Neuromechanical Characterization of in vivo Lumbar Spinal Manipulation. Part I. Vertebral Motion

Tony S. Keller, PhD,[a] Christopher J. Colloca, DC,[b] and Robert Gunzburg, MD, PhD[c]

Abstract

Objective: To quantify in vivo spinal motions and coupling patterns occurring in human subjects in response to mechanical force, manually assisted, short-lever spinal manipulative thrusts (SMTs) applied to varying vertebral contact points and utilizing various excursion (force) settings.

Methods: Triaxial accelerometers were attached to intraosseous pins rigidly fixed to the L1, L3, or L4 lumbar spinous process of 4 patients (2 male, 2 female) undergoing lumbar decompressive surgery. Lumbar spine acceleration responses were recorded during the application of 14 externally applied posteroanterior (PA) impulsive SMTs (4 force settings and 3 contact points) in each of the 4 subjects. Displacement time responses in the PA, axial (AX), and medial-lateral (ML) axes were obtained, as were intervertebral (L3-4) motion responses in 1 subject. Statistical analysis of the effects of facet joint (FJ) contact point and force magnitude on peak-to-peak displacements was performed. Motion coupling between the 3 coordinate axes of the vertebrae was examined using a least squares linear regression.

Results: SMT forces ranged from 30 N (lowest setting) to 150 N (maximum setting). Peak-to-peak ML, PA, and AX vertebral displacements increased significantly with increasing applied force. For thrusts delivered over the FJs, pronounced coupling was observed between all axes (AX-ML, AX-PA, PA-ML) (linear regression, $R^2 = 0.35\text{-}0.52$, $P < .001$), whereas only the AX and PA axes showed a significant degree of coupling for thrusts delivered to the spinous processes (SPs) (linear regression, $R^2 = 0.82$, $P < .001$). The ML and PA motion responses were significantly ($P < .05$) greater than the AX response for all SMT force settings. PA vertebral displacements decreased significantly ($P < .05$) when the FJ contact point was caudal to the pin compared with FJ contact cranial to the pin. FJ contact at the level of the pin produced significantly greater ML vertebral displacements in comparison with contact above and below the pin. SMTs over the spinous processes produced significantly ($P < .05$) greater PA and AX displacements in comparison with ML displacements. The combined ML, PA, and AX peak-to-peak displacements for the 4 force settings and 2 contact points ranged from 0.15 to 0.66 mm, 0.15 to 0.81 mm, and 0.07 to 0.45 mm, respectively. Intervertebral motions were of similar amplitude as the vertebral motions.

Conclusions: In vivo kinematic measurements of the lumbar spine during the application of SMTs over the FJs and SPs corroborate previous spinous process measurements in human subjects. Our findings demonstrate that PA, ML, and AX spinal motions are coupled and dependent on applied force and contact point. (J Manipulative Physiol Ther 2003;26:567-78)

Key Indexing Terms: *Acceleration; Biomechanics; Chiropractic; Kinematics; Lumbar Spine; Manipulation*

Introduction

As spinal manipulation (SM) and chiropractic adjustment continue to be investigated for their clinical outcomes, basic science research into the mechanisms of the interventions lag behind and remain poorly understood. Because spinal manipulation is a mechanical intervention, it is inherently logical to assume that its mechanisms of therapeutic benefit may lie in the mechanical properties of the applied force (mechanical mech-

[a]Professor and Chair, Department of Mechanical Engineering, The University of Vermont, Burlington, Vt.

[b]Director, State of the Art Chiropractic Center, Phoenix, Ariz, and Postgraduate and Continuing Education Department Faculty, New York Chiropractic College, Seneca Falls, NY.

[c]Senior Consultant, Department of Orthopaedic Surgery, Eeuwfeestkliniek Hospital, Antwerpen, Belgium.

Submit requests for reprints to: Dr Christopher J. Colloca, State of the Art Chiropractic Center, PC, 11011 S 48th Street, Suite 205, Phoenix, AZ 85044 (e-mail: *cjcolloca@neuromechanical.com*).

Paper submitted June 12, 2002; in revised form September 6, 2002.

0161-4754/2003/$30.00 + 0
doi:10.1016/j.jmpt.2003.08.003

anisms), the body's response to such force (mechanical or physiologic mechanisms), or a combination of these and other factors. Biomechanical investigations of the spine's response to SM, therefore, should assist researchers, educators, and clinicians to understand the mechanisms of SM, more fully develop SM techniques, better train clinicians, and ultimately minimize risks while achieving better results with patients.

A number of studies have characterized the forces and force-time histories associated with various spinal manipulation therapies.[1-9] Such studies provide important information concerning the loading history and forces transmitted to patients. The posteroanterior (PA) stiffness or PA load-displacement response of the prone lying subject during SM has also been investigated using static or low-frequency indentation types of techniques, including mobilization and other physiotherapy simulation devices.[10-15] These studies indicate that the thoracolumbar spine has a quasi-static PA structural stiffness of approximately 15 N/mm to 30 N/mm at loads up to about 100 N. Stiffness measurements capture the displacement response of the area under test (vertebrae, disks, and adjacent structures—skin, muscles, and fascia) but cannot easily distinguish the contribution and/or displacement of individual vertebral components. To precisely quantify relative and absolute movements of individual vertebrae, it is necessary to rigidly attach intraosseous pins to the spine. Due to the invasiveness of such procedures, however, these techniques have only been performed in human cadavers[16,17] or in animals.[18,19] Research of this nature in living humans is very rare.[20]

In 1994, Nathan and Keller[21] first reported sagittal plane bone movements of the lumbar spine of human subjects during mechanical force, manually-assisted, short-lever (MFMA) spinal manipulative thrusts (SMTs). In their study, forces were delivered to the spinous processes (SPs) of the thoracolumbar spine using a spring-loaded adjusting instrument (Activator Adjusting Instrument, or AAI). Intersegmental or intervertebral movements of adjacent lumbar vertebrae were quantified using an intervertebral motion device (IMD)[22] attached directly to intraosseous pins fixed to the spinous processes. They found that the peak-to-peak amplitude of intervertebral motions were up to 6-fold greater when the short duration (< 5 milliseconds [ms]) AAI thrusts were delivered over spinous processes closer to the IMD measurement site. They also found that PA-directed forces produced coupled axial and flexion-extension rotation movements of the vertebrae. The study by Nathan and Keller[21] was limited to a single force amplitude PA thrust applied over the spinous processes in 3 subjects, and only the relative movements of 2 adjacent vertebrae (intervertebral motion) were determined. To our knowledge, there are no data in the literature that characterize the in vivo vertebral and intervertebral coupled motion responses of the spine to varying force amplitudes and contact points mimicking normal clinical practice.

The objective of this study was to quantify vertebral and intervertebral lumbar spinal motions occurring during spinal manipulation in human subjects in vivo. Mechanical force, manually assisted spinal manipulative thrusts of varying force amplitude were applied to vertebral contact points overlying the facet joints and spinous processes, as they are in routine clinical practice. We hypothesized that the vertebral motion response of the spine to PA thrusts would be coupled in different axes and that the force setting and vertebral contact point would modulate the motion response of the lumbar spine.

Methods

Four patients (2 male, 2 female; 48-75 years of age, mean age = 64.25 years, SD = 12.18) undergoing lumbar decompressive spinal surgery volunteered to participate in the study after providing informed consent of the surgical procedure and research protocol. The procedures used were in accordance with the ethical standards of the hospital's ethical committee on human experimentation. Patients were brought to the operating room and general endotracheal anesthesia was induced. Initial anesthetics did not include any long-lasting (>15 minutes) paralyzing agents. Patients were placed prone on a surgical frame and their lower backs were prepped and draped in a normal aseptic fashion (Fig 1). Padded supports were placed at the level of the iliac crests and sternum, with a slight flexion of hips and knees to assure that the subjects were lying in a lordotic position simulating the normal erect posture.

Finely threaded, 1.8-mm–diameter intraosseous stainless steel pins were rigidly fixed to the lumbar spinous process (L1, L3, and/or L4) using fluoroscopic guidance. Pin placements were at L1, L3, and L1 for patients 001, 002, and 004, respectively. Two vertebral levels (L3 and L4) were examined for patient 003 (Figs 1 and 2). A high-frequency (0.3 Hz to 10 KHz), low noise (0.0003*g* root-mean-square [RMS] resolution), alternating current (AC)-coupled piezoelectric, integral sensor, triaxial accelerometer (Crossbow Model CXL100F3, Crossbow Technology, Inc, San Jose, Calif) was mounted to the intraosseous pin. The x-, y-, and z-axes of the accelerometer were oriented with respect to the medial-lateral (ML), PA, and cranial-caudal or axial (AX) axes of the vertebrae. Prior to the SMT protocol, the natural frequency of the pin(s) was determined by "plucking" the pins in the ML and AX axes.

Mechanical force, manually-assisted spinal manipulative thrusts were delivered using an Activator II Adjusting Instrument (AAI II, Activator Methods International, Ltd, Phoenix, Ariz). Four different AAI II force excursion settings (0, 1, 2, and 3) were examined with thrusts delivered using an anterior-superior loading vector to the left and right facet joints (LFJ, RFJ) at the level of the pin (Table 1). Anterior-superior thrusts were also delivered at the maximum excursion setting over the facet joints (FJs) (left and

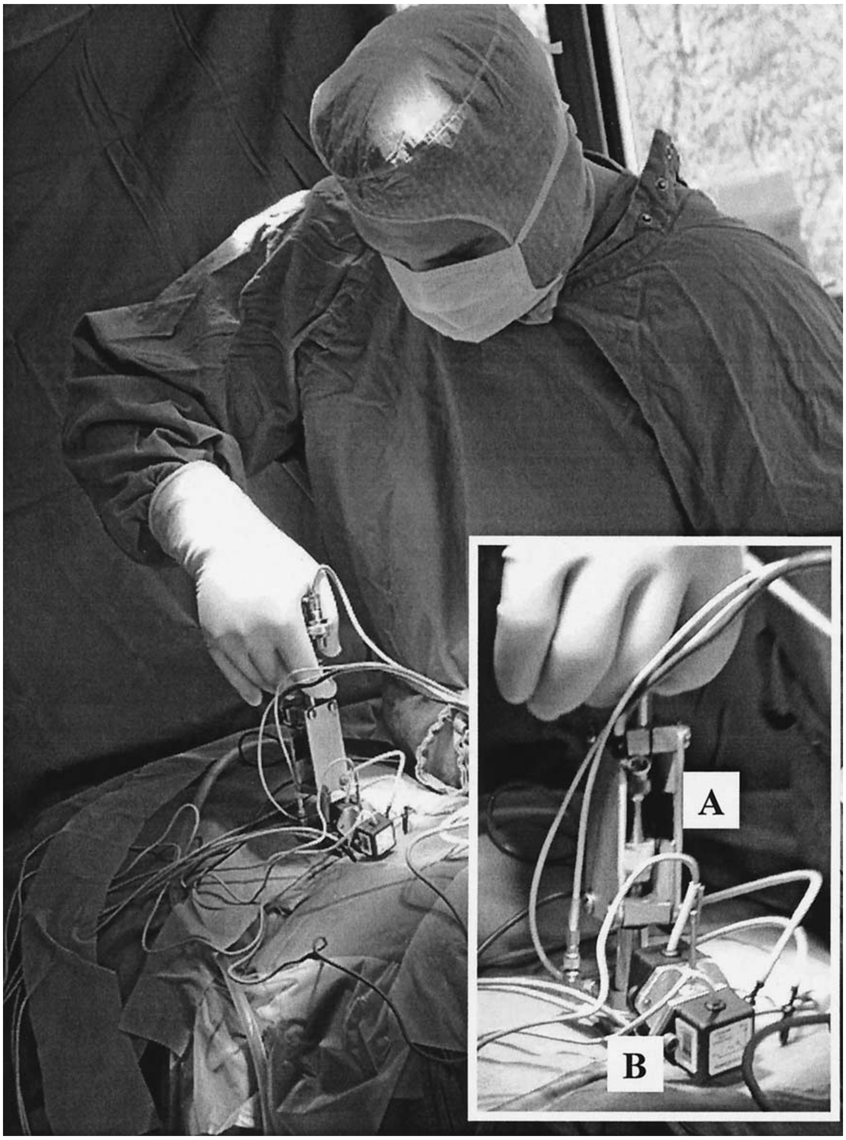


Fig 1. *Experimental protocol noting surgical preparation (patient 003) with detail of the AAI instrumented with preload control frame, force and acceleration transducers (*A*), and the 3-axis accelerometers affixed to the intraosseous pins (*B*).*

right) and to the SP above and below the level of the pin. All thrusts were delivered at the end of expiration during the patients breathing cycle. External thrusts were performed by a clinician with 7 years experience (CC), who was careful to perform the thrusts in a manner consistent with delivery of MFMA SMT in routine clinical practice. Namely, the anterior-superior loading vector was approximately 20°. In each patient, 2 SMTs were performed over the spinous processes and 12 SMTs were performed over the FJs. Segmental contact points for the spinous processes were determined using fluoroscopic guidance. The FJ contact point was unable to be obtained with fluoroscopic imaging but rather was consistently located by contacting 10 mm to 15 mm lateral to the SPs. A total of 14 external SMTs were delivered to each patient. For the 4 patients, 8 thrusts were applied to the facet joints for each force excursion setting (0, 1, 2, 3) and for each contact point (above, at, and below pin).

In patient 003, thrusts above the superior accelerometer pin corresponded to the L2 segment, whereas thrusts below the inferior accelerometer pin were delivered to the L5 segment. In this patient, an AAI equipped with a 5000-*g* quartz accelerometer (PCB model 305A04, PCB Piezotronics, Buffalo, NY) and a 2200-N quartz load sensor (PCB model 201A03) attached to the end of the stylus were used to deliver the thrusts and to simultaneously quantify the force input and acceleration response.[6,23]

The vertebral accelerations, AAI acceleration, and AAI force responses were recorded at a sampling frequency of 8192 Hz using a Biopac MP100 12-bit data acquisition system (Biopac Systems, Inc, Santa Barbara, Calif) and Acknowledge software (Biopac Systems, Inc). Velocity

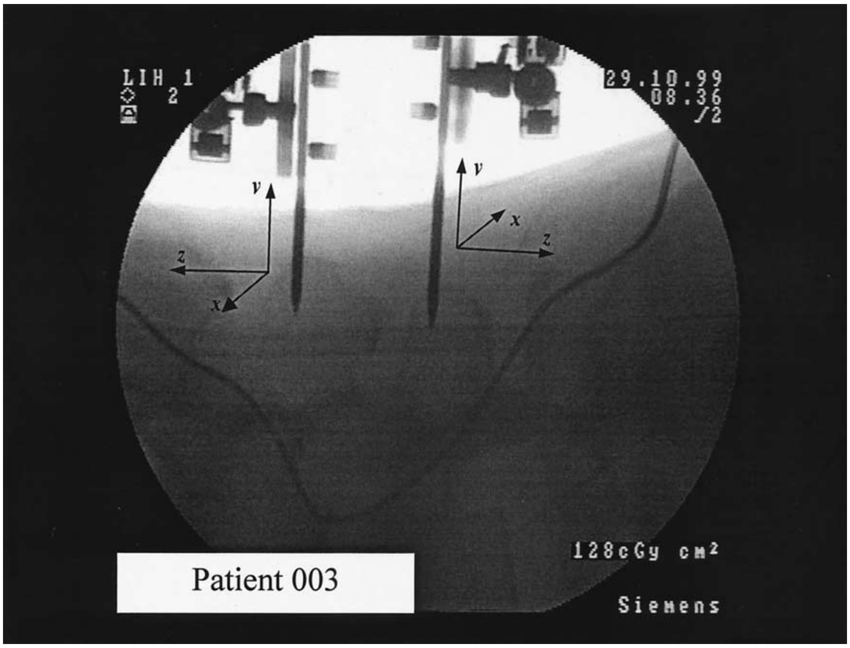


Fig 2. *Lateral fluoroscopic image of surgical pin-accelerometer preparation (patient 003). The Cartesian coordinate system of each of the accelerometers is illustrated, where the x-axis, y-axis, and z-axis correspond to the ML, PA, and AX axes, respectively.*

Table 1. *Summary of AAI thrust locations and excursion force settings*

	AAI excursion setting			
Contact point	0 (8)*	1 (8)	2 (8)	3 (32)
Above pin				LFJ RFJ SP
At pin	LFJ RFJ	LFJ RFJ	LFJ RFJ	LFJ RFJ
Below pin				LFJ RFJ SP
Force (N)†	30	88	117	150

AAI, Activator Adjusting Instrument; *LFJ,* left facet joint; *RFJ,* right facet joint; *SP,* spinous process; *SMT,* spinal manipulative thrust.
*Total number of thrusts for each force setting (4 patients).
†Patient 003 only (average of 2 SMTs).

time and displacement time responses were obtained from the acceleration time histories using trapezoidal numerical integration (Matlab, MathWorks, Boston, Mass). Peak-to-peak magnitudes of the vertebral acceleration, velocity, and displacement time histories were computed using Matlab. For statistical purposes, only peak-to-peak acceleration and displacement responses are considered in this report. A least squares linear regression was performed to examine acceleration motion coupling between the 3 coordinate axes of the vertebrae. Intervertebral (L3-4) displacement time histories were obtained for patient 003 by taking the difference of the L3 and L4 PA axis displacement time histories and adding the L3 and L4 ML and AX axes displacement time histories. L3 and L4 ML and AX vertebral displacement time histories were added as the accelerometer x- and y-axes were reversed due to the placement of the transducer (refer to Fig 2).

A robust analysis of variance (RANOVA) was performed to determine the effects of force setting and contact point on the ML, PA, and AX vertebral motion responses of the lumbar vertebrae to thrusts applied over the facet joints. The RANOVA consisted of a Kruskal-Wallis one-way analysis of variance by ranks to test for independence among the group means, followed by a post hoc analysis (Scheffé test) to establish significance. A RANOVA was also performed to assess differences in the ML versus PA and ML versus AX motion responses for each of the 4 force settings. The nominal type I error rate of 0.05 was used.

Results

The short duration (~ 5 ms), high-acceleration (±1000 ms^{-2}) impulsive force thrusts over the spinous processes (Fig 3) and facet joints (Fig 4) produced transient oscillations in the vertebrae, which decreased to near-0 amplitude over an approximately 100- to 150-ms time period. Peak-to-peak MFMA SMT forces ranged from 30 N (setting 0) to 150 N (setting 3) (Table 1). Peak-to-peak MFMA SMT accelerations ranged from 689 m/s^2 (setting 0) to 2013 m/s^2 (setting 3). The motion response amplitude and duration of oscillation varied substantially with respect to the type and location of the thrusts and among the 4 patients. Table 2 summarizes the minimum, maximum, and mean peak-to-

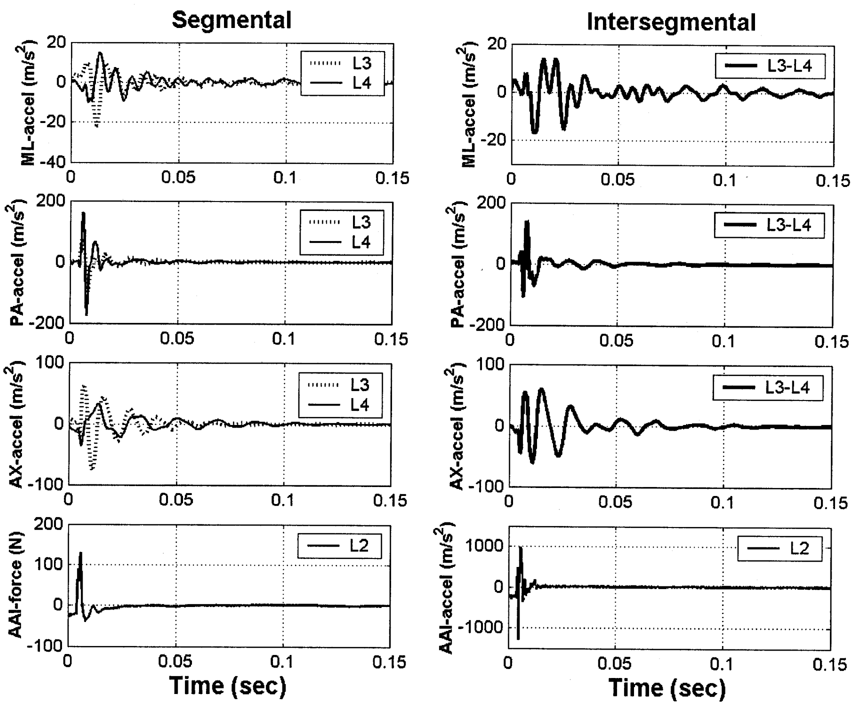


Fig 3. *Segmental (L3 and L4 vertebrae) and intersegmental (L3-4) vertebral acceleration response to a setting 4 MFMA thrust on the L2 spinous process of patient 003. The MFMA SMT (AAI) input force and acceleration response are shown in the bottom left and bottom right graphs, respectively.* ML, *Medial-lateral axis;* PA, *posterior-anterior axis;* AX, *axial axis.*

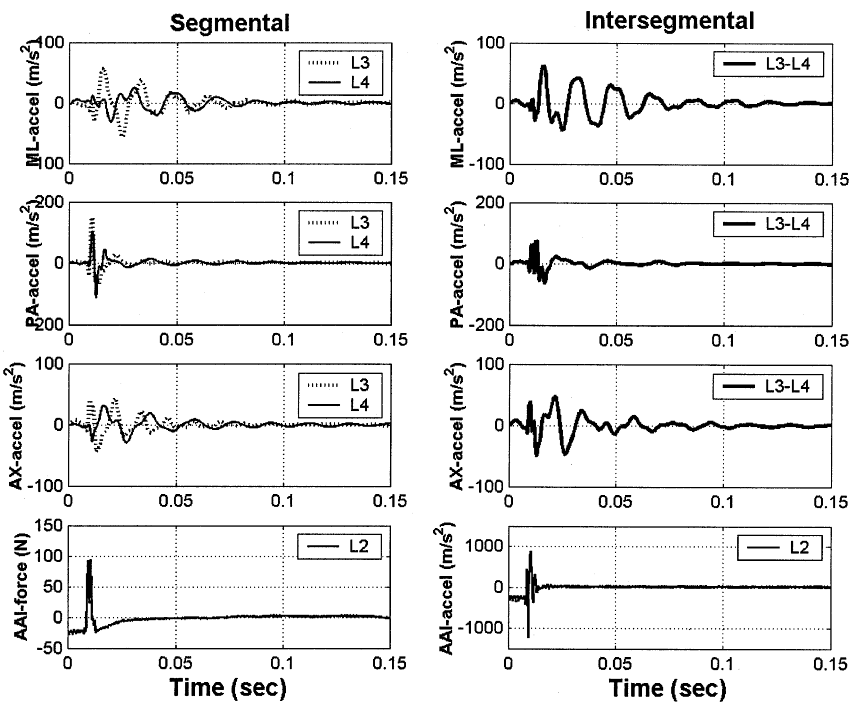
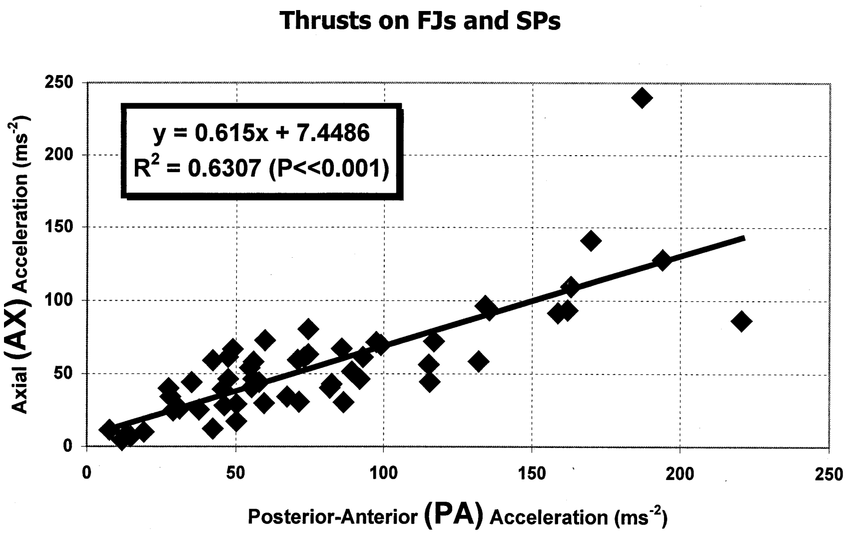


Fig 4. *Segmental (L3 and L4 vertebrae) and intersegmental (L3-4) vertebral acceleration response to a setting 4 MFMA thrust on the L2 left facet joint of patient 003. The MFMA SMT (AAI) input force and acceleration response are shown in the bottom left and bottom right graphs, respectively.* ML, *Medial-lateral axis;* PA, *posterior-anterior axis;* AX, *axial axis.*

Table 2. *Vertebral segment motion summary*

	Medial-Lateral (ML)	Axial (AX)	Posteroanterior (PA)
Displacement (mm)	0.15–0.66 (0.43)*	0.07–0.45 (0.25)	0.15–0.81 (0.48)
Velocity (mm/s)	42.2–210.1 (125)	23.5–169.9 (98.8)	37.8–198 (112)
Acceleration (m/s^2)	21.9–99.8 (59.2)	12.1–108 (55.9)	20.5–150 (78.6)

Minimum, maximum, and mean values.
All thrusts (N = 56).
*Mean values.



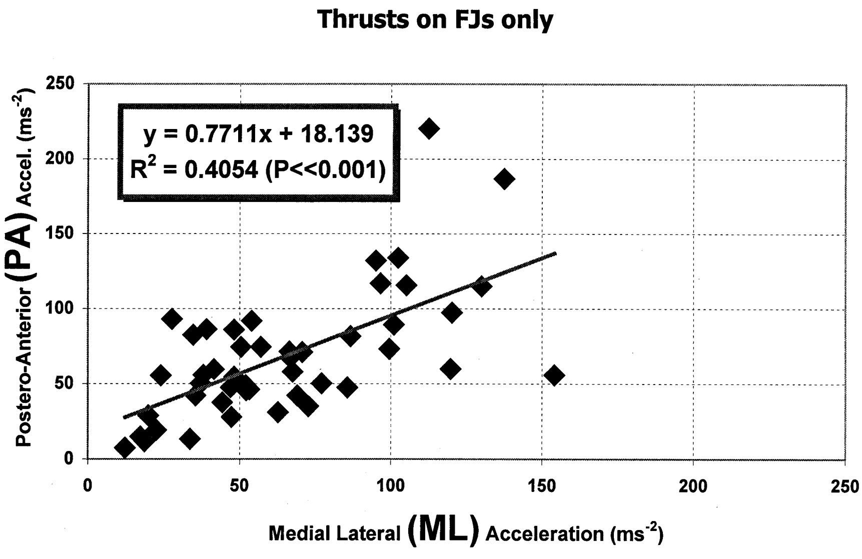


Fig 5. **A**, *Correlation between axial (*AX*) and posteroanterior (*PA*) motion in response to anterior-superior vector PA thrusts of varying force magnitude and varying contact point.* **B**, *Correlation between medial-lateral (*ML*) and posteroanterior (*PA*) motion in response to anterior-superior vector PA thrusts of varying force magnitude and contact over the facet joints.*

peak axial, posterior-anterior, and medial-lateral vertebral displacement, velocity, and acceleration responses obtained for the 4 subjects during the application of various externally applied SMTs.

There was a significant amount of off-axis vertebral motion or coupling in response to the primarily PA-directed thrusts applied over both the SPs and FJs (Fig 5). For PA thrusts delivered over the FJs, significant coupling was observed be-

Table 3. *Linear regression results for acceleration coupling*

Thrust location	Linear regression slope and coefficient of determination (R^2)		
	AX/ML	AX/PA	PA/ML
SPs (n = 8)	0.95 (0.13)	0.54 (0.82)†	1.69 (0.15)
FJs (n = 48)	0.60 (0.35)‡	0.61 (0.52)‡	0.77 (0.41)‡
SPs + FJs (n = 56)	0.34 (0.10)*	0.62 (0.63)‡	0.39 (0.08)*

AX, axial; *ML,* medial-lateral; *PA,* posteroanterior; *SP,* spinous process; *FJ,* facet joint.
*$P < .05$.
†$P < .01$.
‡$P < .001$.

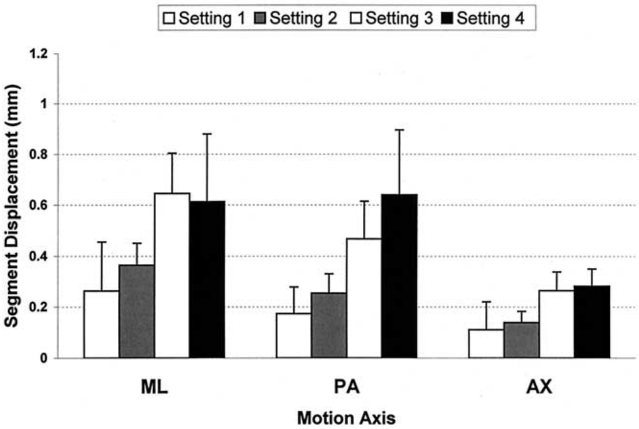


Fig 6. *Mean lumbar vertebral segment motion associated with anterior-superior vector PA thrusts over the facet joints at the level of the pin. Medial-lateral (*ML*), posteroanterior (*PA*), and axial (*AX*) motion responses to the 4 force settings (defined in text) are shown. Error bars indicate SDs. Eight measurements are associated with each force setting (LFJ and RFJ for 4 patients, refer to Table 1).*

tween all axes (AX-ML, AX-PA, PA-ML) (linear regression, R^2 = 0.35-0.52, $P < .001$), whereas only the AX/PA axes showed a significant coupling for thrusts delivered to the SPs (linear regression, R^2 = 0.82, $P < .01$) (Table 3).

Comparison of the segment displacement responses for thrusts applied over facet joints indicated that the ML and AX segment displacement increased in an incremental manner with increasing force up to setting 2 (Fig 6). Only the PA axis showed an incremental increase in the segment motion response over all 4 force settings. Increases in the ML, PA, and AX motion responses were significant ($P < .05$) for the 0 versus 2, 0 versus 3, 1 versus 2, and 1 versus 3 excursion settings. As expected, SMTs applied over the facet joints produced a more marked ML motion response in comparison with AX and PA motions. The ML and PA motion responses were significantly ($P < .05$) greater than the AX response for all force settings. Differences between the ML and PA motion responses to thrusts applied over the facet joints were significant ($P < .05$) for force settings 0 and 1 only.

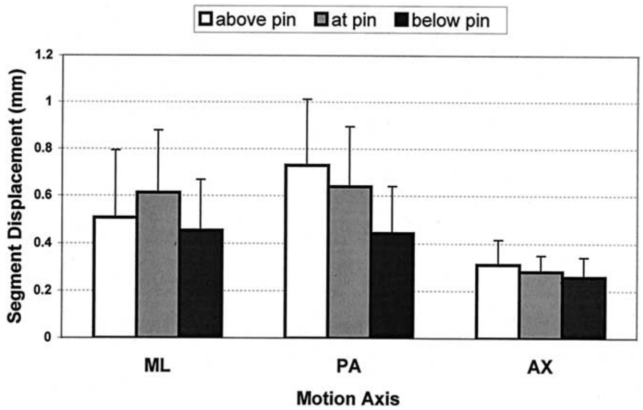
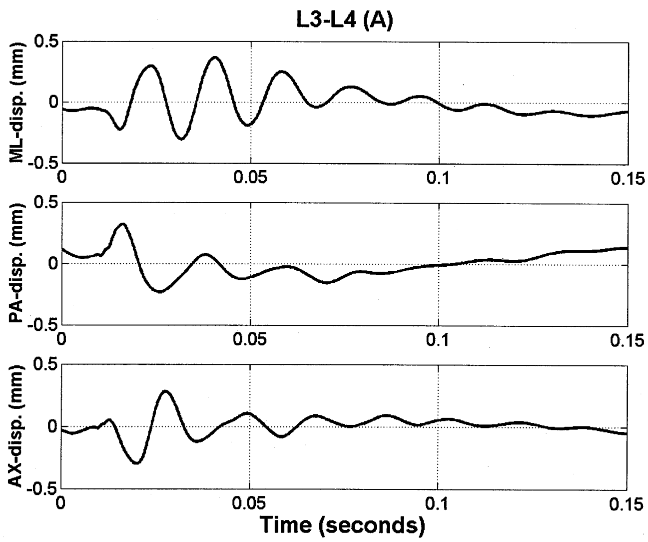


Fig 7. *Mean lumbar vertebral segment motion response associated with anterior-superior vector PA thrusts over the facet joints. Medial-lateral (*ML*), posteroanterior (*PA*), and axial (*AX*) motion responses to the maximum force setting (defined in text) at above and below the level of the pin and at the level of the pin are shown. Error bars indicate SDs. Eight measurements are associated with each contact point (LFJ and RFJ for 4 patients, refer to Table 1).*

Examination of the displacement data based on the vertebral contact level indicated that the ML vertebral displacement was greatest for maximum force thrusts (excursion 3 setting) delivered over the facet joints at the level of the pin (Fig 7). Thrusts over the facet joints above and below the level of the pin resulted in ML vertebral displacements that were 17% and 26% lower, respectively, than thrusts at the level of the pin. The PA vertebral displacements decreased significantly ($P < .05$) when the facet joint segmental contact point was more caudal. Combining the results obtained for the above pin and below pin contact points (n = 8), excursion 3 thrusts over the spinous processes were found to produce maximum displacements in the PA axis (0.60 ± 0.33 mm), followed by the AX axis (0.40 ± 0.15 mm) and ML axis (0.17 ± 0.09 mm). Differences between the PA and ML and AX and ML vertebral displacements were statistically significant for thrusts delivered over the spinous processes ($P < .05$).

The dynamic displacement response of the L3-4 motion segment of patient 003 is illustrated in Figure 8. The transient oscillations produced by thrusts over the L2 facet joints (Fig 8, *A*) and the L2 spinous processes (Fig 8, *B*) had a natural frequency of 50 Hz. The natural frequency of the pin-accelerometer construct determined by plucking the pin(s) in the axial and medial-lateral axes was 80 Hz or greater. Results of the L3-4 intervertebral analysis for thrusts on the facet joints at L3 are summarized in Figure 9. The magnitude of the intervertebral displacements tended to increase with increasing thrust force magnitude and was of similar magnitude as the vertebral responses. Setting 3 (maximum force) thrusts over the facet joints at L2 (above superior pin) and L5 (below inferior pin) resulted in PA,



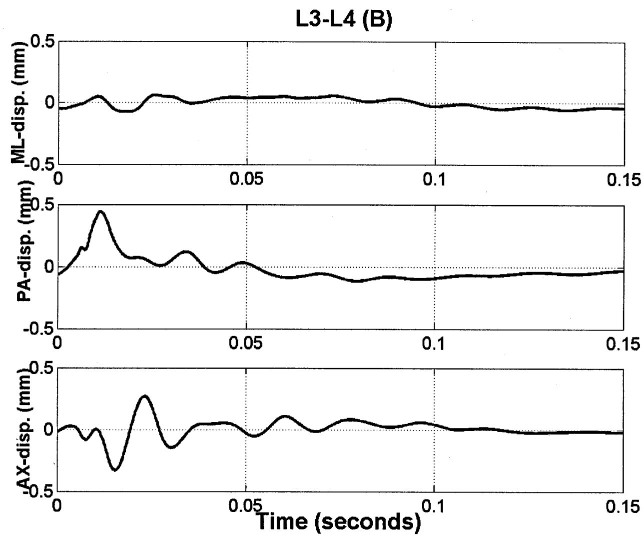


Fig 8. *Lumbar intervertebral (L3-4) vertebral displacement response to a setting 3 MFMA thrust on the L2 right facet joint (***A***), and on the L2 spinous process (***B***) of patient 003.* ML, *Medial-lateral axis;* PA, *posteroanterior axis;* AX, *axial axis.*

AX, and ML intervertebral displacements ranging from 0.31 to 0.93 mm (mean 0.58 mm), 0.28 to 0.67 mm (mean 0.48 mm), and 0.50 to 0.81 mm (mean 0.65 mm), respectively. In patient 003, a single maximum force thrust was delivered over the spinous processes above and below the L3-4 motion segment, resulting in maximum intervertebral displacements of 0.51 mm, 0.53 mm, and 0.17 mm for the PA, AX, and ML axes, respectively.

Discussion

This study characterizes the in vivo dynamic PA motion response of the lumbar spine during spinal manipulation in patients undergoing surgery. Spinal motions (L1 in 2 patients, L3 in 2 patients, and L4 in 1 patient) were measured in response to different excursion (force) settings and varying segmental contact points (spinous processes and facet joints) at the same spinal levels and adjacent to the pin placement (facet joints). To our knowledge, this marks the first study to report in vivo vertebral and intervertebral motion responses of humans during the application of PA forces in a manner consistent with spinal manipulative therapy.

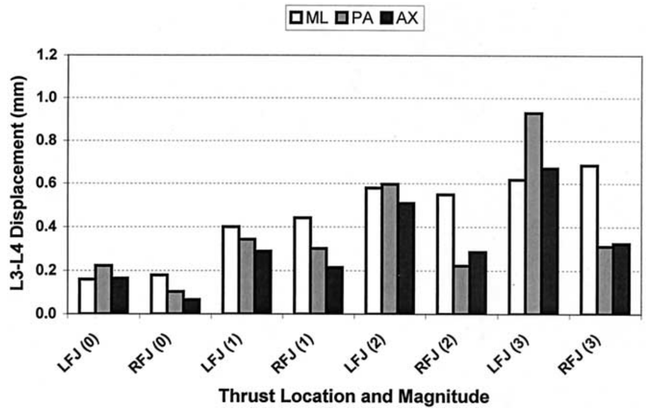


Fig 9. *Lumbar intervertebral (L3-4) vertebral displacement response associated with anterior-superior vector PA thrusts over the left and right facet joints at L3 (patient 003). Medial-lateral (*ML*), posteroanterior (*PA*), and axial (*AX*) motion responses to the 4 force settings (defined in text) are shown. Each bar represents a single thrust.*

Due to the invasiveness necessary to quantify spinal motions during spinal manipulation, previous research has typically been limited to cadaver studies.[1,16,17,24] Gál et al[16] reported their work in measuring relative movements between vertebral bodies during PA thoracic SM. In this study, steel bone pins were embedded into the vertebral bodies of 2 unembalmed postrigor cadavers (each aged 77 years) at the levels of T10, T11, and T12. High-speed cinematography measured spinal motions during SM delivered at the level of T11. Preload and peak forces were approximately 80 and 525 N, respectively, in this study. The authors reported statistically significant mean relative translations and rotations ranged from 0.3 ± 0.2 mm to 0.6 ± 0.4 mm and 0.0 ± 0.3° to 1.9 ± 0.2°, respectively, between the 2 subjects. Similarly, Maigne and Guillon[24] measured relative lumbar spinal motions during lumbar spinal manipulation in 2 unembalmed cadavers (aged 49 and 71 years) by implanting accelerometers into the vertebral bodies. Using side-posture manipulation, the authors reported a maximum translation between the L4-5 functional spinal unit of 1.1 mm. While the work of Gál et al[16] and Maigne and Guillon[24] report similar magnitudes of relative vertebral movements, a number of factors make the research difficult to generalize to our results, such as subject differences, recording and sampling methodologies utilized, and differences in the force-time profiles of the techniques used in the re-

Table 4. *Differences in methodology of studies of relative vertebral motions during spinal manipulation in human subjects*

Study	Subjects (*n*)	Methodology and recording technique	SMT technique (≈Force, Time)
Nathan and Keller[21]	In vivo (3)	Intervertebral motion device and strain gauge	Mechanical force, manually-assisted short lever (150 N, 5 ms)
Gal et al[16]	Cadavers (2)	High-speed cinematography	Reinforced hypothenar (525 N, 200 ms)
Maigne and Guillon[24]	Cadavers (2)	Accelerometers	Side posture (F-not reported, 200-700 ms)
Keller et al[25]	In vivo (4)	Accelerometers	Mechanical force, Manually-assisted short lever (150 N, 5 ms)

SMT, spinal manipulative thrust.

search. Table 4 highlights the differences in methodology in these 3 studies.

The amplitude and time history of the intervertebral motion responses are generally of the same magnitude as previously reported in situ and in vivo relative or intervertebral motion studies. Noteworthy, Nathan and Keller[21] used a 3–degree-of-freedom spatial linkage displacement sensor attached to 2.4-mm–diameter pins to quantify the in vivo motion response of the lumbar spine of 1 normal subject and 2 patients with spinal disorders requiring surgery. Pin placement was performed using a local anesthetic. In response to an approximately 90 N peak-to-peak PA impulsive force applied over spinous processes superior to the spatial linkage sensor, they reported intervertebral peak-to-peak PA displacements and axial displacements of the L3-4 and L4-5 vertebrae ranging from 0.10 to 0.51 mm and 0.25 to 1.5 mm, respectively. Accounting for differences in force magnitude, the PA intervertebral motion response to impulsive thrusts reported in this study agree with that of Nathan and Keller.[21] Axial displacements, however, were substantially lower than that reported by Nathan and Keller.[21]

The lower amplitude axial motion response obtained in the current study compared with Nathan and Keller[21] may reflect other factors, including the age and pathology of the patients. Patients in the Nathan and Keller[21] study were relatively young (36-53 years) and had minimal pathology (1 subject) or moderate lumbar degenerative disk disease (2 patients), in comparison with the patients in this study who were older (48-75 years) and who were undergoing decompressive spinal surgery for spinal canal stenosis. Other factors, notably the thrust force vector, segmental contact points in relation to the pin mount, posture during testing, and motion measurement method, may also have contributed to the observed differences. In the current study, thrusts were applied to the spinous process (and over the facet joints) in a manner consistent with clinical practice in contrast with Nathan and Keller,[21] who only examined thrusts over the spinous processes and who specifically applied vertically vectored forces with respect to the table on which the prone lying subjects were tested. In addition, the patients examined in the current study were given general anesthesia and were placed in a prone posture with their legs and hips slightly flexed, producing a more lordotic posture compared with the prone lying patients examined by Nathan and Keller.[21]

A limitation of the current study was the fact that we did not quantify the precise anterior-superior thrust angle and segmental contact points during the SMTs. Both of these factors may influence the motion response, but the surgical setting and the complexity of the motion and neurophysiological measurements performed precluded such measurements. Care was taken to perform the SMTs in a consistent and clinically relevant manner, namely anterior-superior angulations of 20° ± 5° and offset of 10 to 15 mm from the midline (thrusts over FJs). Indeed, our aim was to quantify the lumbar vertebral motion response associated with spinal manipulation as it is performed in routine clinical chiropractic practice. Recent studies, however, indicate that the sagittal plane PA and axial motion responses of the lumbar spine to impulsive forces are relatively insensitive to thrust angle/contact point variations of 20°/5 mm or less.[25] According to computer simulations performed by Keller and associates,[25] a 5° angulation difference (−15° versus −20°) and 5-mm contact point offset are predicted to result in less than an 0.1 mm difference in the peak-to-peak PA and axial motion responses to impulsive forces. Given the specificity of the SMT force vector and contact points, we feel that the methodology was justified. While imaging technology is currently available to identify the underlying segmental contact points during biomechanical assessments, we do not believe that this specificity would have assisted our aim of quantifying vertebral motions during clinically applied SMT. Nevertheless, the influence of variations in force vector and contact point on the in vivo motion response deserves further consideration.

The MFMA instrument used for the SMTs produced a very short time duration (impulsive) force that induced a transient dynamic oscillatory motion response. For a given force amplitude, impulsive forces are associated with smaller displacements in comparison with longer duration nonperiodic forces such as that commonly applied during manual manipulation.[25] Consequently, high-precision, low-noise, dynamic accelerometers were used in this study to quantify the dynamic motion response of individual segments and adjacent vertebral segments. The posteroanterior, medial-lateral, and axial acceleration responses and displacements derived from the acceleration responses indicate that the method yields results comparable with other kinematic measurement methods, including the aforementioned spatial linkage sensor. Additional work is needed to determine the reproducibility of the acceleration-based vertebral motion analysis method.

In the current study, we did not transform the Cartesian components of acceleration (x, y, z) to account for rotations of the vertebral segments or to estimate the flexion-extension rotation and medial-lateral rotation of the segments. Such transformations require knowledge of the location of the rotation axes relative to the accelerometer axes, and although we obtained fluoroscopic images of the pin-accelerometer sites, the image quality and image coverage were insufficient to perform these measurements in a manner precise enough to warrant transformation. Given the small absolute x, y, z vertebral displacements measured (< 1 mm), vertebral rotations would be predicted to be extremely small and therefore the transformed vertebral motions would not be expected to vary appreciably from that reported in this study. The absolute intervertebral flexion-extension rotations ($< 1°$) reported by Nathan and Keller[21] and vertebral and intervertebral flexion-extension rotations reported by Keller et al[25] support this assumption. A 6–degree-of-freedom motion measurement system (3 translations and 3 rotations) would provide a more precise description of vertebral displacements and could be used to obtain vertebral rotations.

Complex, force-dependent motion patterns were observed in response to the application of impulsive forces over the facet joints and the spinous processes. We found that SMTs applied over the facet joints tended to produce a more marked ML motion response, whereas thrusts applied over the spinous processes resulted in a greater posteroanterior and axial displacement response. We expected that vertebral motions would occur in each of the 3 orthogonal axes in response to thrusts delivered in primarily one axis; however, the significant off-axis motions or “coupling” response that was observed between all axes (AX-ML, AX-PA, PA-ML) was much more appreciable than we had originally hypothesized. Motion coupling may play a significant role in terms of the putative therapeutic response associated with spinal manipulative therapy. Also noteworthy was our finding that the vertebral motion response was modulated in proportion to the force amplitude. Namely, a 5-fold increase in the facet joint SMT force produced a significant increase in the ML (2.3×), PA (3.7×), and AX (2.5×) peak-to-peak displacements. Results obtained for the intervertebral motion response showed similar trends and were of similar amplitude to the vertebral motion response, but statistical analyses could not be performed since intervertebral motion responses were obtained in only one patient. Additional work is needed to quantify the effects of SMT force amplitude and contact point on in vivo intervertebral motion responses.

It is important to note that our results are presented for patients undergoing surgery for significant spinal disorders and therefore should not be considered “normal lumbar segment motion responses.” As previously noted, investigations into spinal motions during SM are in their infancy, so readily available data regarding spinal motions in normal subjects as opposed to subjects with spinal disorders are sparse.[21] A number of studies indicate that it is likely that spinal motions are highly dependent on the force-time input of the directed thrust,[14,26-28] as well as a variety of clinical factors such as pain,[7,13,29] spinal morphology,[30] the presence of degeneration,[31-33] and muscular stiffness.[34,35] Therefore, vertebral motions observed in the spinal surgery patients are not expected to be representative of normal or asymptomatic subjects.

Recent work by Kaigle et al[36] examined in vivo spinal motions and muscular responses in patients and asymptomatic subjects performing unresisted flexion-extension tasks. They found that intervertebral motions and trunk mobility were significantly lower in the patients than controls both in terms of range and pattern of motion. In addition, persistent muscle activation as noted from a lack of flexion-relaxation phenomena was observed in the patients as opposed to the asymptomatic subjects. Kaigle et al[36] concluded that such persistent muscular activity may be characteristic of low back pain patients where said etiology may act to restrict intervertebral motion to provide stability to help protect diseased passive spinal structures from movements that may cause pain. Still other factors such as intra-abdominal pressure,[37] cycle of breathing,[38] spinal level being tested,[21,39] vector of applied force,[40-42] and spinal positioning during testing[43] have been found to be important variables of spinal motion. In the current study, we accounted for many of these variables by placing patients in the same position on the same frame, standardizing the segemental level, vector, and cycle of breathing during performance of the SMTs. Further work in this regard with respect to understanding spinal motion differences among patients and asymptomatic subjects is warranted.

The results obtained from this study provide basic biomechanical information that is useful to both clinicians and researchers. The dynamic motion response data, force dependence, and coupling characteristics of the spinal segments to PA thrusts reported in this study will also assist researchers in the development and validation of computer models that aim to simulate the static and dynamic motion response of the spine.[25,44-47] Based on the results of this study, a recent model developed by Keller et al[25] is currently being refined to include motion coupling in each of the orthogonal axes of the spine.

Conclusion

Complex spinal motions occur during MFMA SMTs that are dependent on the applied posteroanterior force and segmental contact point. Our findings indicated the following:

- Posteroanterior impulsive forces applied over the facet joints or spinous processes produce posteroanterior vertebral motions that are coupled in the axial (cranial-caudal) and medial-lateral axes.
- Posteroanterior impulsive forces applied over the facet joints result in vertebral displacements that are greatest in the medial-lateral axis, followed by the posteroanterior axis and the axial axis.
- Increases in the posteroanterior impulsive force applied over the facet joints result in a significant increase in the posteroanterior, medial-lateral, and axial vertebral displacement responses. Medial-lateral and posteroanterior motion responses were significantly greater than the axial response for all facet joint force settings.
- Vertebral and intervertebral displacement responses were of similar amplitude. Additional studies of this nature, including other forms of spinal manipulation with varying force-time profiles, are needed in both normal subjects and patients. From such studies, one may be able to identify motion patterns that can be linked to specific pathological musculoskeletal conditions. Further, more work in this area may assist in identifying thrust force/acceleration time profiles and vectors that may maximize the putative aspects of chiropractic adjustments or spinal manipulative therapy.

Acknowledgments

We thank the Foundation for the Advancement of Chiropractic Education, Chiropractic Biophysics Non-profit, Inc, and the National Institute for Chiropractic Research for their support of this study. This study was presented, in part, at the Association of Chiropractic Colleges/Research Agenda Conference VII, New Orleans, La, March 13-17, 2002.

References

1. Gal JM, Herzog W, Kawchuk GN, Conway PJ, Zhang YT. Forces and relative vertebral movements during SMT to unembalmed post-rigor human cadavers: peculiarities associated with joint cavitation. J Manipulative Physiol Ther 1995;18:4-9.
2. Kawchuk GN, Herzog W. Biomechanical characterization (fingerprinting) of five novel methods of cervical spine manipulation. J Manipulative Physiol Ther 1993;16:573-7.
3. Herzog W, Conway PJ, Kawchuk GN, Zhang Y, Hasler EM. Forces exerted during spinal manipulative therapy. Spine 1993;18:1206-12.
4. Kawchuk GN, Herzog W, Hasler EM. Forces generated during spinal manipulative therapy of the cervical spine: a pilot study. J Manipulative Physiol Ther 1992;15:275-8.
5. Triano J. The mechanics of spinal manipulation. In: Herzog W, editor. Clinical biomechanics of spinal manipulation. Philadelphia: Churchill Livingstone; 2000. p. 92-190.
6. Keller TS, Colloca CJ, Fuhr AW. Validation of the force and frequency characteristics of the activator adjusting instrument: effectiveness as a mechanical impedance measurement tool. J Manipulative Physiol Ther 1999;22:75-86.
7. Colloca CJ, Keller TS. Stiffness and neuromuscular reflex response of the human spine to posteroanterior manipulative thrusts in patients with low back pain. J Manipulative Physiol Ther 2001;24:489-500.
8. Hessell BW, Herzog W, Conway PJ, McEwen MC. Experimental measurement of the force exerted during spinal manipulation using the Thompson technique. J Manipulative Physiol Ther 1990;13:448-53.
9. Triano J, Schultz AB. Loads transmitted during lumbosacral spinal manipulative therapy. Spine 1997;22:1955-64.
10. Kawchuk GN, Elliott PD. Validation of displacement measurements obtained from ultrasonic images during indentation testing. Ultrasound Med Biol 1998;24:105-11.
11. Kawchuk GN, Fauvel OR, Dmowski J. Ultrasonic indentation: a procedure for the noninvasive quantification of force-displacement properties of the lumbar spine. J Manipulative Physiol Ther 2001;24:149-56.
12. Latimer J, Goodsel MM, Lee M, Maher CG, Wilkinson BN, Moran CC. Evaluation of a new device for measuring responses to posteroanterior forces in a patient population. Part 1: reliability testing. Phys Ther 1996;76:158-65.
13. Latimer J, Lee M, Adams R, Moran CM. An investigation of the relationship between low back pain and lumbar posteroanterior stiffness. J Manipulative Physiol Ther 1996;19:587-91.
14. Latimer J, Lee M, Adams RD. The effects of high and low loading forces on measured values of lumbar stiffness. J Manipulative Physiol Ther 1998;21:157-63.
15. Shirley D, Ellis E, Lee M. The response of posteroanterior lumbar stiffness to repeated loading. Man Ther 2002;7:19-25.
16. Gál J, Herzog W, Kawchuk G, Conway PJ, Zhang YT. Movements of vertebrae during manipulative thrusts to unembalmed human cadavers. J Manipulative Physiol Ther 1997;20:30-40.
17. Gál J, Herzog W, Kawchuk G, Conway P, Zhang YT. Measurements of vertebral translations using bone pins, surface markers and accelerometers. Clin Biomech 1997;12:337-40.
18. Smith DB, Fuhr AW, Davis BP. Skin accelerometer displacement and relative bone movement of adjacent vertebrae in response to chiropractic percussion thrusts. J Manipulative Physiol Ther 1989;12:26-37.
19. Fuhr AW, Smith DB. Accuracy of piezoelectric accelerometers measuring displacement of a spinal adjusting instrument. J Manipulative Physiol Ther 1986;9:15-21.
20. Lee R, Evans J. Load-displacement-time characteristics of the spine under posteroanterior mobilization. Aust J Physiother 1992;38:115-23.
21. Nathan M, Keller TS. Measurement and analysis of the in vivo posteroanterior impulse response of the human thoracolumbar spine: a feasibility study. J Manipulative Physiol Ther 1994;17:431-41.
22. Kaigle AM, Pope MH, Fleming BC, Hansson T. A method for the intravital measurement of interspinous kinematics. J Biomech 1992;25:451-6.
23. Keller TS, Colloca CJ, Fuhr AW. In vivo transient vibration assessment of the normal human thoracolumbar spine. J Manipulative Physiol Ther 2000;23:521-30.
24. Maigne JY, Guillon F. Highlighting of intervertebral movements and variations of intradiskal pressure during lumbar spine manipulation: a feasibility study. J Manipulative Physiol Ther 2000;23:531-5.
25. Keller TS, Colloca CJ, Beliveau JG. Force-deformation response of the lumbar spine: a sagittal plane model of posteroanterior manipulation and mobilization. Clin Biomech 2002;17:185-96.

26. Kawchuk GN, Fauvel OR, Dmowski J. Ultrasonic quantification of osseous displacements resulting from skin surface indentation loading of bovine para-spinal tissue. Clin Biomech 2000;15:228-33.
27. Colloca CJ, Keller TS, Seltzer DE, Fuhr AW. Mechanical impedance of the human lower thoracic and lumbar spine exposed to in vivo posterior-anterior manipulative thrusts. Proceedings of the 12th Conference of the European Society of Biomechanics; 2000 Aug 27-30; Dublin, Ireland: Royal Academy of Medicine in Ireland; 2000. p. 171.
28. Lee M, Svensson NL. Effect of loading frequency on response of the spine to lumbar posteroanterior forces. J Manipulative Physiol Ther 1993;16:439-46.
29. Shirley D, Lee M. A preliminary investigation of the relationship between lumbar posteroanterior mobility and low back pain. J Manipulative Man Ther 1993;1:22-5.
30. Lundberg G, Gerdle B. Correlations between joint and spinal mobility, spinal sagittal configuration, segmental mobility, segmental pain, symptoms and disabilities in female home care personnel. Scand J Rehabil Med 2000;32:124-33.
31. Colloca CJ, Keller TS, Peterson TK, Seltzer DE. Comparison of dynamic posteroanterior spinal stiffness to plain film images of lumbar disk height. J Manipulative Physiol Ther 2003;26:233-41.
32. Kawchuk GN, Kaigle AM, Holm SH, Rod FO, Ekstrom L, Hansson T. The diagnostic performance of vertebral displacement measurements derived from ultrasonic indentation in an in vivo model of degenerative disc disease. Spine 2001;26: 1348-55.
33. Burton AK, Battie MC, Gibbons L, Videman T, Tillotson KM. Lumbar disc degeneration and sagittal flexibility. J Spinal Disord 1996;9:418-24.
34. Colloca CJ, Keller TS, Seltzer DE, Fuhr AW. Muscular and soft-tissue contributions of dynamic posteroanterior spinal stiffness. Proceedings of the 2000 International Conference on Spinal Manipulation; 2000 Sep 21-23; Bloomington, Minnesota. Norwalk (IA): Foundation for Chiropractic Education and Research; 2000. p. 159-60.
35. Shirley D, Lee M, Ellis E. The relationship between submaximal activity of the lumbar extensor muscles and lumbar posteroanterior stiffness. Phys Ther 1999;79:278-85.
36. Kaigle AM, Wessberg P, Hansson TH. Muscular and kinematic behavior of the lumbar spine during flexion-extension. J Spinal Disord 1998;11:163-74.
37. Kawchuk GN, Fauvel OR. Sources of variation in spinal indentation testing: indentation site relocation, intra-abdominal pressure, subject movement, muscular response, and stiffness estimation. J Manipulative Physiol Ther 2001;24:84-91.
38. Shirley D, Hodges PW, Eriksson AE, Gandevia SC. Spinal stiffness changes throughout the respiratory cycle. J Appl Physiol 2003;95:1467-75.
39. Viner A, Lee M, Adams R. Posteroanterior stiffness in the lumbosacral spine. The correlation between adjacent vertebral levels. Spine 1997;22:2724-9.
40. Caling B, Lee M. Effect of direction of applied mobilization force on the posteroanterior response in the lumbar spine. J Manipulative Physiol Ther 2001;24:71-8.
41. Allison G. Effect of direction of applied mobilization force on the posteroanterior response in the lumbar spine. J Manipulative Physiol Ther 2001;24:487-8.
42. Allison GT, Edmondston SJ, Roe CP, Reid SE, Toy DA, Lundgren HE. Influence of load orientation on the posteroanterior stiffness of the lumbar spine. J Manipulative Physiol Ther 1998;21:534-8.
43. Edmondston SJ, Allison GT, Gregg CD, Purden SM, Svansson GR, Watson AE. Effect of position on the posteroanterior stiffness of the lumbar spine. Man Ther 1998;3:21-6.
44. Lee M, Kelly DW, Steven GP. A model of spine, ribcage and pelvic responses to a specific lumbar manipulative force in relaxed subjects. J Biomech 1995;28:1403-8.
45. Solinger AB. Theory of small vertebral motions: an analytical model compared to data. Clin Biomech 2000;15:87-94.
46. Keller TS, Colloca CJ. A rigid body model of the dynamic posteroanterior motion response of the human lumbar spine. J Manipulative Physiol Ther 2002;25:485-96.
47. Keller TS, Beliveau JG, Colloca CJ. Determination of posterior-anterior lumbar spine motion patterns: a twenty-one degree of freedom sagittal plane model. Proceedings of the Sixth Biennial World Federation of Chiropractic; 2001 May 21-26; Paris France. Toronto: World Federation of Chiropractic; 2001. p. 272-4.