with flexion rotation). The two primary off-diagonal terms relate the AP shear forces to the applied flexion/extension rotations (or the complementary flexion/extension moments to AP shear displacements) and lateral shear forces with lateral bending rotations (or the complementary lateral bending moments to lateral shear displacements). The complementary pairing of off-diagonal terms is a result of stiffness matrix symmetry.

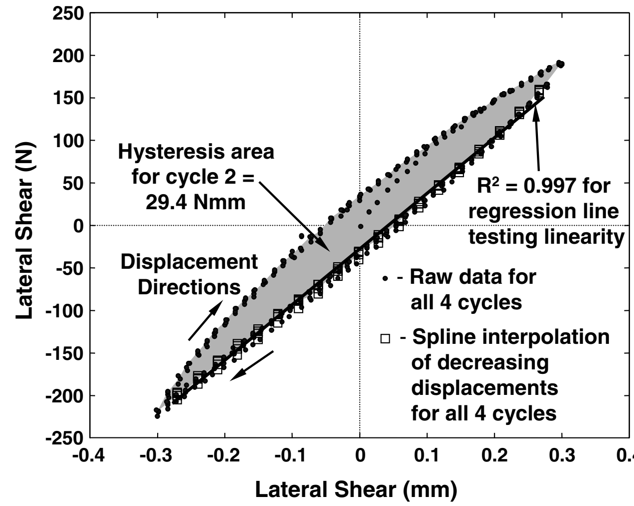

Fig. 1. Typical data for a porcine intact motion segment with lateral shear forces over all four cycles of lateral shear displacements with a 400 N axial compressive preload. The fitted straight line shows the regression analysis for decreasing displacements. Both increasing and decreasing displacements were used to evaluate linearity (see text). The shaded area shows the hysteresis area enclosed by the second cycle of displacement.

The linearity of the load–displacement relationship was evaluated from data from the four repeat cycles of displacement by calculating the proportion of variability explained by linear regression, lack of fit (nonlinearity) and pure experimental error, using the coefficient of determination R^2. To remove the variation associated with hysteresis, the analyses were done separately for the increasing and decreasing displacements of the four cycles of each recording. Spline curvefits were used to obtain load data at the same displacements in each of the four cycles (see Fig. 1). The coefficient of determination values for the two displacement directions were then pooled. The linearity estimates of each of the two primary off-diagonal load–displacement recordings were also pooled.

The hysteresis (a measure of damping) was evaluated as the enclosed area in the load–displacement recording for the second and third displacement cycles (see Fig. 1). Correlation analyses were done to determine whether there was any relationship between hysteresis area and stiffness, and also whether physical dimensions of the isolated disc and its stiffness were related.

Differences in stiffness coefficients, linearity and hysteresis area with preload were analyzed using repeated-measures ANOVA both for intact motion segments and for isolated discs. Linear and quadratic contrasts were used to determine whether there were significant linear or quadratic relationships between preload and the load–displacement stiffness, linearity, or hysteresis area. The significance level for all statistical analyses was set at $p = 0.05$.

To estimate the contribution of the posterior elements to motion segment behavior with increasing preloads, the stiffness and hysteresis area of the isolated discs were subtracted from those of the intact motion segment to estimate the stiffness and hysteresis area of the posterior elements. Then the effect of the preload was partitioned between the disc and the posterior elements by regression analysis.

Results

Increased preload produced progressively increased stiffness in all eight of the principal stiffness terms. Mean

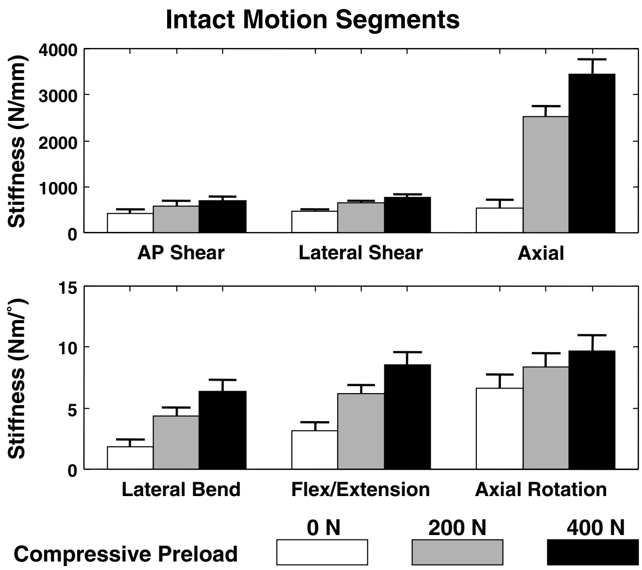

Fig. 2. Mean and standard error of diagonal terms of the stiffness matrix for intact motion segments at three levels of axial compressive preload. All six stiffnesses and the two primary off-diagonal stiffness terms increased linearly with preload ($p < 0.001$). The increases in stiffness with preload decreased slightly with increasing preload for the axial stiffness ($p = 0.012$).

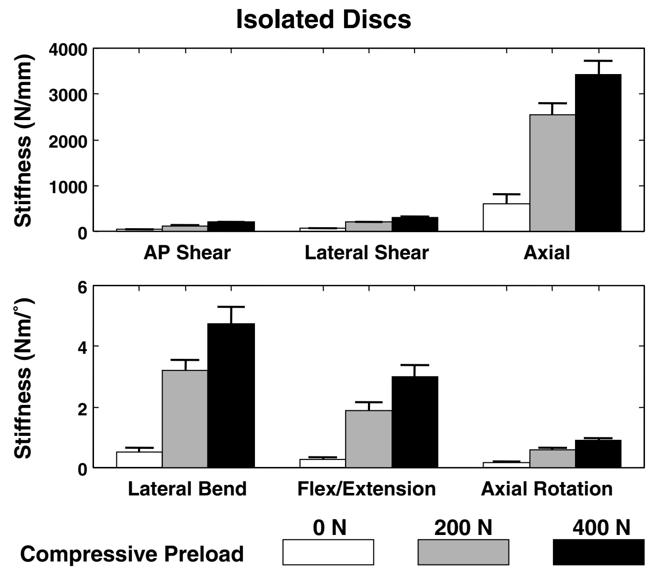

Fig. 3. Mean and standard error of diagonal terms of the stiffness matrix for isolated discs at three levels of axial compressive preload. All six stiffnesses and the two primary off-diagonal stiffness terms increased linearly with preload ($p \leqslant 0.003$). The increases in stiffness with preload decreased slightly with increasing preload for the axial stiffness ($p = 0.007$).

values of the six diagonal terms of the stiffness matrix for intact motion segments increased by an average factor of 2.2 and 2.9 from the no-preload condition with 200 and 400 N compression respectively (all six $F_{2,10} \geqslant 32.45$, $p < 0.001$) (Fig. 2). After removal of the posterior elements (i.e. for isolated discs), the diagonal terms of the stiffness matrix increased by a mean 4.6 and 6.9 times compared to the no-preload condition with 200 and 400 N preload (all six $F_{2,10} \geqslant 54.88$, $p < 0.001$) (Fig. 3). The linear increase in stiffness with preload was highly significant for both intact motion segments and isolated discs for all eight stiffness terms ($F_{1,10} \geqslant 15.39$, $p \leqslant 0.003$).

Without preload the stiffness was very low in some cases (Figs. 2 and 3), and for the case of AP shear in an isolated disc with no preload the mean stiffness was 37 N/mm, which was not significantly different from zero. The two primary off-diagonal stiffness terms behaved similarly to the diagonal stiffness terms. These terms increased significantly ($p < 0.001$) by an average factor of 1.4 and 1.6 with 200 and 400 N preload respectively for intact motion segments and by a mean 3.5 and 5.4 times with 200 and 400 N preload for isolated discs.

There appeared to be a tendency for the stiffness increase with preload to be less when preload was increased from 200 to 400 N, compared to the increase from 0 to 200 N. However, a significant second-order effect of preload was only found for the case of axial stiffness, and this was found in both intact motion segments and in isolated discs ($F_{1,10} \geqslant 9.40$, $p < 0.012$).

For intact motion segments, axial compressive preload had the greatest effect on axial stiffness (4.7 and 6.4 times increases with 200 and 400 N preload). Axial compressive preload also had a large effect on lateral bending stiffness (2.4 and 3.5 times increases) and flexion/extension stiffnesses (2.0 and 2.7 times increases) with 200 and 400 N preloads. It was observed that the stiffness of isolated disc specimens with 400 N preload correlated with their disc cross-sectional area, but no correlations were evident in the no-preload condition.

The linearity of the load–displacement relationships (measured by the R^2 in linear regression analyses) also increased significantly with axial compressive preload (Table 1). By pooling results for all eight terms in the stiffness matrices, the mean R^2 values for intact motion segments were 0.93, 0.95 and 0.96 at 0, 200 and 400 N preloads and $R^2 = 0.70$, 0.95 and 0.96 at 0, 200 and 400 N preloads for isolated discs. Despite the high no-preload values of R^2, preloads produced significant further increases in linearity for three of the eight terms for intact motion segments and for all eight stiffness terms of isolated discs.

There was a very strong correlation between hysteresis area and stiffness under all testing conditions (see Fig. 4). The correlation for all six diagonal load–displacement relationships for intact motion segments ranged from $r = 0.90$ to 0.96 and for isolated discs ranged from $r = 0.88$ to 0.97. Thus, the increases in hysteresis area with preload were of very similar magnitude to those for stiffness. Hysteresis areas (averaged over the eight terms) increased by an average factor of 1.8 and 2.4 times the no-preload condition with 200 and

Table 1
Linearity of the load–displacement relationships of intact motion segments measured by the R^2 of the linear regression (pooled mean of six porcine specimens) at each of three levels of preload (0, 200 and 400 N)

	Intact motion segments			Isolated discs		
	0 N	200 N	400 N	0 N	200 N	400 N
AP shear	0.92	0.95	0.96[a]	0.78	0.97	0.97[b]
Lateral shear	0.98	0.99	0.99	0.82	0.96	0.98[b]
Axial	0.85	0.90	0.94[a]	0.82	0.91	0.95[a]
Lateral bend	0.96	0.97	0.98[a]	0.65	0.95	0.97[b]
Flex/extension	0.88	0.91	0.94	0.55	0.97	0.97[b]
Axial rotation	0.98	0.99	0.99	0.71	0.98	0.98[b]
AP shear-flex/extension[c]	0.90	0.92	0.93	0.58	0.90	0.91[a]
Lateral shear-rotation[c]	0.98	0.99	0.99	0.69	0.97	0.98[a]

There is an increase in R^2 with preload for all eight load–displacement relationships. Since the R^2 values are already high for the intact motion segments, only three relationships showed a significant increase in linearity with preload.

[a] Significant linear increase in R^2 with preload ($p \leqslant 0.012$).

[b] Significant linear increases and second-order changes in R^2 with preload ($p \leqslant 0.042$).

[c] Linearity of complementary pairs of primary off-diagonal values were pooled based on their having equal stiffness in a symmetric stiffness matrix.

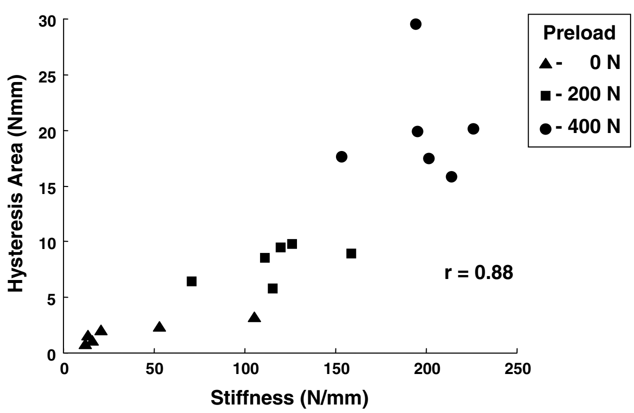

Fig. 4. A graph of the relationship between experimentally measured hysteresis and stiffness. This example is for the diagonal AP shear load–displacement relationships in isolated discs. Each point represents the measurement of one specimen. A strong correlation was observed between hysteresis area and stiffness for all six diagonal load–displacement relationships for both intact motion segments ($r =$ 0.90–0.96) and isolated discs ($r = 0.88$–0.97).

400 N compression preload respectively for the intact specimens ($p < 0.001$). For isolated discs, hysteresis area increased by a mean 4.2 and 8.4 times with 200 and 400 N axial compression preload ($p < 0.001$).

The posterior elements were found to contribute substantially to the stiffness, as well as being sensitive to the effects of preload. Intact porcine specimens were on average 12.2 times stiffer than isolated discs when tested without preload. The addition of preload reduced this mean difference between intact specimens and isolated discs to 4.6 times and 3.6 times stiffer at 200 and 400 N preload. As expected, the contribution of posterior elements to the stiffness was greatest for axial rotation (10.7 times increase at 400 N preload) and least for axial stiffness (1.01 times increase at 400 N preload). The regression analyses of the disc and posterior elements stiffnesses with preload demonstrated that for most stiffness terms the discs were more sensitive than the posterior elements to the addition of axial preload (Table 2). In the case of hysteresis, the increase with preload was almost entirely attributable to the disc for the shear and axial displacements and for lateral bending.

Discussion

It was found that motion segment behavior measured without physiological levels of axial compressive pre-

Table 2
Percent of increase in stiffness and hysteresis area with axial compressive preload attributable to the isolated disc and posterior elements

	Stiffness		Hysteresis area	
	Isolated discs	Posterior elements	Isolated discs	Posterior elements
AP shear	60.0 (31.1)	40.0 (54.1)	97.6 (15.6)	2.4 (13.7)
Lateral shear	79.6 (21.7)	20.4 (23.2)	114.3 (13.9)	−14.3 (8.3)
Axial	96.6 (18.1)	3.4 (4.1)	87.1 (15.6)	12.9 (5.4)
Lateral bend	93.2 (23.8)	6.8 (17.0)	94.2 (12.1)	5.8 (5.8)
Flex/extension	49.9 (12.4)	50.1 (19.3)	51.6 (7.3)	48.4 (9.0)
Axial rotation	24.2 (13.1)	75.8 (65.9)	62.2 (19.3)	37.8 (31.5)
AP shear-flex/extension	21.9 (15.5)	78.1 (78.9)	69.0 (19.5)	31.0 (19.9)
Lateral shear-rotation	112.1 (66.0)	−12.1 (49.9)	147.1 (43.9)	−47.1 (21.4)

The standard errors are in parentheses.

load underestimates the in vivo values of stiffness and hysteresis in all six degrees of freedom. Load–displacement behavior also was more linear with application of axial compressive preload. These effects were present in intact motion segments and isolated intervertebral discs. These findings indicate that the elastic energy storage and energy absorption (damping) that occurs with displacements of motion segments in vivo increases with the magnitude of the prevailing muscle force and other applied loading. This has implications for spinal stability.

This study only addressed small displacements from the specimen's neutral posture to avoid large displacement effects such as finite changes in height resulting from large rotations. In relation to humans, the displacements in this study do represent at least 20% of the average range of motion, as observed during functional activities in vivo [12]. All the tests reported here are for a single, relatively slow, rate of displacement. This rate was considered appropriate for quasi-static analyses of the spine.

The load–displacement measurements were estimated over the tested range of positive and negative displacements without distinguishing between data for opposite displacement directions. Differences in stiffness for positive and negative directions for AP shear, axial tension/compression and flexion/extension displacements were observed, despite the high values of the linearity measured by R^2.

Using the vertebral body centers to define the local axis system for displacements and forces resulted in negligible values for 12 of the 13 secondary off-diagonal terms of the stiffness matrix. The exception was the relation between axial tension/compression and flexion/extension. The magnitude of this relationship was related to the alignment of the specimen in the sagittal direction, so it was excluded from these analyses of preload effect.

Our analyses that partitioned the preload effect between the disc and the posterior elements (Table 2) indicate that both components are affected by preload, but overall the disc's contribution is larger, especially for hysteresis. The facets are considered to engage as the motion segment is compressed, thereby explaining their altered contribution to stiffness. However, it is not clear how their contribution to the hysteresis would increase by this mechanism.

There are several possible explanations for how preload causes an increase in stiffness and linearity of the load–displacement behavior of the disc. Using an analytical model of the disc, Broberg [2] predicted a doubling in stiffness for rotational degrees of freedom with axial preload increased from 700 to 3000 N. In Broberg's model of a constant volume disc with annular fibers containing a pressurized nucleus, the increased stiffness was caused by the geometrical effects of disc bulging and by nonlinear elastic properties of annular fibers.

For hysteresis, we believe that a combination of fluid flow effects and viscoelastic tissue properties [9] were responsible for the increase in hysteresis with preload. At a higher frequency (12 Hz) of compressive displacement, Ohshima et al. [13] reported that the hysteresis in porcine tail discs decreased when compressive preload was applied. This appears to be compatible with viscoelastic effects predominating at higher frequencies and poroelastic effects (time-dependent behavior associated with fluid flow relative to a porous solid) predominating at the lower frequency that was employed in this study.

Porcine spines were tested in this investigation because they were less likely to have any degeneration and were expected to have more uniform mechanical properties. While anatomically similar to human spines, porcine spines have thinner discs, the vertebrae have longer processes, and the facet joints appeared to be slightly more constraining. In comparison to the stiffness values for human lumbar specimens reported by Janevic et al. [10], the porcine lumbar motion segments tested in this study had shear stiffnesses 1.5–6.2 times higher and similar rotational stiffnesses.

Similar findings for human lumbar motion segments for the stiffness increase with preload have been reported by Janevic et al. [10], and for sagittal plane stiffnesses by Edwards et al. [5]. Wilke et al. [21] used an apparatus with cables and deadweights to simulate muscle forces of 80–400 N. They also reported increased stiffness with increased applied 'muscular' forces, but these forces also extended the spine, potentially confounding the results. Janevic et al. [10] reported that the stiffening effect was approximately proportional to preload magnitude. With 2200 N preload, rotational flexibility decreased on average 2.6 times, and shear flexibility 6.16 times, the effects being even greater at 4400 N preload. Thus our findings were similar for the increases in rotational stiffness with preload, but were much smaller for shear.

Conversely, Panjabi et al. [15] reported some loss of stiffness with axial load, but this was probably an experimental artifact resulting from the displacement of the preload point of application accompanying the displacements used to measure the flexibilities in other degrees of freedom [4,5]. This illustrates the methodological difficulties in simulating in vivo preload. Experimental systems that aim to simulate muscle actions using cables under tension [16,21] can produce confounding effects where the effects of forces in the cables may not be readily distinguishable from the intrinsic load–displacement behavior of the isolated motion segment. Tensioned cables generate transverse forces if their attachment points displace, and the energy changes associated with these displacements produce apparent (geometric) stiffness [4,11,18]. The methodology used in the present study uses computer servo-controlled displacements to eliminate these effects.

The load–displacement behavior was very repeatable over the four cycles of loading in each of the degrees of freedom as is evident in the sample data in Fig. 1. The pooled standard deviations of the force measurements over the four displacement–load cycles for the six diagonal degrees of freedom expressed as a percent of the mean forces were 11.0%, 9.0%, 10.0%, 9.3%, 12.2%, 12.8% respectively. In the past, several cycles of 'preconditioning' have been recommended [14] prior to recording load–displacement data in order to achieve representative behavior. It appears that the equilibration of the specimens to the preload in an isotonic fluid bath created more repeatable, and probably more physiological testing conditions. Testing without a bath probably permits successive cycles of load and displacement to expel more fluid than is reabsorbed. Pflaster et al. [17] demonstrated that discs equilibrated to a physiological saline bath achieve a greater hydration than discs that are just exposed to saline spray and wrap.

The findings of this study indicate that in vivo axial compressive loading substantially alters both the stiffness and hysteresis (energy absorbing) properties of the spine. The findings suggest that many of the mechanical studies and simulations of human spine function in relation to stability and effects of surgical interventions may have substantially underestimated the contribution of the motion segments. Biomechanical analyses of the spine that are intended to simulate in vivo loading conditions should take these effects into account. Recently a number of stability analyses [1,3,6] have emphasized the importance of muscle forces and muscle stiffness in spinal stability. The present study makes it evident that an additional consequence of increased muscle forces is that they increase compressive loading on the spine, thereby increasing its stiffness and hysteresis, and consequently its static and dynamic stability.

Acknowledgements

Supported by NIH R01 AR 44119. Gary Badger and Richard Single performed the statistical analyses. Porcine lumbar motion segments were obtained with the kind assistance of Donita Bylski-Austrow.

References

[1] Bergmark A. Stability of the lumbar spine: A study in mechanical engineering. Acta Orthop Scand Suppl 1989;230:1–54.
[2] Broberg KB. On the mechanical behaviour of intervertebral discs. Spine 1983;8:151–65.
[3] Cholewicki J, McGill SM. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. Clin Biomech 1996;11(1):1–15.
[4] Cripton PA, Bruehlmann SB, Orr TE, et al. In vitro axial preload application during spine flexibility testing: towards reduced apparatus-related artefacts. J Biomech 2000;33(12):1559–68.
[5] Edwards WT, Hayes WC, Posner I, et al. Variation of lumbar spine stiffness with load. J Biomech Eng 1987;109:35–42.
[6] Gardner-Morse M, Stokes IA, Laible JP. Role of muscles in lumbar spine stability in maximum extension efforts. J Orthop Res 1995;13(5):802–8.
[7] Goel VK. Three-dimensional motion behavior of the human spine—a question of terminology. J Biomech Eng 1987;109(4):353–5.
[8] Hauerstock D, Reindl R, Steffen T. Telemetric measurement of compressive loads in the sheep lumbar spine. In: Transactions of the 47th Annual Meeting of the Orthopaedic Research Society, San Francisco, CA, Abstract no. 0931, 2001.
[9] Iatridis JC, Setton LA, Weidenbaum M, Mow VC. The viscoelastic behavior of the nondegenerate human lumbar nucleus pulposus in shear. J Biomech 1997;30(10):1005–13.
[10] Janevic J, Ashton-Miller JA, Schultz AB. Large compressive preloads decrease lumbar motion segment flexibility. J Orthop Res 1991;9(2):228–36.
[11] Knapp RH. Derivation of a new stiffness matrix for helically armoured cables considering tension and torsion. Int J Numer Meth Eng 1979;14(4):515–29.
[12] Marras WS, Lavender SA, Leurgans SE, Fathallah FA, Ferguson SA, Allread WG, et al. Biomechanical risk factors for occupationally related low back disorders. Ergonomics 1995;38(2):377–410.
[13] Ohshima H, Tsuji H, Hirano N, et al. Water diffusion pathway, swelling pressure, and biomechanical properties of the intervertebral disc during compression load. Spine 1989;14(11):1234–44.
[14] Panjabi M, Abumi K, Duranceau J, Oxland T. Spinal stability and inter-segmental muscle forces. A biomechanical model. Spine 1989;14:194–200.
[15] Panjabi MM, Krag MH, White AA, Southwick WO. Effects of preload on load displacement curves of the lumbar spine. Orthop Clinics North Am 1977;8:181–92.
[16] Patwardhan AG, Havey RM, Meade KP, et al. A follower load increases the load-carrying capacity of the lumbar spine in compression. Spine 1999;24(10):1003–9.
[17] Pflaster DS, Krag MH, Johnson CC, et al. Effect of test environment on intervertebral disc hydration. Spine 1997;22(2):133–9.
[18] Przemieniecki JS. Theory of matrix structural analysis. New York: McGraw-Hill Inc.; 1968.
[19] Stokes IAF, Gardner-Morse M, Churchill D, Laible JP. Direct measurement of spinal motion segment stiffness matrix. J Biomech 2002;35(4):517–21.
[20] Weaver Jr W, Gere JM. Matrix analysis of framed structures. Second ed. New York: Van Nostrand Reinhold Company Inc.; 1980.
[21] Wilke HJ, Wolf S, Claes LE, et al. Stability increase of the lumbar spine with different muscle groups. A biomechanical in vitro study. Spine 1995;20(2):192–8.