Neuromechanical Characterization of In Vivo Lumbar Spinal Manipulation. Part II. Neurophysiological Response

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

Abstract

Objective: To simultaneously quantify vertebral motions and neuromuscular and spinal nerve root responses to mechanical force, manually assisted, short-lever spinal manipulative thrusts.

Methods: Four patients underwent lumbar laminarthrectomy to decompress the central spinal canal and neuroforamina, as clinically indicated. Prior to decompression, finely threaded, 1.8-mm diameter intraosseous pins were rigidly fixed to the lumbar spinous process (L1 or L3) using fluoroscopic guidance, and a high-frequency, low-noise, 10-g, triaxial accelerometer was mounted to the pin. Following decompression, 4 needle electromyographic (nEMG) electrodes were inserted into the multifidus musculature adjacent to the pin mount bilaterally, and 2 bipolar platinum electrodes were cradled around the left and right S1 spinal nerve roots. With the spine exposed, spinal manipulative thrusts were delivered internally to the lumbosacral spinous processes and facet joints and externally by contacting the skin overlying the respective spinal landmarks using 2 force settings ($\approx$ 30 N, $<$ 5 milliseconds (ms); $\approx$ 150 N, $<$ 5 ms) and 2 force vectors (posteroanterior and superior; posteroanterior and inferior).

Results: Spinal manipulative thrusts resulted in positive electromyographic (EMG) and compound action potential (CAP) responses that were typically characterized by a single voltage potential change lasting several milliseconds in duration. However, multiple EMG and CAP discharges were observed in numerous cases. The temporal relationship between the initiation of the mechanical thrust and the neurophysiologic response to internal and external spinal manipulative therapy (SMT) thrusts ranged from 2.4 to 18.1 ms and 2.4 to 28.6 ms for EMG and CAP responses, respectively. Neurophysiologic responses varied substantially between patients.

Conclusions: Vertebral motions and resulting spinal nerve root and neuromuscular reflex responses appear to be temporally related to the applied force during SMT. These findings suggest that intersegmental motions produced by spinal manipulation may play a prominent role in eliciting physiologic responses. (J Manipulative Physiol Ther 2003; 26:579-91)

Key Indexing Terms: *Biomechanics; Electromyography; Low Back Pain; Chiropractic Manipulation; Neurophysiology; Sciatica*

Introduction

In the understanding of musculoskeletal pain and the treatment of spinal disorders, basic science research has revealed a variety of pain generators in spinal tissues. The presence of mechanosensitive and nociceptive afferent fibers in spinal tissues (disk, facet, ligaments, and muscles)[1-5] and the subsequent neurophysiologic research demonstrating the role of such afferent stimulation in pain production[6-8] and coordinated neuromuscular stabilization of the spine[9-14] provide a theoretical framework to investigate the mechanisms of chiropractic adjustments or spinal manipulative therapy (SMT). The mechanical and physiologic influence of SMT on the targeted spinal tissues has recently begun to be quantified experimentally. An important first step in validating chiropractic theories is to quantify the mechanical and neurophysiologic responses that occur during chiropractic adjustments.

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Table 1. *Patient demographics, diagnosis, clinical presentation, and levels of decompression*

Patient	Age (y), gender	Diagnosis	Clinical presentation	Level(s) of decompression
001	72, Male	Sciatica and spinal stenosis (Cong and Acq)	Hx - Several year hx of low back and left leg pain worse on rotatory movements; Ex − + SLR reproducing symptoms	L2-3; L4-5; L5-S1
002	75, Female	Sciatica and spinal stenosis (Acq)	Hx - 12-year hx of back pain, stiffness, left leg pain, and bilateral groin pain which improves on sitting or laying down; L4-5 diskectomy in 1987; epidural injections in 1988 (3), 1990, 1994, and 1998 (2); Ex − + SLR bilaterally (L − 30°, R − 60°) reproducing symptoms, + Valsalva, + L'Hermitte's, left S1 motor strength diminished; EMG exam revealed loss of motor unit responses at L4-5 left and L5-S1 left.	L4-5; L5-S1
003	48, Female	Sciatica, disk protrusion and spinal stenosis (Cong)	Hx - 5-month hx of left leg radiculopathy (S1 dermatome); epidural injection 3 months prior; Ex − + Left SLR at 70° reproducing leg symptoms	L4-5; L5-S1
004	62, Male	Spinal stenosis (Acq)	Hx - 6-month hx of low back and bilateral leg pain (worse on the right) worse on flexion, urinary urgency, neurogenic claudication, Parkinson disease since 1992; Ex - Flexion antalgia; + SLR bilaterally reproduc ing leg symptoms	L2-3; L4-5; L5-S1

Cong, Congenital; *Acq,* acquired, *Hx,* history; *Ex,* significant examination findings, *SLR,* straight-leg raising; *EMG,* electromyograph.

Previous experimental and clinical work has identified certain neurophysiologic and biomechanical (neuromechanical) factors to be of central importance to understanding the underlying mechanistic nature of chiropractic. However, this work has been limited to animal models, noninvasive procedures, or minimally invasive procedures. For example, Pickar and McLain[15] measured afferent unit discharge to facet manipulation and muscle spindle and Golgi tendon organ responses to spinal manipulative-like loads in the feline. Basic animal research has now demonstrated the existence of neural discharge during spinal manipulative-like loads,[16] but the results are not easily extrapolated in humans. Moreover, only limited research has been conducted to investigate the vertebral motions that occur during spinal manipulative therapy.[17-19]

Intraoperative monitoring techniques have proven beneficial for monitoring neurophysiologic events during spinal surgery, but such techniques have only recently been used to study responses of spinal manipulation. Colloca et al[20] recently completed an investigation of spinal nerve root action potentials in response to intraoperative lumbosacral spinal manipulation. Spinal nerve root responses were found to be related to segmental contact point, and applied force vector and similarities were observed between internal and external thrusts. Due to the limitations of the study design, only 1 subject was investigated, nerve root measurements were unilateral, and the temporal relationships of the SMTs and nerve root response could not be studied. Nevertheless, such research assists in the understanding of the neuromechanical mechanisms of spinal manipulation.

To our knowledge, no other study has simultaneously recorded spinal motions and physiological responses from spinal nerve roots and paraspinal muscles during spinal manipulation. Building on our earlier work,[20] we performed a series of in vivo intraoperative neuromechanical experiments in human subjects. The objective of these experiments was to simultaneously quantify vertebral motions and bilateral neuromuscular and spinal nerve root responses to spinal manipulative thrusts.

Methods

Four patients (2 male patients, 2 female patients; 48 to 75 years of age, mean age = 64.3 years, SD = 12.2) 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 selected for spinal surgery based on their history, clinical findings, and confirmed diagnostic imaging documentation of either spinal stenosis, osteoarthritis, and/or disk protrusion. All patients were unresponsive to conservative care for at least 6 months. Patient demographics, diagnosis, clinical presentation, and levels of spinal surgical decompression appear in Table 1. Patients were brought to the operating room and general endotracheal anesthesia was induced. Preoperative medication included Lorazepam. For induction, propofol, Sufenta, and Thivacron or Esmeron (rocuronium bromide) were administered,

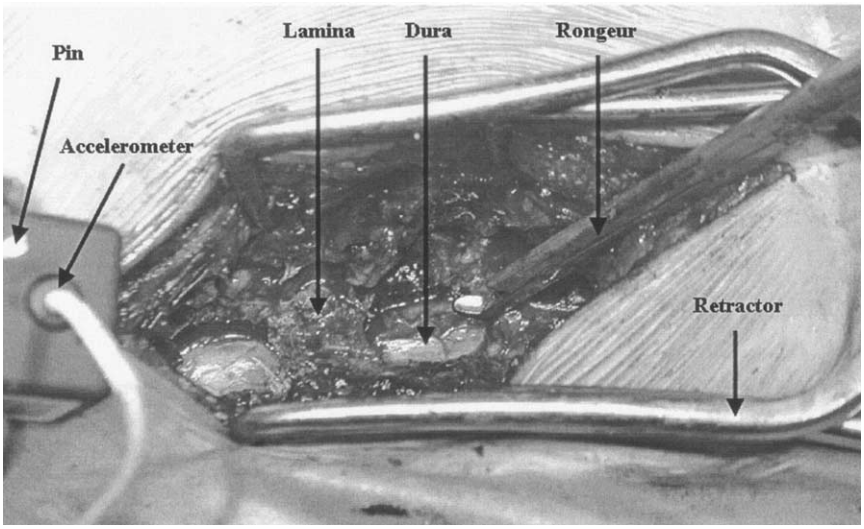

Fig 1. *Photograph showing laminarthrectomy, surgical decompressive technique. In this procedure, an osteotomy of the spinous process is performed, leaving the laminae exposed. Using a rongeur, the interspinous ligament is then incised and removed, the laminae are reshaped, and the ligamenta flava are decompressed. This surgical procedure provides visualization of the dura overlying the spinal cord and exposes the L5 and S1 nerve roots. The pin-mounted accelerometer is shown in the superior spinous process.*

and for maintenance we used a mixture of N_20, 0_2, and Sevorane. For antibiotic prophylaxis, we used cefamandol. 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.

Spinal Surgery Protocol

Incisions were made over L3 through S2 in the midline and brought through the subcutaneous tissue. The fascia was incised and the musculature was carefully dissected on the left side of the spinous process, which was osteotomized at the base. Self-retaining retractors were set in place, thus exposing the full posterior arches and ligamenta flava, and manual suction was performed within the incised area. A laminarthrectomy was performed to decompress the central spinal canal and neuroforamina, as clinically indicated, and the integrity of the neural arches, facet joints, and most muscle attachments was preserved. This surgical procedure affords excellent visualization and a wide area available, while minimizing destruction to tissues not directly involved in the pathologic process, including the paraspinal musculature, interspinous/supraspinous ligament complex, and facets (Fig 1). This surgical technique is described elsewhere.[21] Decompression of L4-5 and L5-S1 were performed in all patients, and decompression was also performed at L2-3 in 2 patients (Table 1). In each case, inspection of the epidural space indicated that the L4-5 and L5-S1 intervertebral disks were not ruptured. Following the decompression, the L5 and S1 nerve root sleeves were clearly identified and free of all compression. The integrity of the facet joints was respected, in spite of the partial laminarthrectomy.

Bone Pin and Electrode Placement

Using fluoroscopic guidance, a single, finely threaded, 1.8-mm diameter stainless steel pin was rigidly fixed to the lumbar spinous process just superior to the spinal level being decompressed. Pins were located at L1 for patients 1 and 4 and at L3 for patients 2 and 3. In each case, the intraosseous pin was fixed into the spinous process immediately superior to the most superior level of spinal decompression. A triaxial accelerometer was then attached to the pin.

Four 28-gauge concentric biopolar needle electromyographic (nEMG) electrodes (Model EL451, Biopac Systems, Inc, Santa Barbara, Calif) were inserted into the multifidus musculature adjacent to the pin mount bilaterally (at the level of L1 in 2 subjects and L3 in 2 subjects, as noted above). The nEMG electrodes are 460 μm in diameter and 3.0 cm long with a recording area of 0.06 mm^2. The electrodes were spaced 2 cm apart each right and left, and the leads were secured to the draping with clips and adhesive tape. Prior to draping and surgery, a monopolar ground needle electrode (Model EL452, Biopac Systems, Inc) was inserted at the level of the trochanter and secured with adhesive tape. Two bipolar platinum hooked electrodes with 10-mm spacing and 64-mm tip length (PolarProbe, Nicolet, Inc, Madison, Wis) were cradled around the S1 spinal nerve roots just proximal to the dorsal root ganglion adjacent to the level of decompression. These electrodes were shielded and insulated such that the most distal (hooked) end was

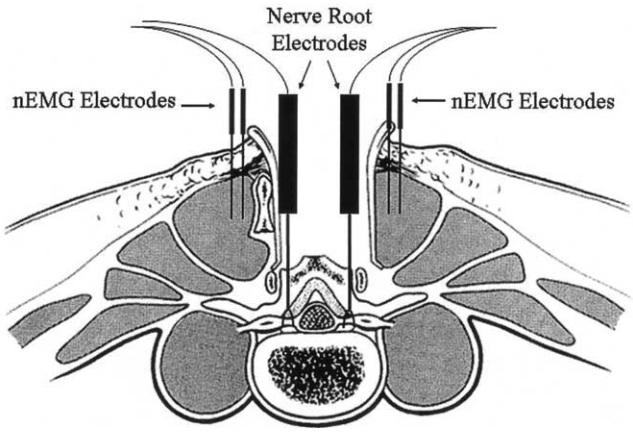

Fig 2. *Schematic illustration of the surgical exposure and experimental placement of the bipolar platinum nerve root electrodes around the spinal nerve roots. The needle electromyographic (nEMG) electrodes were inserted into the multifidus muscles.*[21]

exposed for recording. Electrode placement is depicted in Figure 2.

Spinal Manipulation Protocol

With the spine exposed, spinal manipulative thrusts were delivered internally (inside the surgical cavity) by directly contacting the sacral base at S1 and the L5-S1 facet joints. Similar thrusts were repeated on the skin overlying the respective anatomical landmarks externally by contacting the skin overlying the respective spinal landmarks. A total of 8 external and 8 internal thrusts were applied using an Activator II Adjusting Instrument (AAI) (Activator Methods International, Ltd, Phoenix, Ariz). The AAI is a mechanical force, manually assisted, short-lever clinical SMT device. Additional details of the AAI and its clinical usage are noted in our cited references.[22-24] Each AAI included a trigger to initiate data collection using a Biopac MP100 data acquisition system (Biopac Systems, Inc). Two force settings, a "0" setting ($\approx$ 30 N, $<$ 5 milliseconds [ms]) and a "maximum" force setting ($\approx$ 150 N, $<$ 5 ms) and 2 force vectors (posterior-anterior and superior; posterior-anterior and inferior) were used in delivering the spinal manipulative thrusts. In summary, there were 4 nEMG electrodes $\times$ 16 spinal manipulative thrusts (8 internal, 8 external) and 2 spinal nerve root (NR) electrodes $\times$ 16 spinal manipulative thrusts (8 internal, 8 external) for a total of 64 electromyographic (EMG) recordings and 32 compound action potential (CAP) recordings for each patient. Table 2 provides details of the segmental contact points, force vectors, and levels targeted in the research protocol.

Data Collection—Recording and Analyses

All equipment (electrodes, accelerometers, bone pins, and adjusting instruments) were gas sterilized prior to surgery. A photograph of the intraoperative setup is shown in Figure 3. Neurophysiologic (CAP) responses, neuromuscular needle electrode (nEMG) responses, and axial pin accelerations were simultaneously recorded at 4096 Hz. Neuromuscular signals were amplified and filtered using biopotential amplifiers (MEC 100, Biopac Systems, Inc) and stored for analytical and statistical processing using custom Matlab (The Math Works, Inc, Natick, Mass) programs. A third-order elliptic, band stop (45-55 Hz), zero-phase forward and reverse digital filter followed by a third-order Butterworth, low-pass (500 Hz) zero-phase forward and reverse digital filter were applied to the data. For each thrust, time histories were characterized in terms of several descriptive parameters, including minimum, maximum, peak-peak, and the time interval (ΔT, ms) between the application of the SMT thrust and the onset of the CAP and EMG responses (Fig 4). Positive CAP and EMG time histories were defined as responses that elicited a peak-peak signal response greater than 2.5 times the baseline (resting) signal.[25] Since the AAI thrust time profiles were not recorded during the neurophysiologic response measurements reported in this study, the precise time interval from the AAI thrust onset to the peak EMG and CAP responses could not be determined. ΔT, however, was estimated by adding the time interval from the onset of the AAI thrust acceleration to the resulting pin acceleration (mean = 2.2 ms reported in part I of this article) to the peak-to-peak time interval of the pin axial acceleration to the peak EMG or CAP responses.

Results

The axial displacement responses (L1 or L3 vertebrae) to the 8 internal and 8 external spinal manipulative thrusts at L5-S1 are summarized in Figure 5. Axial displacements of the L1 or L3 vertebrae were substantially greater for the maximum force setting in comparison with the zero force setting. In the case of thrusts applied at the maximum force setting, both internal and external spinal manipulative thrusts resulted in approximately similar magnitude vertebral motions. Zero force setting internal thrusts on the facet tended to produce a greater axial displacement response in comparison with external thrusts applied over the same landmark.

Spinal manipulative thrusts resulted in positive EMG and CAP responses that were characterized by a single voltage potential change several milliseconds in duration. Both internal and external thrusts evoked positive neurophysiologic responses (Fig 6). Multiple EMG and CAP discharges were observed in numerous cases. Spinal nerve root responses (CAPs) were generally more prevalent than nEMG responses. The number of positive EMG and CAP responses ranged from 0% to 37.5% and from 25% to 75%, respectively (Table 3 and Fig 7). AAI thrusts produced positive ipsilateral and contralateral responses (Fig 8). Maximum setting spinal manipulative thrusts resulted in more positive neuromuscular and neurophysiologic responses. In general, the right spinal nerve roots tended to produce greater num-

Table 2. *Segmental contact points, force settings, and force vectors for the eight spinal manipulative thrusts delivered internally and externally to the lumbosacral joints during the research protocol*

SMT trial	Segmental contact point	Force setting	Force vector
1	S1	≈ 30 N	Posterior-anterior and anterior-inferior
2	S1	≈ 150 N	Posterior-anterior and anterior-inferior
3	Left L5-S1 facet	≈ 30 N	Posterior-anterior and anterior-superior
4	Left L5-S1 facet	≈ 150 N	Posterior-anterior and anterior-superior
5	Right L5-S1 facet	≈ 30 N	Posterior-anterior and anterior-superior
6	Right L5-S1 facet	≈ 150 N	Posterior-anterior and anterior-superior
7	Left L5-S1 facet	≈ 150 N	Posterior-anterior and anterior-inferior
8	Right L5-S1 facet	≈ 150 N	Posterior-anterior and anterior-inferior

SMT, Spinal manipulative therapy.

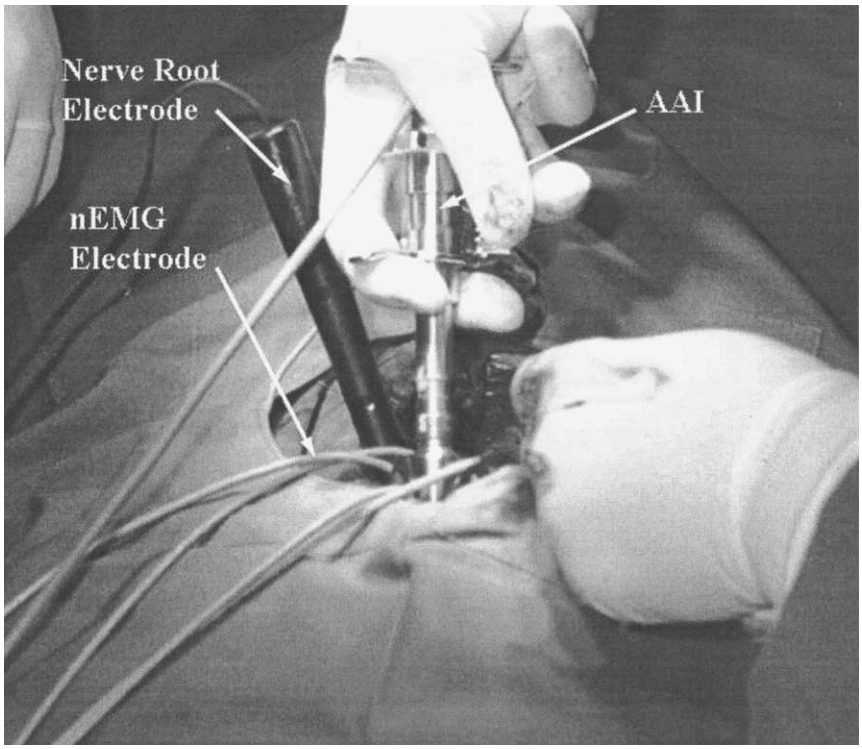

Fig 3. *Intraoperative detail of an SMT thrust delivered to the sacral base at S1 using an Activator II Adjusting Instrument (AAI). Neuromuscular responses were measured by needle electromyographic (nEMG) electrodes, and neurophysiological responses were obtained using hooked spinal nerve root electrodes. Simultaneous neurophysiological and neuromuscular responses were measured and spinal deformation was quantified using an accelerometer mounted to a bone pin located in the superior spinous process (not shown).*

bers of responses, especially for external applied spinal manipulative thrusts (Fig 9).

Table 3 summarizes the number of positive EMG and CAP responses and the corresponding time interval ΔT between the application of the SMT thrust and the onset of the neurophysiologic response for each of the patients. ΔT ranged from 2.4 to 18.1 ms and 2.4 to 28.6 ms for EMG and CAP responses, respectively. With the exception of patient 2, the mean CAP response interval was less than the mean EMG response interval. In general, the number of EMG and CAP responses and the time duration to peak response varied among each of the patients, segmental contact point, and applied force.

Discussion

Several findings emerge from this study, the most important of which is the confirmation that SMT can induce spinal motion and subsequent spinal nerve root and neuromuscular reflex responses in the adjacent musculature. This appears to be the first study to simultaneously measure vertebral movements, nerve root responses, and neuromuscular reflexes dur-

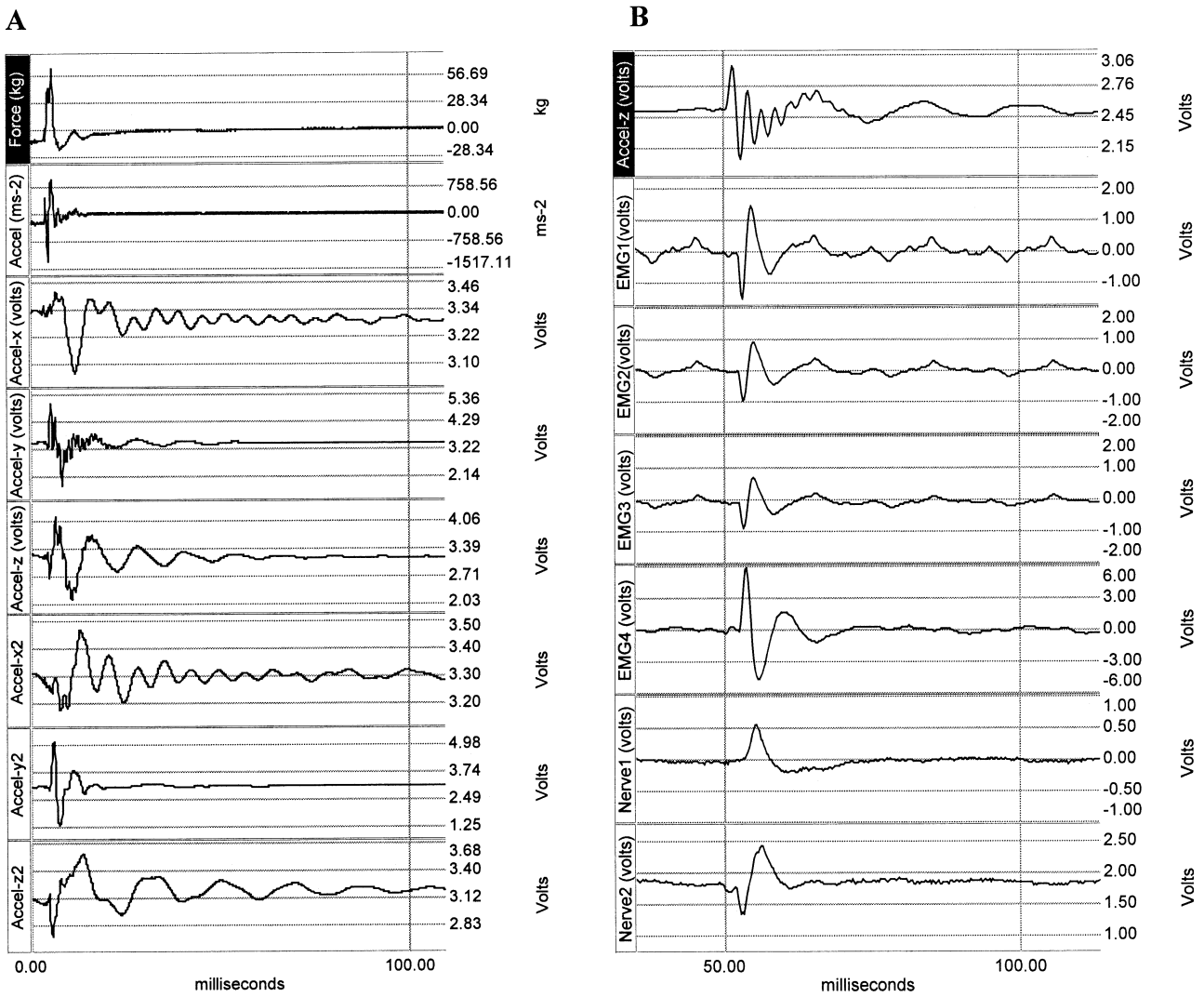

Fig 4. *(**A**) Activator II Adjusting Instrument (AAI) force and time histories and corresponding triaxial vertebral segment displacement response (patient 3). (**B**) Axial acceleration time history and corresponding EMG and nerve root voltage responses for patient 3. The time interval (ΔT) was determined from the temporal relationship between the AAI acceleration and the corresponding electromyographic (*EMG1 = *left superior,* EMG2 = *right superior,* EMG3 = *left inferior,* EMG4 = *right inferior) or nerve (*Nerve 1 = *L,* Nerve 2 = *R) responses.*

ing SMT in human subjects. Such neuromechanical responses may be related to the therapeutic benefits associated with spinal manipulation as administered in routine clinical practice.

We hypothesized that mechanical stimulation of viscoelastic structures during SMT would result in physiologic responses in human subjects based on the knowledge of the presence of mechanosensitive afferents in the discoligamentous and muscular spinal tissues.[2,3,6] Despite the fact that preliminary work had demonstrated relationships between mechanical and electrical stimulation of spinal articulations resulting in neurophysiologic and neuromuscular responses, such research has mostly been limited to the laboratory utilizing animal models.[13,16,26] Intraoperative monitoring techniques are commonly used in spinal surgery and offer promise for evaluating neurophysiologic responses during SMT.[27-31] Thus, the objective of the current study was to measure intraoperative neuromechancial responses with a commonly used conservative therapeutic approach, SMT.

Because our measurements were taken just adjacent to the dorsal root ganglion, it is likely that the CAPs observed in the S1 spinal nerve roots were afferent traffic resulting from the stimulation of mechanosensitive afferent fibers in the viscoelastic spinal tissues during the spinal manipulative thrusts. Sensory receptors within a tissue, such as spinal ligaments, facets, disks, and muscles, can initiate neural outflow to the spinal cord during application of various mechanical stimuli (eg, pressure, elongation, vibration, friction, tissue crushing) and application of chemical stimulants.[8] Due to the participation of human subjects, we were not able to directly ascertain the exact source of the neuro-

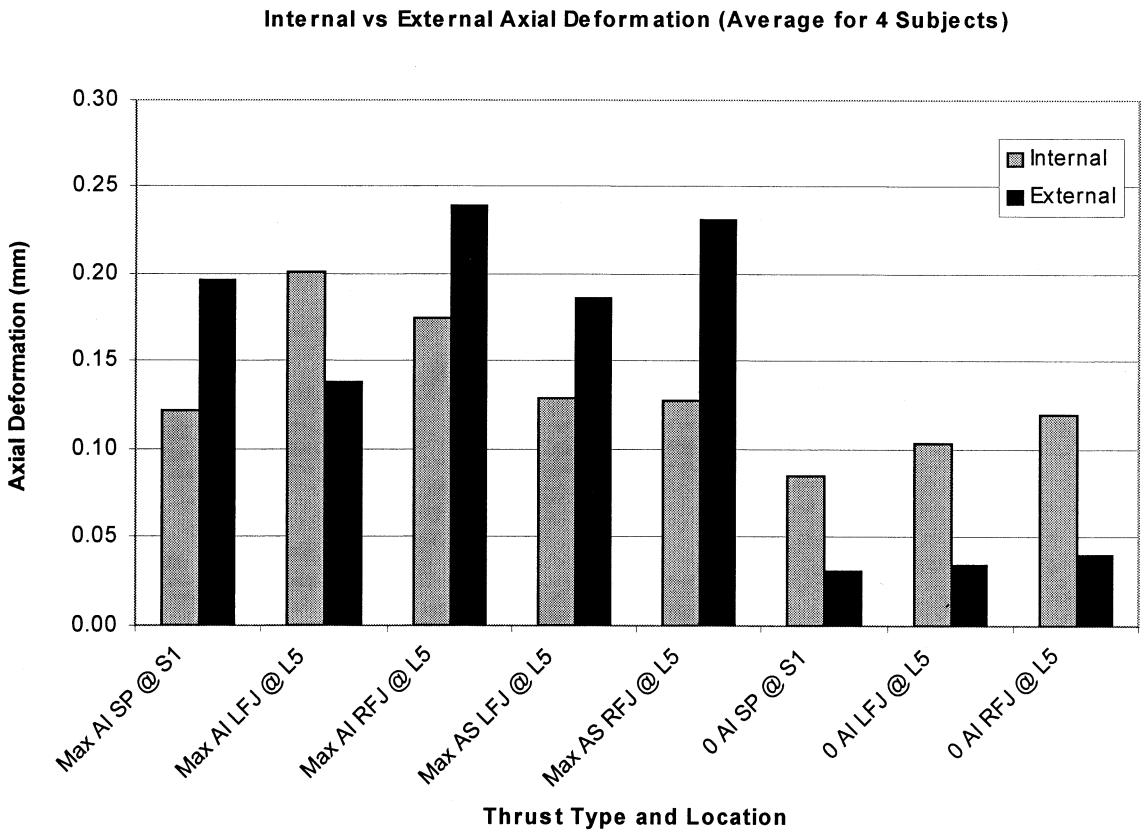

Fig 5. *Mean axial deformation results for spinal manipulative thrusts delivered with the zero force setting (≈ 30 N, < 5 ms) and maximum (*max*) force setting (≈ 150 N, < 5 ms) for posteroanterior and anterior-inferior (*AI*) and posteroanterior and anterior-superior (*AS*) force vectors delivered to the sacral base (*S1*) and right (*R*) and left (*L*) L5-S1 facet joints (*FJ*).*

physiologic responses, as is routinely performed in animal studies.[32,33] This study, however, building on our previous work,[20] enabled the intraoperative monitoring of compound action potentials, which in this case represent the algebraic sum of action potentials arising from respective mechanosensitive axons passing through the epineuria of the dorsal spinal nerve roots. Because the CAP represents many axons with differing thresholds of excitation, the CAP response is graded, and the magnitude is proportional to the intensity of stimulation. In the current study, spinal manipulative thrusts were associated with CAP responses of different amplitudes. The presence (or absence) and amplitude of CAP and EMG responses may not only be related to the neurologic status of the patient, as discussed above, but also to the intensity of the mechanical stimulus. In this study, the stimulus was the spinal manipulative thrust using 2 force-time settings (≈ 30 N, < 5 ms and ≈ 150 N, < 5 ms). Based on our previous work investigating neuromuscular reflex responses, we set the threshold of a "positive" response at 2.5 × baseline, which represents a moderate neurophysiological response (1.5 × baseline = very weak, 5 × baseline = very strong).[25] We reported that the 2.5 × baseline increase corresponded to a relative mean EMG response of Seroussi and Pope,[34] equivalent to 3.5% of the prone-lying trunk extension EMG response, which was deemed to be a significant EMG response. This same criteria was applied to the motor unit action potential (MUAP) responses in the current study. It may be likely that larger force magnitudes, as delivered in other forms of SMT, may indeed cause more frequent and larger amplitude neurophysiologic and neuromuscular responses.[35] Further investigation into the effects of force-time profiles on neuromechanical responses is warranted.

Mean time durations from the mechanical stimulus of the SMT and EMG and CAP responses in this study ranged from 5.5 to 18.3 ms and 8.2 to 10.7 ms, respectively. The finding that in most cases the CAP response preceded the EMG response leads us to believe that the CAP response represents afferent traffic from multiple mechanosensitive units in the muscular and discoligamentous soft tissues and the EMG response may indeed be a reflex. Simply stated, the CAP and EMG responses measured in the current study are suggestive of, but do not provide direct evidence for, the reflexive nature of the paraspinal EMG activity. Later duration responses are normally delayed due to the reflex duration from the time it takes for the stimulus to travel along the Ia fibers, through the dorsal root ganglion, and across the spinal cord to the anterior horn cell, which then propagates the impulse along the alpha motor axon to the muscle. Alternatively, at times when the EMG response

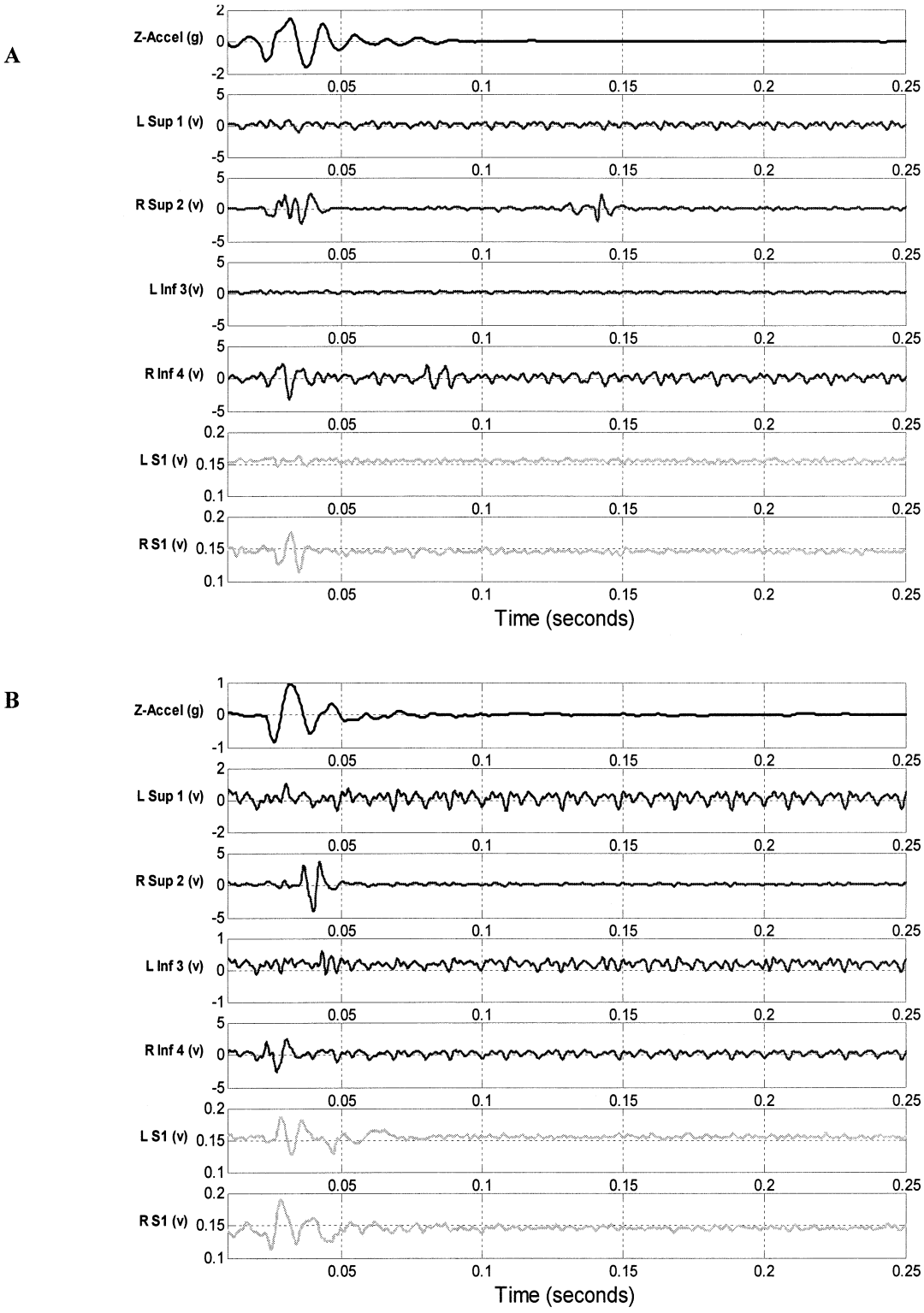

Fig 6. *Neuromechanical responses to spinal manipulative thrusts delivered internal (**A**) to the right L5-S1 facet and external (**B**) to the skin overlying the right L5-S1 facet. Simultaneous time-line recordings of z-axis acceleration (g = 9.81 m/s^2) (spinal motion) is depicted in relation to neuromuscular responses (v = volts) obtained from 4 (1-4) nEMG electrodes placed into the left (L) and right (R) multifidus muscles superior (Sup) and inferior (Inf) to the pin mount. Compound action potential (CAP) responses are also shown for the left (L) and right (R) S1 spinal nerve roots (S1) in response to the spinal manipulative thrusts.*

Table 3. *Summary of positive neuromuscular and compound action potential responses to internally and externally applied spinal manipulative thrusts on L5-S1 segments*

Patient	Thrust location	Number of positive EMG responses	Range of ΔT (ms) EMG responses (mean)	Number of positive CAP responses	Range of ΔT (ms) CAP responses (mean)
001	Int + Ext	14/64	2.9-21.7 (10.8)	16/32	2.4-18.1 (8.2)
	Int only	7/32		9/16	
	Ext only	7/32		7/16	
002	Int + Ext	5/64	2.4-8.8 (5.5)	13/32	5.9-16.4 (8.9)
	Int only	0/32		1/16	
	Ext only	5/32		12/16	
003	Int + Ext	12/64	5.1-28.6 (13.1)	9/32	6.4-17.1 (10.7)
	Int only	8/32		5/16	
	Ext only	4/32		5/16	
004	Int + Ext	1/64	18.3	10/32	6.4-12.2 (8.8)
	Int only	0/32		6/16	
	Ext only	1/32		4/16	

Other parameters defined in text.
EMG, Electromyography; *CAP,* compound action potential; *Int,* internal; *Ext,* external.

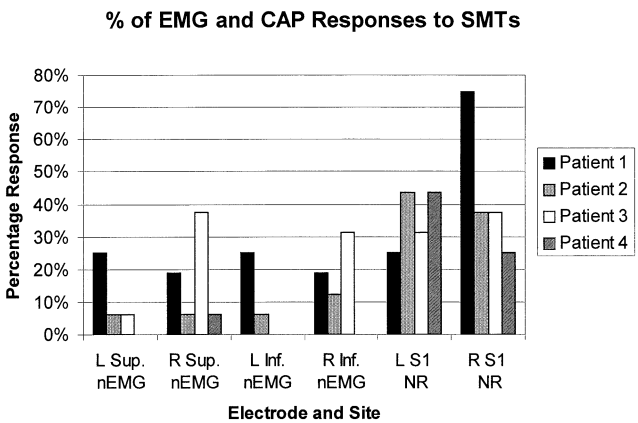

Fig 7. *Bar graph summary of the positive EMG and CAP responses to the 8 internal and 8 external SMT thrusts for each patient. The respective left (*L*) or right (*R*) multifidus muscle needle electrodes (*nEMG*) were spaced 1 cm superior (*Sup*) and inferior (*Inf*) to the pin mount at the level of L1 and L3. Neurophysiological recordings were made from the L and R spinal nerve root (*NR*) at the level of S1. Positive EMG and CAP responses were defined as voltages exceeding 2.5 × baseline (see text).*

preceded the CAP response, it is likely that this may represent a direct local motor response analogous to an M-wave during H-reflex testing. Such a local muscle response may be from tissue preload prior to the delivery of the SMT. Alternatively, early EMG responses could represent a stimulus artifact. Noteworthy, however, are the time durations recorded in the current study being consistent with those measured in animal models and in humans. Other researchers have used electrical stimulation to measure reflexogenic activity in the adjacent spinal musculature. Indahl et al[13,26] reported time durations of 4 to 8 ms in a porcine model on stimulating the intervertebral disk and sacroiliac joint. Kang et al[32] also reported similar stimulus-to-response times of about 10 ms in feline preparations. In addition, Solomonow et al[10] measured stimulus-to-response time durations of 5 to 10 ms in human subjects on electrical stimulation of the supraspinous ligament. Stimulus-to-response times in the current study corroborate these time durations in our human subjects. Neurologic deficits inherent in the patient population of the current study are likely to be responsible for delays in stimulus-to-response times or the absence of said positive responses in certain instances.

Limitations inherent in this study may help to explain some of the experimental results obtained. For example, a significant number of spinal thrusts did not elicit positive neurophysiological responses. Since the subject population in this study was patients with spinal disorders serious enough to undergo spinal surgery, it would not be uncommon to expect neurologic deficits from damaged tissues. Three fourths of patients in this study had radiculopathy in the left lower extremity. Such clinical presentation might help to explain the greater number of right-sided S1 compound action potential responses, as opposed to those measured from the left S1 spinal nerve root. Solomonow et al[10] reported similar problems (absence of EMG response) when performing intraoperative experiments in human subjects on measuring multifidus EMG responses during stimulation of the supraspinous ligament. Nevertheless, neurological deficit among patients could be a possible explanation for the decreased number of positive neurophysiologic responses to SMT. The number of positive responses in the current study is related to the threshold level of 2.5 × baseline that we set in the data analysis from our previous work,[25] and a substantially greater number of positive responses were observed at lower thresholds but were not counted as "positive." The clinical relevance of CAP and EMG threshold should be further clarified experimentally.

Of further interest were the findings in the current study that spinal deformations were smaller than those reported in part I of this article. Spinal manipulative thrusts were delivered to the L5 and S1 spinal segments in the current experimental protocol, while the pin mount placement was located several segments cephalad at L3 (2 patients) and L1 (2 patients). Thus, measuring spinal motions 2 to 4 spinal segments away from the segmental contact point would explain the smaller spinal deformations as compared with thrusts made closer to the pin placement. These results also corroborate those previously noted by Nathan and Keller[19] in regard to the relationship between segmental contact point and adjacent segment spinal motions.

In addition, the less frequent nature of positive EMG responses as opposed to CAP responses may also be attributed to the segmental contact points and recording electrode locations. In this study, the nEMG electrodes were placed adjacent to the pin placement at L1 and L3, while the NR electrodes were placed at the level of the S1 spinal nerve

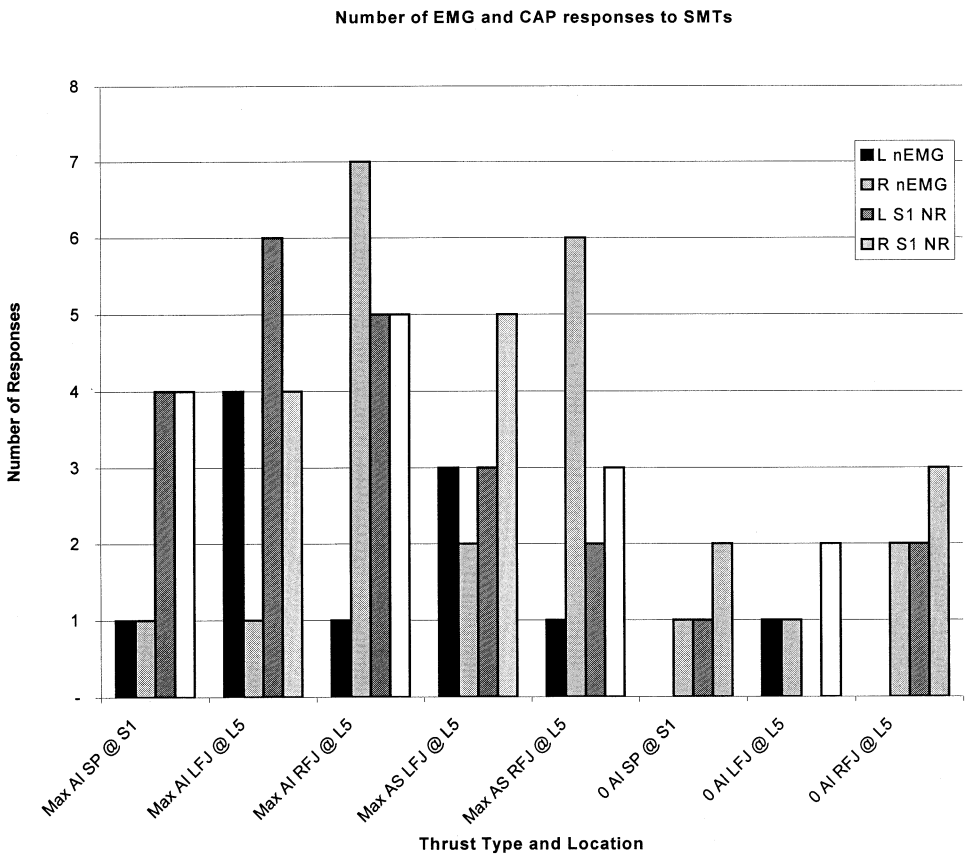

Fig 8. *Bar graph summary of the total number of EMG and CAP responses for the right (*R*) and left (*L*) needle electromyographic (*nEMG*) and S1 spinal nerve root (*NR*) electrodes for each of the 8 internal and 8 external thrusts. Recordings from the superior and inferior nEMG electrodes were summed to provide right and left totals.*

roots. The experimental protocol did not allow for nEMG placement any closer to the segmental contact points due to space constraints. Because spinal manipulative thrusts were delivered to the L5-S1 facet joints and the sacral base, it might be expected that the largest responses would be recorded at the level being thrusted on as opposed to 2 to 4 segments cephalad. There are several explanations for the EMG responses at distant sites, which include the multiple segmental innervated nature of the lumbar spine[36,37] and the fact that spinal manipulative thrusts create spinal motions (and therefore cause deformations in the viscoelastic tissues which contain mechanosensitive afferents) at multiple levels adjacent to the segmental contact point.[19] Such distally recorded EMG responses and the measurement of contralateral responses support the fact that such neuromuscular and neurophysiologic responses are not simply stimulus artifacts.

An inherent limitation in this study is the small sample size (n = 4). The addition of subjects in this line of investigation will assist in clarifying the experimental results obtained in regard to the neuromechanical effects of SMT, including the effects of directional sensitivity of the SMT on neuromechanical response. Further investigation of different force-time profiles, as commonly used in traditional SMT procedures,[38] should serve to better describe the neuromechanical responses of SMT. Neurophysiologic models theorize that SMT may stimulate or modulate the somatosensory system and subsequently may evoke neuromuscular reflexes.[15,39-41] Such reflexes are thought to inhibit hyperactive musculature, inhibit nociceptive traffic, and improve spinal function. This line of investigation assists in understanding the relationships between the mechanical stimulation as delivered in SMT and the concomitant physiological responses. In attempting to understand such neuromechanical relationships, the clinical status of the patient is often overlooked. The highly individualized neuromechanical response characteristics among patients in this study serves to highlight the need to clinically correlate the neuromechanical response characteristics with patient clinical status. The clinical relevance of how SMT may be related to inhibition or stimulation of the central nervous system in modulating nociception in humans awaits clarification. Our current work and the work of others aim to investigate such issues.[42-44]

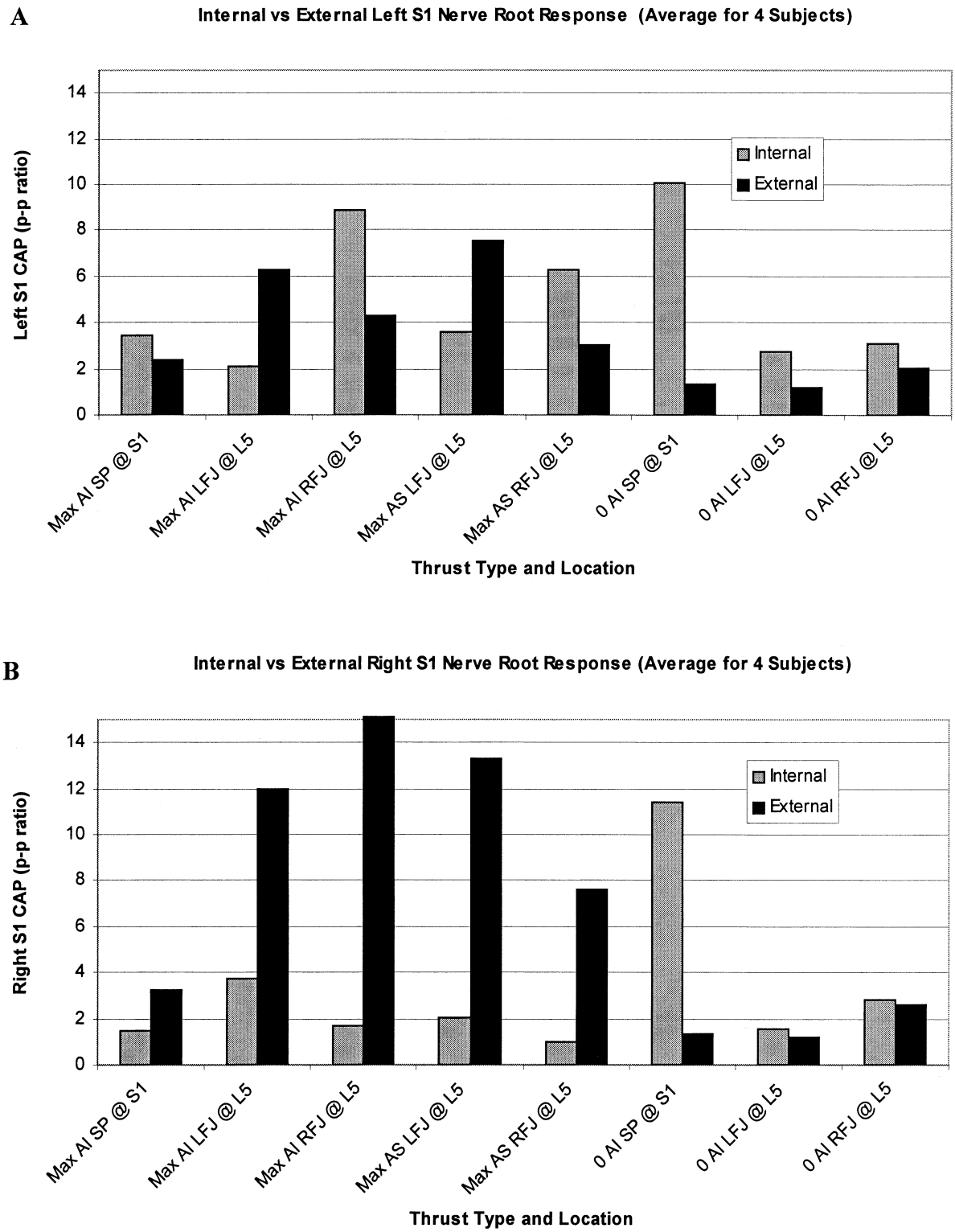

Fig 9. *Mean CAP response obtained from the left (***A***) and right (***B***) S1 spinal nerve roots for internal and external spinal manipulative thrusts. Results are shown for spinal manipulative thrusts delivered with the zero (0) force setting (≈ 30 N, < 5 ms) and maximum (*max*) force setting (≈ 150 N, < 5 ms) for posteroanterior and anterior-inferior (*AI*) and posteroanterior and anterior-superior (*AS*) force vectors delivered to the sacral base (*S1*) and right (*R*) and left (*L*) L5-S1 facet joints (*FJ*).*

Conclusion

Spinal manipulation results in measurable biomechanical and neurophysiologic responses, which appear to be individualized among patients. The vertebral motions that occur (rotations and translations) and resulting spinal nerve root and neuromuscular reflex responses appear to be temporally related to the applied force during SMT. These findings suggest that intersegmental motions produced by spinal manipulation may play a prominent role in eliciting physiologic responses. Further work is necessary in elucidating the clinical relevance of these findings. Knowledge of biomechanical and neurophysiologic events that occur during spinal adjustments assists in formulating a theoretical framework to understand the mechanisms of spinal manipulation.

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