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Validation of a Noninvasive Dynamic Spinal Stiffness Assessment Methodology in an Animal Model of Intervertebral Disc Degeneration

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Study Design. An experimental *in vivo* ovine model of intervertebral disc degeneration was used to quantify the dynamic motion response of the lumbar spine.

Objective. The purpose of this study was to: (1) compare invasively measured lumbar vertebral bone acceleration responses to noninvasive displacement responses, and (2) determine the effects of a single level degenerative intervertebral disc lesion on these responses.

Summary of Background Data. Biomechanical techniques have been established to quantify vertebral motion responses, yet their invasiveness limits their use in a clinical setting.

Methods. Twenty-five Merino sheep were examined; 15 with surgically induced disc degeneration at L1–L2 and 10 controls. Triaxial accelerometers were rigidly fixed to the L1 and L2 spinous processes and dorsoventral (DV) mechanical excitation (20–80 N, 100 milliseconds) was applied to L3 using a spinal dynamometer. Peak force and displacement and peak-peak acceleration responses were computed for each trial and a least squares regression analysis assessed the correlation between L3 displacement and adjacent (L2) segment acceleration responses. An analysis of covariance (ANCOVA) was performed to test the homogeneity of slopes derived from the regression analysis and to assess the mean differences.

Results. A significant, positive, linear correlation was found between the DV displacement of L3 and the DV acceleration measured at L2 for both normal ($R^2 = 0.482$, $P < 0.001$) and degenerated disc groups ($R^2 = 0.831$, $P < 0.001$). The L3 DV displacement was significantly lower (ANCOVA, $P < 0.001$) for the degenerated group (mean: 10.39 mm) in comparison to the normal group (mean: 9.07 mm). Mean peak-peak L2–L1 DV acceleration transfer was also significantly reduced from 12.40 m/s^2 to 5.50 m/s^2 in the degenerated animal group (ANCOVA, $P < 0.001$).

Conclusion. The findings indicate that noninvasive displacement measurements of the prone-lying animal can be used to estimate the segmental and intersegmental motions in both normal and pathologic spines.

Key words: biomechanics, disc degeneration, lumbar spine, stiffness. **Spine 2009;34:1900–1905**

Knowledge of spine segment, or functional spinal unit (FSU), motion patterns (kinematics), and forces (kinetics) is of importance in understanding the response of the spine to externally applied loads. Such biomechanical analyses of the spine play an important role in providing objective data to better understand the biomechanical variables involved in spinal disorders and musculoskeletal pain. In principle, a dysfunctional or unstable FSU may exhibit increased displacement or decreased stiffness, compared to adjacent segments.[1] Conversely, lower lumbar vertebrae[2,3] or segments with degenerated discs[4,5] display increased stiffness. Consequently, the displacement of the FSU and the resistance of spinal tissues to applied forces during assessments or manual treatments may be potentially very useful in spinal diagnosis and for establishing effective treatment protocols.

Physicians, clinicians, and therapists assess the motion of the human spine in an attempt to assess the functional status of underlying anatomy during physical examination of patients with musculoskeletal pain. Clinicians have used mobilization palpation procedures to manually apply posteroanterior (PA) forces over various spinal segments to assess the perceived tissue resistance and pain provocation. Clinicians further use the perceived results of these assessments to formulate clinical diagnoses, to identify spinal levels to target treatment, and to judge the supposed effectiveness of their interventions. Due to the qualitative nature of such assessments, however, many studies have demonstrated that such clinical judgments are unreliable or inaccurate.[6–11] For this reason, mechanical devices have been developed to more objectively quantify spine stiffness.[12–17] To this extent, a series of studies have appeared investigating the reliability of mechanical devices or instruments to assess spinal stiffness with favorable results.[14–20]

Ideally, measurements of the mechanical response of the spine should be accomplished using a procedure wherein motions and forces are measured *in vivo* and directly on the spinal structures, but such measurements generally necessitate an invasive procedure.[21,22] In 1994, Nathan and Keller[23] were the first to quantify the *in vivo* motion char-

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acteristics of human lumbar FSUs during externally applied spinal manipulative therapy using a intervertebral motion device. In this work, approximately 50 to 125 N PA forces applied on the order of 5 milliseconds to the spinous process of L2 produced relative posterior to anterior (PA) spinal displacements that were higher in a normal subject examined in comparison to subjects with an L4–L5 retrospondylolisthesis or L4–L5 degenerated disc. Of interest was the finding that vertebral stiffness derived from noninvasive mechanical impedance (force-velocity) measurements at the site of application of the spinal manipulative therapy impulse showed a close correspondence to the sagittal plane intervertebral motion device motion measurements of adjacent segments. Segments with higher intervertebral displacement and rotation exhibited decreased mechanical impedance (increased stiffness). This indicated that PA force-acceleration measurements may be a valid method to noninvasively probe the mechanical behavior of the human spine and other structures, which has motivated the present study.

Indeed, gold-standard measurements of spinal motion using accelerometers rigidly attached to the spinous processes are only applicable from a research standpoint and lacking any clinical utility. For this reason, a noninvasive measurement technology was developed to measure acceleration responses of the spine at the point of application, using a driving point mechanical impedance technique. To validate the acceleration responses of the spine using this methodology, prompted the current study. Thus, the purpose of this animal experimental study was to: (1) compare invasively measured lumbar vertebral bone acceleration responses to noninvasive dorsoventral (DV) displacement responses measured using a spinal motion dynamometer, and (2) determine the effects of a single level degenerative intervertebral disc lesion on acceleration and displacement responses.

Materials and Methods

Twenty-five healthy, adolescent Merino sheep were examined using a protocol approved by the Institutional Animal Ethics Committee. Fifteen Merino sheep (mean, 47.7 kg, SD, 4.9 kg) underwent a 5-month survival surgical disc injury procedure to experimentally induce disc degeneration at L1–L2 which was histologically confirmed postmortem.[4] Ten sheep (mean, 46.5 kg, SD, 5.6 kg) served as controls.

Disc Degeneration

Under general anesthesia (1 g thiopentone; 2.5% halothane), the lumbar spine of 15 adolescent Merino sheep (mean, 47.7, kg; SD, 4.9 kg) was approached *via* a direct lateral left-side retroperitoneal approach. In each animal, a controlled stab incision was made in the left posterolateral anulus fibrosus midway between the endplates of the L1–L2 disc.[24] Incisions were made with a number 15 scalpel blade directed transversely through the outer aspect of the posterior anulus towards the midline and inserted to the hilt of the scalpel handle (a depth of 5 mm). Fluoroscopic control was used to check the posterior limit of the blade. Care was taken to protect both the spinal cord and the exiting nerve root during the stab incision procedure. The injured disc level was marked with a wire around the associated transverse process. The wound was closed in layers and the animals received an intramuscular antibiotic injection 2 mL/50 kg (consisting of procaine penicillin 250 mg/mL, streptomycin 250 mg/mL, and procaine HCl 20 mg/mL). Animals recovered in an air-conditioned indoor facility on a 12-hour light/dark cycle for 3 days and were then transferred to an outdoor facility. They were kept on a paddock for 20 weeks while the anular lesion-induced disc degeneration matured. There were 10 control sheep (mean, 46.5 kg; SD, 5.6 kg) in which a sham spinal procedure was undertaken. All procedures were approved by the Institutional Animal Ethics Committee.

Experimental Protocol

Before testing, anesthesia was induced with an intravenous injection of 1g thiopentone and was maintained after endotracheal intubation by 2.5% halothane. Throughout testing the animals were ventilated and the respiration rate was linked to the tidal volume keeping the monitored $C0_2$ between 40 and 60 mm Hg. To quantify the dynamic, vibration response of the spine 10*g* piezoelectric, triaxial accelerometers were attached to intraosseous pins rigidly fixed to the L1 and L2 spinous processes under fluoroscopic guidance. The x-, y- and z-axes of the accelerometers were oriented with respect to the medial-lateral, DV, and cranial-caudal or axial axes of the vertebrae. Only DV acceleration responses are reported herein.

DV mechanical excitation was applied to the L3 spinous process using a spinal motion dynamometer (Figure 1), comprised of a computer-controlled, mechanical testing apparatus incorporating a linear voice coil actuator and programmable voice coil amplifier, and equipped with a 665 N load cell and a ±25 mm linear variable displacement transducer. A series of mechanical excitation forces with fixed pulse duration (100 milliseconds) and variable pulse amplitude (20, 40, 60, and 80 N) were administered to the L3 spinous process using the dynamometer. Five trials were performed for each mechanical stimulus intervention in a randomly determined order, resulting in a total of 20 force pulses administered to each animal. During mechanical excitation, DV force and displacement at L3, and L1 and L2 vertebral accelerations were recorded (Figure 2) at a sampling frequency of 5000 Hz using a 16-bit data acquisition system.

Pathologic Examination of Intervertebral Discs

At the conclusion of the study, the sheep were killed by intravenous injection of 6.5 g pentobarbitone sodium and their lumbar spines were removed *en bloc* by transecting the thoracolumbar junction and the midsacrum. Individual motion segments were isolated by cutting midway through the adjacent vertebral bodies with a band saw and fixed in 10% buffered formalin for a minimum of 72 hours before being decalcified in a solution containing 9.5% nitric acid and 10% edetic acid. The specimens were cut into 6 parasagittal slices of equal thickness and the slices showing the anulus lesion and a contralateral slice were processed into paraffin wax for examination. Tissue sections were cut at a nominal thickness of 5 μm, stained with hematoxylin and eosin, and independently examined without knowing identity of each animal. Intervertebral discs from all subjects were graded on a 1 to 4 scale of degeneration (1 = normal; 2 = mildly degenerated; 3 = moderately degenerated; 4 = severely degenerated) with respect to the overall condition of the disc (grade), as well as morphologic characteristics of the anulus fibrosus, nucleus pulposus, vertebral endplates, and subchondral bone.[25]

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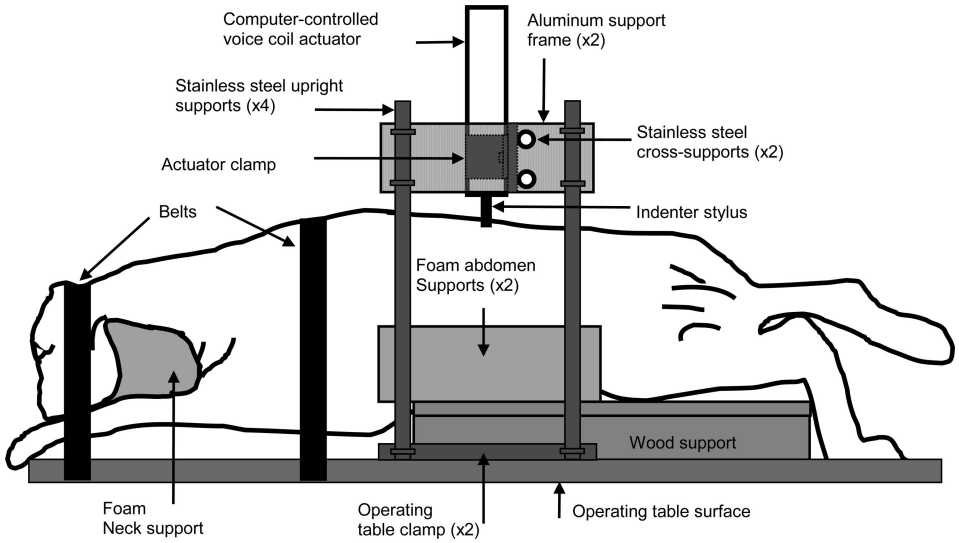

Figure 1. Schematic diagram of the computer-controlled mechanical testing apparatus positioned over the L3 spinous process of the prone-lying sheep. The apparatus consisted of an actuator assembly comprised of a voice coil actuator, linear variable differential transformer, load cell, and stainless steel indenter. The actuator assembly was attached to a stainless steel and aluminum load frame that was rigidly mounted to the operating table. Wood and foam supports were used to position and stabilize the trunk and abdomen.

Data Analysis

Peak force and displacement and peak-peak acceleration responses were computed for each trial. A least squares regression analysis was used to assess the correlation between L3 displacement and adjacent (L2) segment acceleration responses. An analysis of covariance (ANCOVA) was performed to test the homogeneity of slopes derived from the regression analysis and to assess the mean differences in L3 displacement between the normal disc and degenerated disc animal groups. Statistical significance was $P < 0.05$.

■ Results

Typical force-time, displacement-time, and L2–L1 intersegmental acceleration responses produced by the uniform pulse duration mechanical excitation are illustrated in Figure 2. The uniform force pulse resulted in a haversine-like DV displacement response at the point of contact (L3). DV displacement tended to lag behind the force by a few milliseconds. Intersegmental (L2–L1) DV vertebral accelerations showed large amplitude motions during both the onset and removal of the uniform force pulse.

A significant, positive, linear correlation was found between the DV displacement measured at L3 and the DV acceleration measured at L2: normal disc group ($R^2 = 0.482$, $P \ll 0.001$) (Figure 3); degenerated disc group ($R^2 = 0.831$, $P \ll 0.001$) (Figure 4). Tables 1–3 provide the means, standard deviations, and coefficients of variation for the dependent variables of L2 accelerations, L2–L1 acceleration transfers, and L3 displacements, resulting from independent 20 to 80 N mechanical excitation forces with comparison between animals with normal and degenerated intervertebral discs. The L3 DV displacement was significantly lower (ANCOVA, $P \ll 0.001$) for the degenerated group (mean, 10.39 mm) in comparison to the normal group (mean, 9.07 mm), indicating that surgically induced disc degeneration increased the DV stiffness of the ovine spine. Peak-

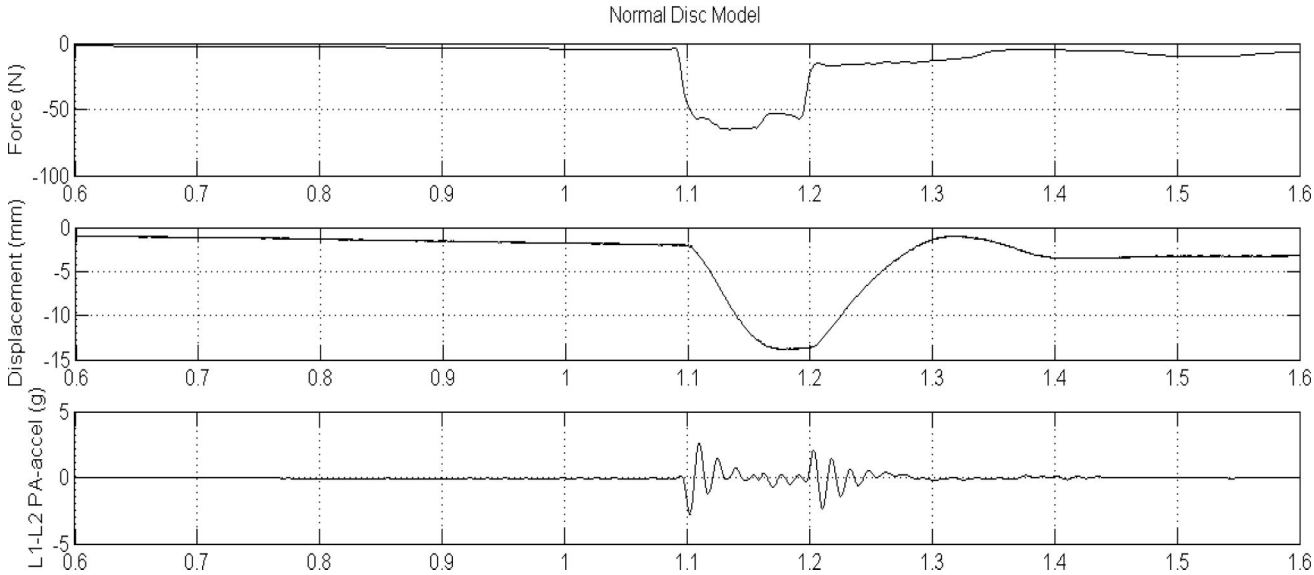

Figure 2. Typical recordings of input force applied to L3 (N), resulting L3 displacement (mm), and adjacent segment L2–L1 posteroanterior (PA) accelerations (*g*) in the normal ovine model.

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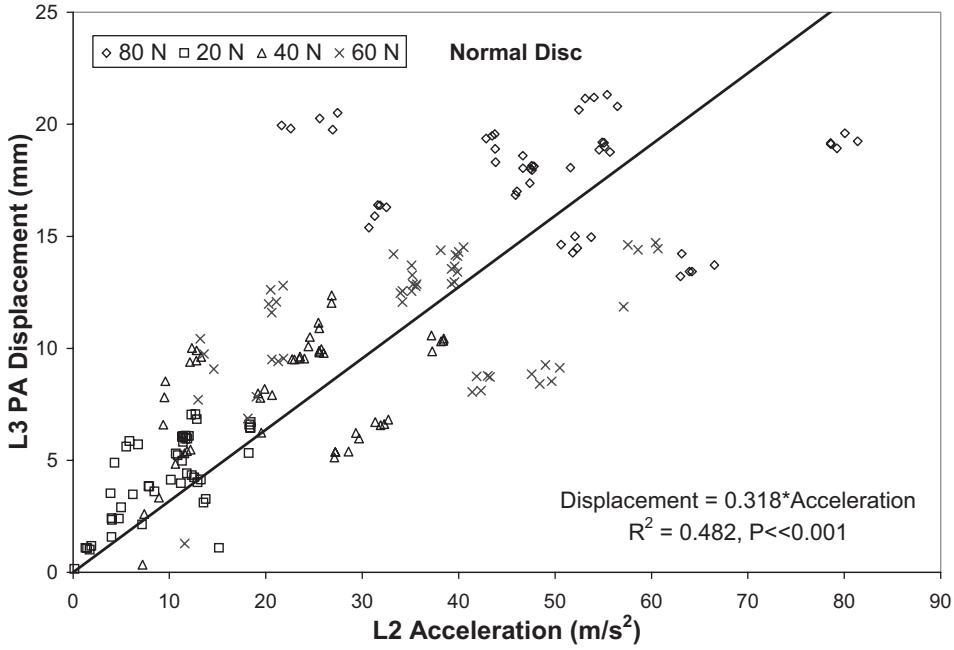

Figure 3. Least squares regression results for all 200 trials obtained for 20 N, 40 N, 60 N, and 80 N mechanical excitations in the normal sheep (control animals) correlating L3 displacement and adjacent segment acceleration responses at L2.

peak L2–L1 DV acceleration transfer was also significantly reduced in the degenerated animal group (normal disc mean = 12.40 m/s^2, degenerated disc mean = 5.50 m/s^2, ANCOVA, $P < 0.001$).

Discussion

The findings in this animal experimental study indicate that noninvasive displacement measurements of the prone-lying animal can be used to estimate the segmental and intersegmental motions in both normal and pathologic vertebrae. The use of motion sensors rigidly attached to intraosseous pins ensures that the dynamic response of the spine is precisely determined and free of motion artifacts associated with the skin and other structures.[1,21,26] Although this biomechanical assessment technique is desirable in a research setting, its invasiveness precludes it from use in clinical assessments of spinal mobility. Therefore, developments of biomechanical techniques that can be used in clinical practice that have been validated against a gold standard are important.

The maximum DV forces applied to the sheep lumbar spine corresponded to approximately 17% of the animal body weight, which is consistent with PA forces applied to the lumbar spine during spinal palpation during physical examination in clinical practice.[27,16] At these forces, we found that noninvasive displacement measurements obtained using a spine dynamometer apparatus were positively and linearly correlated to adjacent segment vertebral

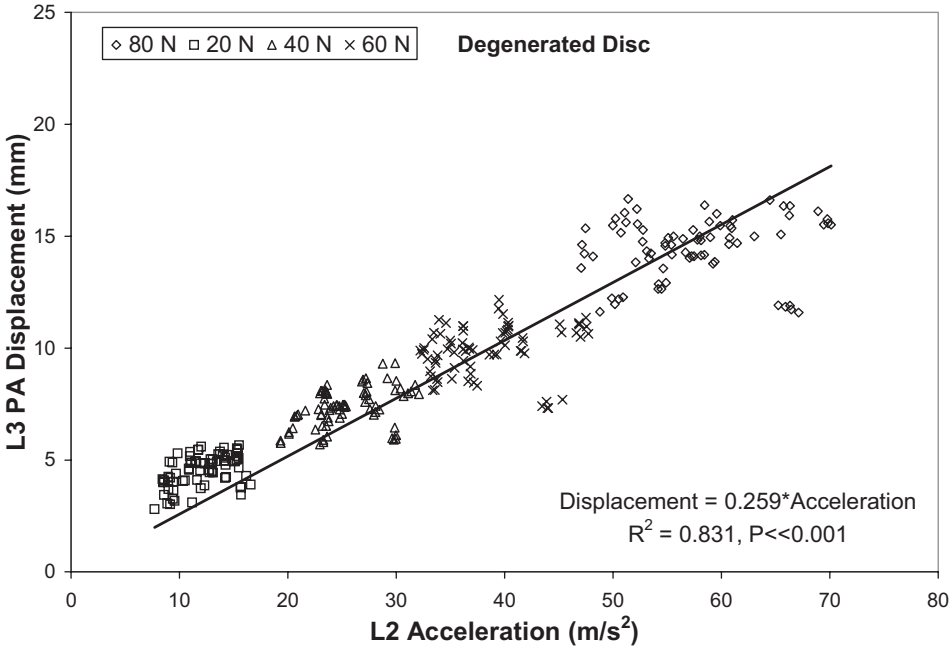

Figure 4. Least squares regression results for all 300 trials obtained for 20 N, 40 N, 60 N, and 80 N mechanical excitations in the sheep with confirmed intervertebral disc degeneration correlating L3 displacement and adjacent segment acceleration responses at L2.

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Table 1. Mean L2 Accelerations and Associated Descriptive Statistics*

	L2 Acceleration (m/s^2)					
	Normal			Degenerated		
Force (N)	Mean	SD	CV	Mean	SD	CV
20	9.70	4.89	50.38	12.18	2.45	20.09
40	22.40	9.06	40.45	25.42	3.32	13.08
60	35.31	13.43	38.02	38.48	4.59	11.93
80	50.01	14.87	29.74	57.35	6.26	10.92
All	29.36	18.72	63.75	33.39	17.26	51.70

*Associated Descriptive Statistics SD and CV resulting from the 20 to 80 N mechanical excitation forces and all combined in animals with normal and degenerated intervertebral discs.
SD indicates standard deviations; CV, coefficients of variation.

Table 3. Mean L3 Displacements and Associated Descriptive Statistics*

	L3 Displacement (mm)					
	Normal			Degenerated		
Force (N)	Mean	SD	CV	Mean	SD	CV
20	4.35	1.90	43.66	4.53	0.71	15.67
40	8.05	2.55	31.70	7.34	0.87	11.86
60	11.33	2.77	24.49	9.92	1.11	11.19
80	17.84	2.31	12.97	14.49	1.35	9.33
All	10.39	5.51	53.05	9.08	3.81	42.01

*Associated Descriptive Statistics SD and CV resulting from the 20 to 80 N mechanical excitation forces and all combined in animals with normal and degenerated intervertebral discs.
SD indicates standard deviations; CV, coefficients of variation.

motions measured using accelerometers rigidly attached to adjacent vertebrae. Noteworthy, was the fact that we were able to differentiate the DV segmental (L3) and intersegmental (L2–L1) displacement and acceleration responses of animals with normal disc anatomy *versus* animals with histologically confirmed intervertebral disc degeneration.

It is important to note that the results of this study arise from an ovine animal model, and acceleration and displacement values are expected to be different in a human population. Nonetheless, the linear correlation between the invasively measured accelerations and those obtained noninvasively in this animal model are encouraging and represent an important first step in validating clinical assessments of intersegmental and segmental spinal motions. Earlier investigations have demonstrated biomechanical and biochemical similarities between sheep and human intervertebral discs.[28] Thus, the ovine animal model is deemed to be a valid model to investigate biomechanical responses to dorsoventral mechanical excitation.

It is also important to point out that the animals examined in this study were anesthetized, which may have altered the mechanical responses (force-displacement) slightly. Most likely any effects of muscle tone on the force-displacement response of the spine were minimal, however, as the ligamentous spine is a highly damped structure.[1] Recent work indicates that although sustained supramaximal muscle stimulation increases the PA stiffness (force/displacement) of the ovine spine up to 2-fold, the effects of low amplitude muscle stimulation are much less dramatic (less than 5% increase in PA stiffness).[29] Therefore, the absence of muscle tone should have a minimal effect on the neuromechanic responses reported in this study.

Table 2. Mean L2–L1 Acceleration Transfer and Associated Descriptive Statistics*

	L2–L1 Acceleration Transfer (m/s^2)					
	Normal			Degenerated		
Force (N)	Mean	SD	CV	Mean	SD	CV
20	3.81	2.57	67.48	1.92	1.19	61.85
40	9.79	4.73	48.31	4.11	2.41	58.66
60	14.67	7.52	51.26	5.63	3.70	65.64
80	21.32	8.91	41.78	10.34	5.14	49.69
All	12.40	9.06	73.09	5.50	4.62	83.91

*Associated Descriptive Statistics SD and CV resulting from the 20 to 80 N mechanical excitation forces and all combined in animals with normal and degenerated intervertebral discs.
SD indicates standard deviations; CV, coefficients of variation.

To perform the regression analysis herein, 20 N, 40 N, 60 N, and 80 N forces were chosen to compare invasively measured pin mounted accelerations with noninvasive measurements of displacements at the segmental contact point. A limitation of our study was our inability to obtain both of these measurements simultaneously at the same segmental level, which is likely responsible for some of the variance observed. Notwithstanding, a significant, positive, linear correlation was found between the DV displacement measured at L3 and the DV accelerations measured at the adjacent segment (L2) for both normal and degenerated animals. In other work, we have begun to make both noninvasive and invasive measures at the same segmental contact point, which is expected to result in an even higher correlation between measures.

The linear correlation between the 2 spinal measurement techniques in the current study has important clinical implications in terms of assessing the mechanical stiffness of the normal and pathologic human spine. Further validation of dynamometer technology for other loading frequencies,[14] pulse durations,[30] and at other regions of the spine[1] will assist in providing an objective biomechanical methodology to quantify the mechanical status of the back.

■ Key Points

- Dynamic spinal stiffness assessments have been developed to objectively quantify vertebral displacements for a given force and frequency.

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• Noninvasive dynamic spinal stiffness results were compared to data obtained from an invasive gold-standard approach using motion sensors rigidly affixed to the spine by intraosseous pins in an animal model. A linear correlation was found for the 2 methodologies and differences in dynamic spinal stiffness were observed between animals with normal and degenerated intervertebral discs.
• These findings indicate that noninvasive displacement measurements can be used to estimate the segmental and intersegmental vertebral motions in both normal and pathologic spines, which have important clinical implications for human assessments.

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