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Spinal manipulation force and duration affect vertebral movement and neuromuscular responses ☆

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Abstract

Background. Previous study in human subjects has documented biomechanical and neurophysiological responses to impulsive spinal manipulative thrusts, but very little is known about the neuromechanical effects of varying thrust force–time profiles.

Methods. Ten adolescent Merino sheep were anesthetized and posteroanterior mechanical thrusts were applied to the L3 spinous process using a computer-controlled, mechanical testing apparatus. Three variable pulse durations (10, 100, 200 ms, force = 80 N) and three variable force amplitudes (20, 40, 60 N, pulse duration = 100 ms) were examined for their effect on lumbar motion response (L3 displacement, L1, L2 acceleration) and normalized multifidus electromyographic response (L3, L4) using a repeated measures analysis of variance.

Findings. Increasing L3 posteroanterior force amplitude resulted in a fourfold linear increase in L3 posteroanterior vertebral displacement ($p < 0.001$) and adjacent segment (L1, L2) posteroanterior acceleration response ($p < 0.001$). L3 displacement was linearly correlated ($p < 0.001$) to the acceleration response over the 20–80 N force range (100 ms). At constant force, 10 ms thrusts resulted in nearly fivefold lower L3 displacements and significantly increased segmental (L2) acceleration responses compared to the 100 ms (19%, $p = 0.005$) and 200 ms (16%, $p = 0.023$) thrusts. Normalized electromyographic responses increased linearly with increasing force amplitude at higher amplitudes and were appreciably affected by mechanical excitation pulse duration.

Interpretation. Changes in the biomechanical and neuromuscular response of the ovine lumbar spine were observed in response to changes in the force–time characteristics of the spinal manipulative thrusts and may be an underlying mechanism in related clinical outcomes.
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1. Introduction

In the treatment of patients with pain of musculoskeletal origin, chiropractic practitioners typically employ short duration, high velocity thrusts (manipulation) designed to restore pain-free movement of the musculoskeletal system and to decrease disability (Meeker and Haldeman, 2002). Of the numerous treatments

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utilized for spinal manipulative therapy (SMT), however, very few studies have examined mechanical variables that may influence physiological responses and putative effects associated with chiropractic therapy (Colloca et al., 2004). Because SMT is a mechanical intervention it is inherently logical to assume that its mechanisms of therapeutic benefit may lie in the underlying mechanical properties of the applied force (mechanical mechanisms), the body's response to such force (mechanical or physiologic mechanisms), or a combination of these and other factors. However, clinical trials have been equivocal in terms of the beneficial nature of these procedures to most comparison treatments (Meeker and Haldeman, 2002; Bronfort et al., 2004). Moreover, although basic science research directed towards understanding the mechanisms of SMT has increased dramatically during the past 15 years, the most fundamental biomechanical aspects of spinal manipulations are still lacking (Herzog, 2000).

From a biomechanical perspective, human cadaver and in vivo studies have characterized the forces and force–time histories associated with various SMT techniques (Gal et al., 1997a,b; Gal et al., 1995; Colloca et al., 2004; Keller et al., 2003; Nathan and Keller, 1994; Maigne and Guillon, 2000; Herzog et al., 1993; Triano and Schultz, 1997). Information on the force–displacement response of functional spinal units have been reported using both in vitro (Gal et al., 1997b) and in vivo (Nathan and Keller, 1994; Keller et al., 2003) studies, and more recently basic science research studies have begun to characterize the temporal relationships between mechanical stimulation and neurophysiological responses (Colloca et al., 2000, 2003, 2004; Sung et al., 2005). Neuromuscular reflex responses have been observed in the paraspinal musculature when SMT is applied to different spinal regions in asymptomatic subjects, and differences have been reported among these responses for different SMT techniques (Herzog et al., 1999; Symons et al., 2000). Differences in paraspinal neuromuscular reflex amplitude have also been reported in patients with low back pain, which is hypothesized to be indicative of the patients underlying clinical status (Colloca and Keller, 2001). Recent animal experimental studies also suggest that pulse duration, not force amplitude during SMT play a prominent role in the neurophysiological response of the lumbar spine (Sung et al., 2005).

Few studies have quantified both the biomechanical and neuromuscular responses associated with dynamic mechanical stimulation. Thus, the aim of this study was to investigate the effects of varying PA mechanical stimulation force–time profiles on lumbar vertebral motion response. Both force amplitude and duration were hypothesized to alter the motion characteristics of the lumbar spine. In addition, we hypothesized that mechanical stimulus force amplitude and duration would affect neurophysiological (EMG) response of the lumbar spine.

2. Methods

2.1. Animal preparation

Ten adolescent Merino sheep (mean 46.5; SD 5.6 kg) were examined using a research protocol approved by the Animal Ethics Committee and institutional board review board of the Institute of Medical and Veterinary Science (Adelaide, South Australia). Following anesthesia, the animals were placed in a standardized prone-lying position with the abdomen and thorax supported by a rigid wooden platform and foam padding, respectively, thereby positioning the lumbar spine parallel to the operating table and load frame.

Bony prominences of the L1–L3 spinous process were exposed using electrocaudery, and finely threaded, 1.8 mm diameter intraosseous stainless-steel pins were rigidly fixed to the L1 and L2 lumbar spinous processes under fluoroscopic guidance. Dynamic (0.3 Hz–10 KHz), low noise (0.0003 g RMS resolution), AC-coupled piezoelectric, integral sensor, 10-g tri-axial accelerometers (Crossbow Model CXL100HF3, Crossbow Technology, Inc., San Jose, CA, USA) were subsequently attached to the L1 and L2 intraosseous pins. The *x*-, *y*- and *z*-axes of the accelerometer were oriented with respect to the medial–lateral (ML), posterior–anterior (PA) and cranial–caudal or axial (AX) axes of the vertebrae. The natural frequency of the pin and transducer, determined intraoperatively by "tapping" the pins in the ML and AX axes, was greater than 80 Hz. Only PA axis motion responses are presented in this paper.

Four 28-gauge concentric bipolar needle electro myographic (nEMG) electrodes (model EL451, Biopac Systems, Inc. Santa Barbara, CA, USA) were inserted bilaterally into the multifidus musculature adjacent to L3 and L4. The nEMG electrodes were 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 into the fascia adjacent to the sheep trochanter.

2.2. Mechanical testing apparatus

A custom, computer-controlled mechanical testing apparatus was used to deliver a uniform "pulse" mechanical excitation directly to the L3 spinous process of the sheep spine under load control (Fig. 1). The apparatus was comprised of a linear voice coil actuator

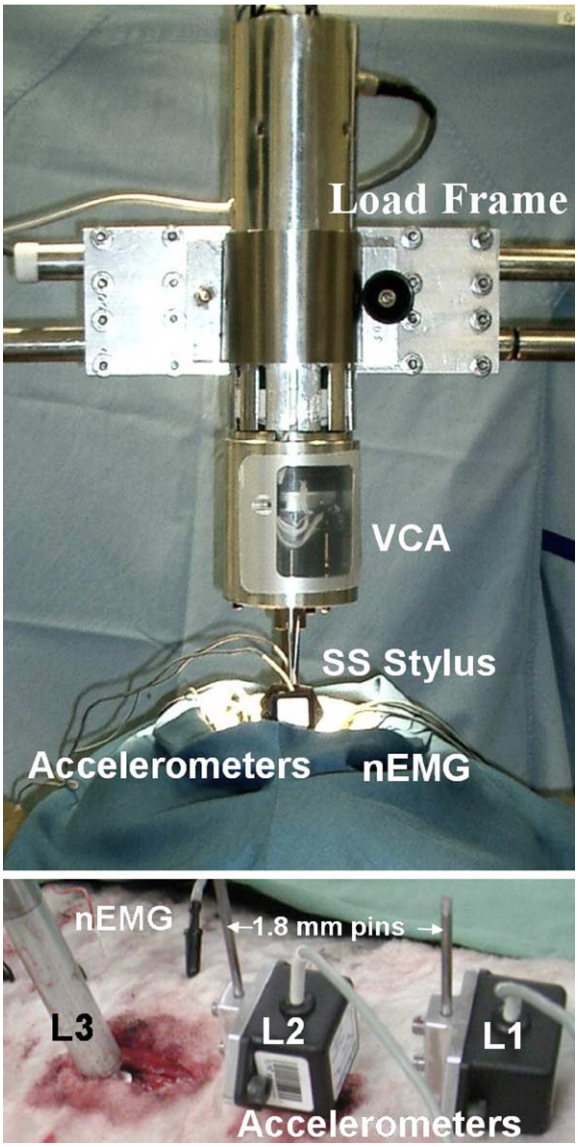

Fig. 1. Computer-controlled mechanical testing apparatus positioned over the ovine L3 spinous process (upper panel). The apparatus consisted of a voice coil actuator (VCA), coil assembly, LVDT, load cell, and stainless-steel (SS) stylus, which were rigidly attached to a load frame and positioned over the prone-lying sheep. Two tri-axial, dynamic accelerometers are attached to stainless-steel pins located at L1 and L2. Four bipolar needle are located in the multifidus muscles adjacent to the L3, L4 spinous processes. Lower panel shows close up of SS stylus, L3 nEMG electrode (left) and accelerometers.

(model LA25-42, BEI Technologies Inc., Ashford, Kent, UK) and a programmable, pulse width modulated servo amplifier, voice coil drive controller (model VCA100, BEI Kimko Magnetics, San Marcos, CA, USA). The voice coil had a continuous stall force of 84 N and total stroke of 25.4 mm. A 665 N load cell (model MLP 150, Transducer Techniques, Temecula, CA, USA) and a ±25 mm linear variable displacement transducer (LVDT, model S1D, Instruments & Control, Inc., Branford, CT, USA) were used to measure the actuator force and displacement signals, respectively. Force and displacement signals were amplified using a dual channel, digital programmable gain amplifier (model PGA204, gain = 1000, Burr-Brown, Tucson, AZ, USA).

2.3. Mechanical testing protocol

PA forces were applied directly to the L3 spinous process via a 12.7 mm-diameter stainless-steel rod with a slotted tip that cradled the exposed bony spinous process. Following a 10 N preload, three mechanical stimulus pulse durations (10, 100, and 200 ms) at a constant force (60 N), and three force levels (20, 40, and 60 N) at constant pulse duration (100 ms) were examined. Thus, a total of four mechanical stimulation force levels (20, 40, 60, 80 N) were performed at a fixed pulse duration. Five trials were performed for each mechanical stimulus intervention in a randomly determined order. The PA force, L3 PA displacement, and vertebral accelerations were recorded at a sampling frequency of 5000 Hz and multifidus nEMG responses at 1250 Hz using a 16-bit data acquisition system (Model MP150, Biopac Systems, Inc. Santa Barbara, CA, USA).

3. Data analysis

Peak-to-peak force (L3), peak-to-peak displacement (L3), segmental accelerations (L1, L2) and intersegmental (L2–L1) acceleration responses were computed for each trial. The effect of mechanical stimulation pulse duration and amplitude on the PA motion response (displacement or acceleration) was assessed using a repeated measures analysis of variance (ANOVA). Statistical significance was $p < 0.05$. A least squares regression analysis was performed to assess the correlation between L3 displacement and L1, L2 acceleration responses. EMG amplitude ratios (peak-to-peak EMG response during mechanical stimulation divided by baseline response) were computed for each of the four needle EMG electrodes. Positive EMG responses were defined as an amplitude ratio $\geqslant 1.5$. The percentage of positive responses corresponding to amplitude ratios of 1.5, 2.0 and 2.5 were determined for each mechanical excitation protocol as the sum of positive responses for all 10 animals divided by the total number of thrusts (5 thrusts × 10 animals = 50).

4. Results

4.1. Displacement and acceleration responses

The uniform pulse PA mechanical excitation resulted in a haversine-like PA displacement of the L3 segment contact point (Fig. 2). Adjacent vertebrae showed expo-

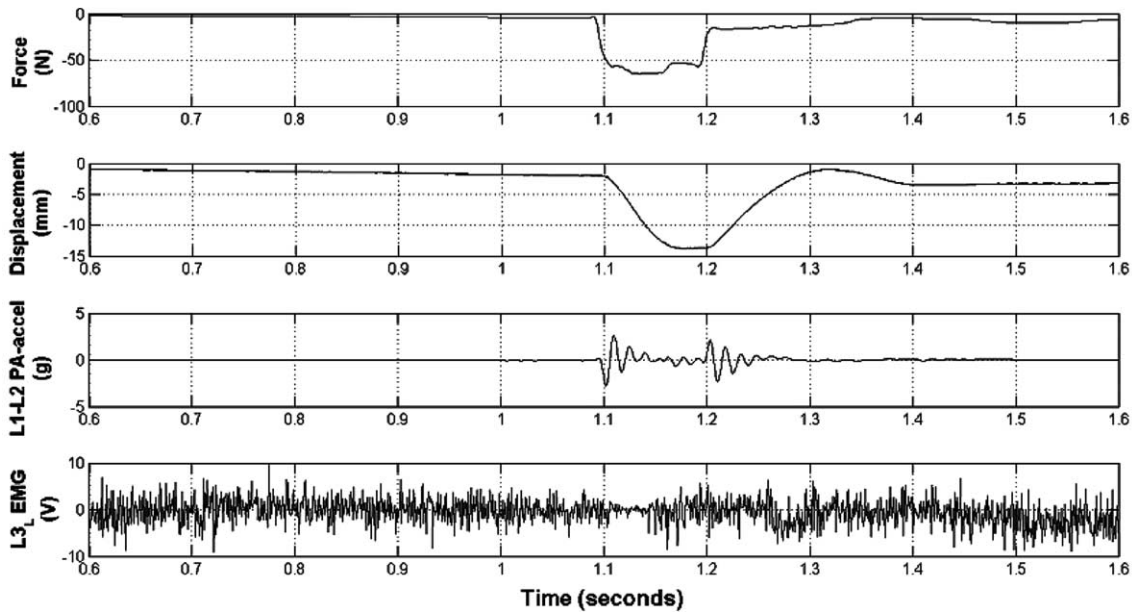

Fig. 2. Typical displacement, intersegmental acceleration (L2–L1) and nEMG (L3-left) responses to a uniform pulse mechanical excitation (60 N at 100 ms) applied to the L3 spinous process. Sheep 006 (48 kg). Inhibition of nEMG during mechanical excitation is evident in this case.

nentially damped oscillations during both the loading and unloading phases of the mechanical excitation pulse. The 10 ms mechanical excitation pulse protocol produced substantially longer duration (~75–150 ms) oscillations in the adjacent L1 and L2 vertebral segments in comparison to the 100 and 200 ms mechanical excitation protocols (~50–75 ms).

PA displacement responses (Fig. 3a) and L1, L2 vertebral acceleration responses (Fig. 3b) increased in a relatively linear manner with increasing mechanical stimulation force (maintaining a constant pulse duration = 100 ms). Increases in displacement and adjacent segment acceleration response were statistically significant (repeated measures ANOVA, $p < 0.001$). When the mechanical excitation force was kept constant, the 100 and 200 ms duration mechanical stimulus protocols resulted in significantly greater (4.83-fold and 4.80-fold, respectively, repeated measures ANOVA, $p < 0.001$) peak–peak L3 PA displacements in comparison to the 10 ms pulse protocol (Fig. 4a). However, the 10 ms pulse duration resulted in significantly greater (19% and 16%, respectively, repeated measures ANOVA, $p < 0.05$) amplitude vertebral motion responses (PA peak–peak acceleration) in the adjacent L2 vertebral segments in comparison to the 100 ms and 200 ms pulse duration SMT protocols (Fig. 4b). Vertebral acceleration responses were consistently greater for the L2 vertebral segment, which was adjacent to the mechanical excitation segmental contact point (L3). Intersegmental acceleration responses are summarized in Fig. 5, wherein there was a significant (repeated measures ANOVA, $p < 0.05$), linear increase in intersegmental motion associated with increasing mechanical excitation force (Fig. 5a). Pulse duration did not have a statistically significant effect on intersegmental acceleration (Fig. 5b).

Combining the results from the 20, 40, 60, and 80 N mechanical stimulation thrusts (five trials each), the adjacent segment (L2) PA acceleration response was linearly correlated to the L3 displacement response: displacement (mm) = 0.30 * Acceleration (m/s^2) + 3.65 ($R^2 = 0.61$, $p < 0.001$).

4.2. nEMG responses

Multifidus muscle nEMG responses were observed for all mechanical excitation protocols (at least one trial). In some cases, however, mechanical excitation elicited muscle inhibition (refer to Fig. 2). Pulse duration at the 80 N thrust force did not influence the percentage of lower amplitude (1.5× baseline) nEMG responses, but a greater percentage of higher amplitude (2.0×, 2.5× baseline) nEMG responses were observed for the 100 ms and 200 ms duration protocols (Fig. 6). The magnitude and percentage of positive EMG responses increased with increasing force magnitude for both low amplitude and high amplitude nEMG responses.

5. Discussion

Administration of mechanical stimuli to the spine is standard practice in the fields of orthopaedics, physical therapy, and chiropractic. In this study, larger magnitude mechanical excitation forces applied to the L3 spinous process resulted in significantly greater L3 vertebral displacements and adjacent segment accelerations.

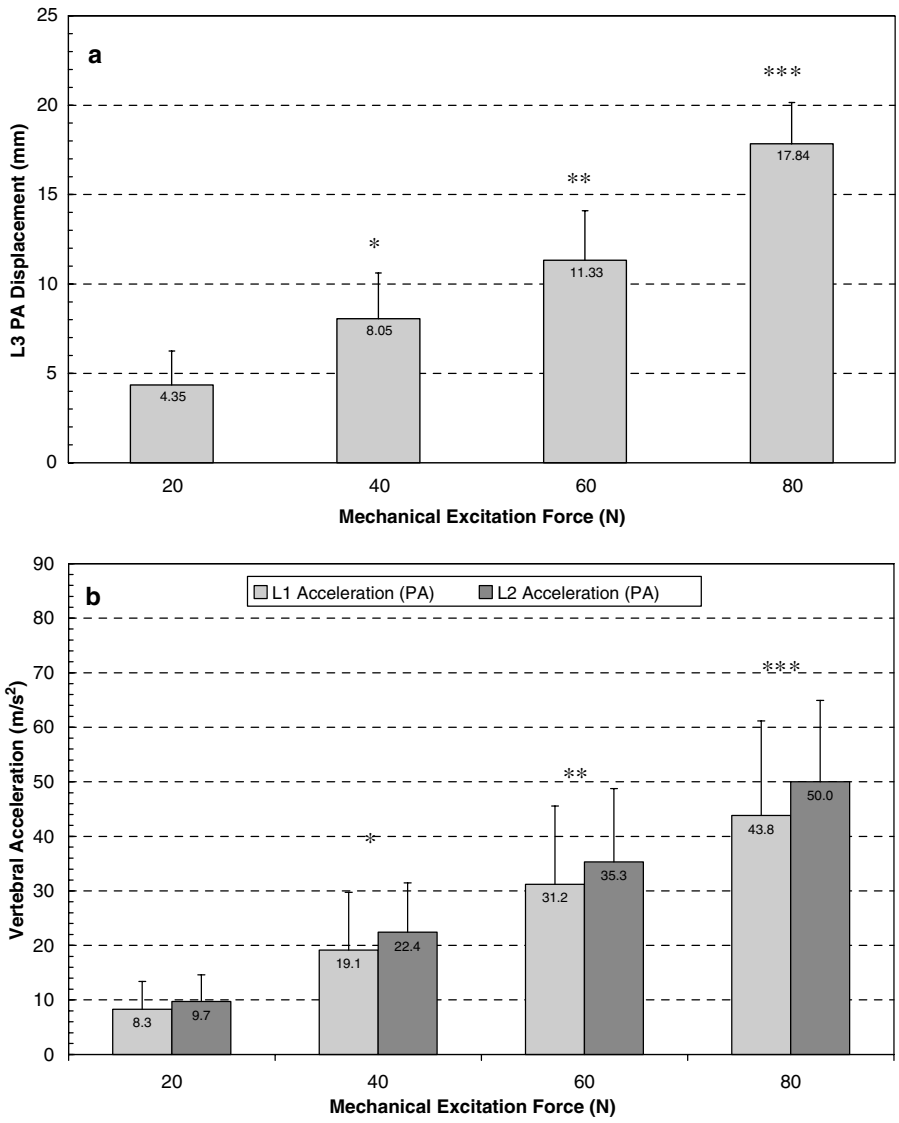

Fig. 3. (a) Actuator displacement response during constant pulse duration (100 ms), variable force mechanical excitation at L3. (*) Statistically significant from 20 N load amplitude; (**) statistically significant from 20 N and 40 N load amplitude; (***) statistically significant from 20 N, 40 N and 60 N load amplitude (repeated measures ANOVA). (b) L1, L2 vertebral acceleration response during constant pulse duration (100 ms), variable force mechanical excitation at L3. (*) Statistically significant from 20 N load amplitude (L1 and L2 acceleration); (**) statistically significant from 20 N and 40 N load amplitude (L1 and L2 acceleration); (***) statistically significant from 20 N, 40 N and 60 N load amplitude (L1 and L2 acceleration) (repeated measures ANOVA).

With constant force magnitude, however, shorter or faster pulse duration mechanical stimulation (10 ms thrust) was found to produce larger adjacent segment vertebral motions at L1 and L2, in comparison to longer pulse duration thrusts (100 or 200 ms). These findings are consistent with impulsive-type SMTs where the abrupt change in velocity causes the spine to vibrate freely following the SMT (Keller et al., 2002). Similar findings of adjacent vertebral motion in response to mechanical force manually assisted SMTs have also been reported in human subjects in vivo (Nathan and Keller, 1994).

Using a custom mechanical actuator to apply SMT-like forces to the ovine spine, we found that L3 vertebral displacement increased linearly with increasing force. This indicates that the applied loads were in the linear region of the load–deformation curve. The non-linear, load–deformation characteristics of the ovine spine, however, would be expected to result in variations in the measured PA displacement. Hence, the application of lower or higher force magnitudes may have resulted in a non-linear force–displacement responses as reported elsewhere (Lee et al., 1997; Latimer et al., 1998). We also found that shorter pulse durations (faster) SMTs produced larger adjacent segment vertebral motions in comparison to longer pulse duration SMTs, which is consistent with previous in vivo studies in human subjects (Nathan and Keller, 1994; Colloca et al., 2004; Keller et al., 2003). Short duration (less than 25 ms)

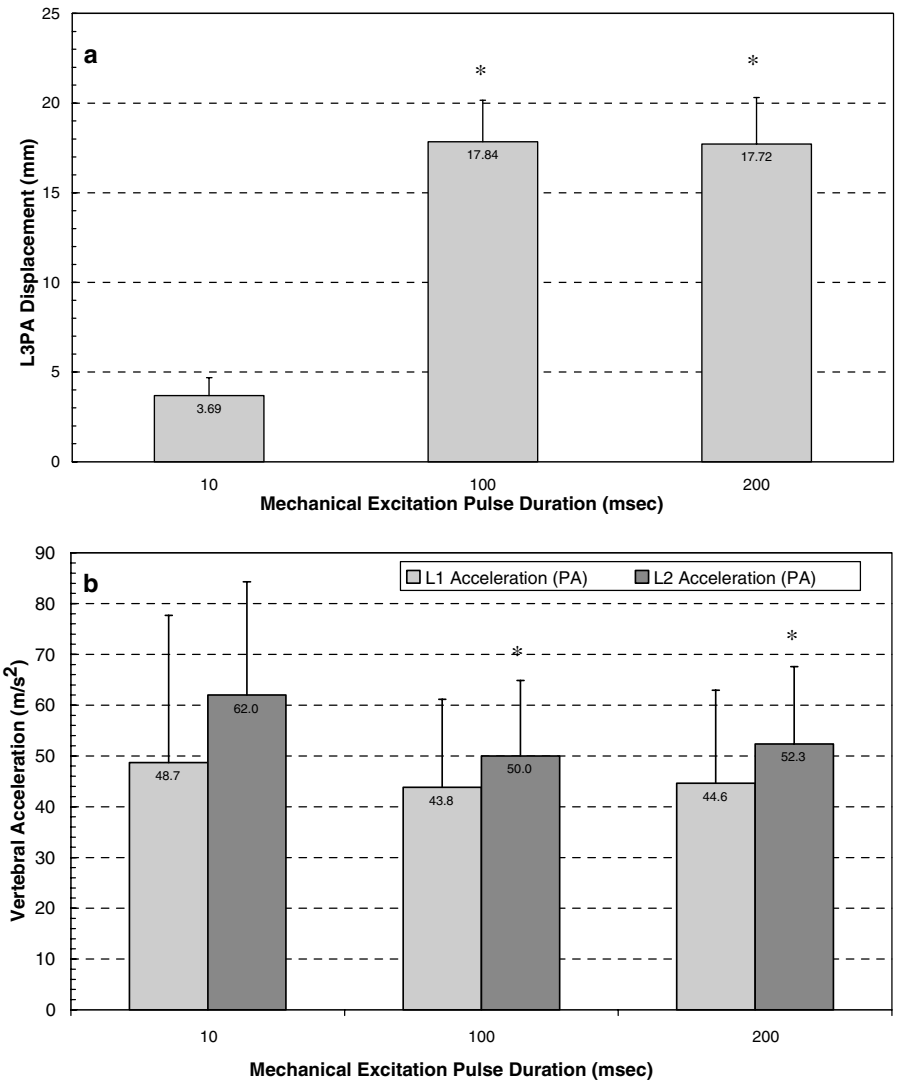

Fig. 4. (a) Actuator displacement response during constant force (80 N), variable pulse duration mechanical excitation at L3. (*) Statistically significant from 10 ms pulse duration (repeated measures ANOVA). (b) L1 and L2 vertebral acceleration response during constant force (80 N), variable pulse duration mechanical excitation at L3. (*) statistically significant from 10 ms pulse duration (L2 acceleration) (repeated measures ANOVA).

instrument adjusting SMTs are known to produce an abrupt change in velocity, which causes the spine to vibrate freely (Keller et al., 2002). For heavily damped structures such as the ovine and human spine, however, the vibration response dissipates within 150 ms. Given the putative effects of impulsive-type chiropractic adjustment procedures (Wood et al., 2001; Gemmell and Jacobson, 1995; Yurkiw and Mior, 1996; Keller and Colloca, 2000), the enhanced segmental and intersegmental vibration response observed in this study may represent one mechanism by which impulsive-type SMTs produce clinically relevant results.

Measurement of bone movement using intraosseous pins equipped with accelerometers (Colloca et al., 2004; Keller et al., 2003; Nathan and Keller, 1994) and other invasive motion measurement devices (Kaigle et al., 1997; Kaigle et al., 1992) has been previously shown to be a precise measure of spine segmental and intersegmental motion. However, such invasive procedures currently have limited clinical utility. Of fundamental importance, however, was our finding that mechanical excitation externally applied at the segmental contact point (L3) significantly correlated to the adjacent segment acceleration transfer (L2–L1) data obtained from the accelerometers mounted to rigidly affixed interosseous pins. The ability to non-invasively characterize spinal biomechanics is a novel finding that has implications for the development of objective quantitative biomechanical spinal assessments.

In the current study SMT loads were applied directly to the spinous processes and not to the overlying skin as

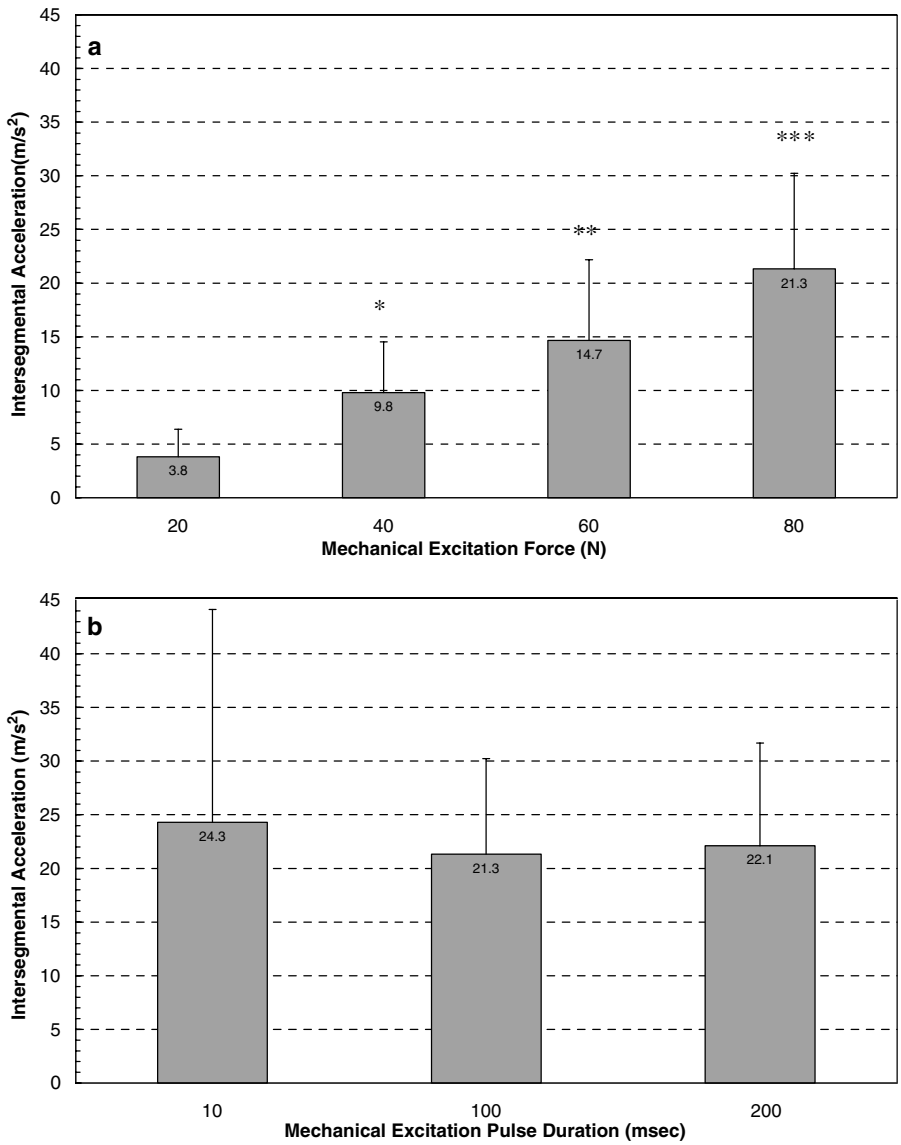

Fig. 5. (a) L2–L1 intersegmental vertebral acceleration response during constant pulse duration (100 ms), variable force mechanical excitation at L3. (*) statistically significant from 20 N load amplitude; (**) statistically significant from 20 N and 40 N load amplitude; (***) statistically significant from 20 N, 40 N and 60 N load amplitude (repeated measures ANOVA). (b) L2–L1 intersegmental vertebral acceleration response during constant force (80 N), variable pulse duration mechanical excitation at L3. No significant differences among groups.

with clinically applied SMT. Question may arise of whether the viscoelastic components of the overlying skin and fascia may attenuate the load amplitudes and frequencies as they are transmitted. It is likely that the 10–20 N preload commonly preceding SMT in clinical practice (Keller et al., 2002) sufficiently compresses these tissues against the spinous process likewise to the segmental contact points in the experimental design of the current study. Future work should quantify our experimental variables among direct spinous process contacts and those applied to the skin overlying the spinous process to clarify any subsequent differences in spinal motion and neurophysiological responses to SMT that may exist.

Each of the mechanical force–time profiles examined in the current study were found to elicit positive nEMG responses. Larger force magnitudes and pulse durations, however, were necessary to elicit larger amplitude ratio nEMG thresholds (2.0× and 2.5× baseline). These findings support the findings of Herzog et al. (1999) and Symons et al. (2000) whose data indicated that larger force magnitude SMTs elicited larger numbers of neuromuscular responses. Noteworthy was our finding that mechanical excitation evoked an inhibitory response in a number of cases which may represent an unloading reflex previously described in the literature (Reeves et al., 2005). The unloading reflex is a common occurrence in everyday activities where during sudden unload-

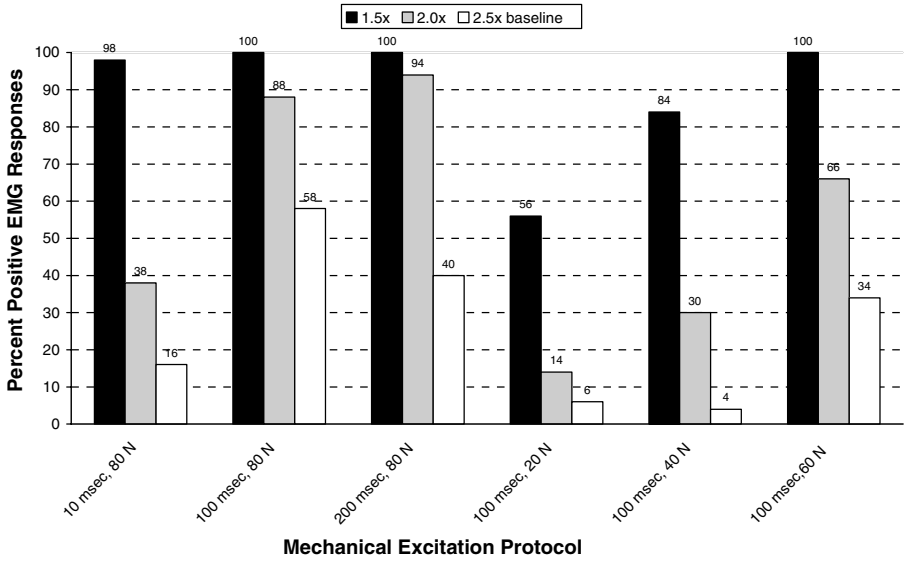

Fig. 6. Needle EMG responses during variable mechanical excitation pulse duration (10, 100, 200 ms) and variable mechanical excitation pulse force (20, 40, 60 N). Bars represent percentages of positive nEMG responses for low (1.5×), medium (2.0×) and high (2.5×) amplitude responses (normalized with respect to the baseline or pre-thrust voltage). Percentages represent occurrences of at least one positive response for each animal during a given mechanical stimulation protocol.

ing, agonist muscles experience a brief period of inhibition, while concurrently, antagonist muscles activation levels are increased. This neuromuscular activation pattern minimizes the perturbation by altering the net joint torque (Reeves et al., 2005). While the neural pathways for neuromuscular control of the trunk are not clearly understood, a number of receptors have been found to provide feedback to respond to an unloading perturbation, including muscle spindles, and Types I–III receptors (Kang et al., 2002; Pickar and McLain, 1995; Pickar and Wheeler, 2001; Sung et al., 2005; Solomonow and Krogsgaard, 2002; Stubbs et al., 1998). Convergent afferent input from various receptors in the IVD, spinal ligaments and paraspinal musculature most likely contributes to the neuromuscular response observed during loading that was observed in the current study. Just how force–time profiles of SMT modulate such neuromuscular responses are of interest in the clinical utility of SMT and in the development of more effective interventions and treatment plans.

6. Conclusions

Increasing mechanical stimulus force amplitude caused larger vertebral motions at the segmental contact point, but shorter pulse duration mechanical stimuli resulted in greater motions in the adjacent vertebral segments. Neuromuscular responses were modulated by increasing force amplitude and duration. Further work is necessary to understand the significance of these and other neuromechanical variables in physiologic and clinical outcomes associated with SMT.

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References

Bronfort, G., Haas, M., Evans, R.L., Bouter, L.M., 2004. Efficacy of spinal manipulation and mobilization for low back pain and neck pain: a systematic review and best evidence synthesis. Spine J. 4, 335–356.

Colloca, C.J., Keller, T.S., 2001. Electromyographic reflex response to mechanical force, manually-assisted spinal manipulative therapy. Spine 26, 1117–1124.

Colloca, C.J., Keller, T.S., Gunzburg, R., Vandeputte, K., Fuhr, A.W., 2000. Neurophysiologic response to intraoperative lumbosacral spinal manipulation. J. Manipulat. Physiol. Ther. 23, 447–457.

Colloca, C.J., Keller, T.S., Gunzburg, R., 2003. Neuromechanical characterization of in vivo lumbar spinal manipulation. Part II. Neurophysiological response. J. Manipulat. Physiol. Ther. 26, 579–591.

Colloca, C.J., Keller, T.S., Gunzburg, R., 2004. Biomechanical and neurophysiological responses to spinal manipulation in patients with lumbar radiculopathy. J. Manipulat. Physiol. Ther. 27, 1–15.

Gal, J.M., Herzog, W., Kawchuk, G.N., Conway, P.J., Zhang, Y.T., 1995. Forces and relative vertebral movements during SMT to unembalmed post-rigor human cadavers: peculiarities associated with joint cavitation. J. Manipulat. Physiol. Ther. 18, 4–9.

Gal, J., Herzog, W., Kawchuk, G., Conway, P., Zhang, Y.T., 1997a. Measurements of vertebral translations using bone pins, surface markers and accelerometers. Clin. Biomech. 12, 337–340.

Gal, J., Herzog, W., Kawchuk, G., Conway, P.J., Zhang, Y.T., 1997b. Movements of vertebrae during manipulative thrusts to unembalmed human cadavers. J. Manipulat. Physiol. Ther. 20, 30–40.

Gemmell, H.A., Jacobson, B.H., 1995. The immediate effect of activator vs. meric adjustment on acute low back pain: a randomized controlled trial. J. Manipulat. Physiol. Ther. 18, 453–456.

Herzog, W., 2000. Clinical Biomechanics of Spinal Manipulation. Churchill Livingstone, Philadelphia.

Herzog, W., Conway, P.J., Kawchuk, G.N., Zhang, Y., Hasler, E.M., 1993. Forces exerted during spinal manipulative therapy. Spine 18, 1206–1212.

Herzog, W., Scheele, D., Conway, P.J., 1999. Electromyographic responses of back and limb muscles associated with spinal manipulative therapy. Spine 24, 146–152.

Kaigle, A.M., Pope, M.H., Fleming, B.C., Hansson, T., 1992. A method for the intravital measurement of interspinous kinematics. J. Biomech. 25, 451–456.

Kaigle, A.M., Holm, S.H., Hansson, T.H., 1997. 1997 Volvo Award winner in biomechanical studies. Kinematic behavior of the porcine lumbar spine: a chronic lesion model. Spine 22, 2796–2806.

Kang, Y.M., Choi, W.S., Pickar, J.G., 2002. Electrophysiologic evidence for an intersegmental reflex pathway between lumbar paraspinal tissues. Spine 27, E56–E63.

Keller, T.S., Colloca, C.J., 2000. Mechanical force spinal manipulation increases trunk muscle strength assessed by electromyography: A comparative clinical trial. J. Manipulat. Physiol. Ther. 23, 585–595.

Keller, T.S., Colloca, C.J., Beliveau, J.G., 2002. Force–deformation response of the lumbar spine: a sagittal plane model of posteroanterior manipulation and mobilization. Clin. Biomech. 17, 185–196.

Keller, T.S., Colloca, C.J., Gunzburg, R., 2003. Neuromechanical characterization of in vivo lumbar spinal manipulation. Part I. Vertebral motion. J. Manipulat. Physiol Ther. 26, 567–578.

Latimer, J., Lee, M., Adams, R.D., 1998. The effects of high and low loading forces on measured values of lumbar stiffness. J. Manipulat. Physiol. Ther. 21, 157–163.

Lee, M., Latimer, J., Maher, C., 1997. Normal response to large posteroanterior lumbar loads—a case study approach. J. Manipulat. Physiol. Ther. 20, 369–371.

Maigne, J.Y., Guillon, F., 2000. Highlighting of intervertebral movements and variations of intradiskal pressure during lumbar spine manipulation: a feasibility study. J. Manipulat. Physiol. Ther. 23, 531–535.

Meeker, W.C., Haldeman, S., 2002. Chiropractic: a profession at the crossroads of mainstream and alternative medicine. Ann. Intern. Med. 136, 216–227.

Nathan, M., Keller, T.S., 1994. Measurement and analysis of the in vivo posteroanterior impulse response of the human thoracolumbar spine: a feasibility study. J. Manipulat. Physiol. Ther. 17, 431–441.

Pickar, J.G., McLain, R.F., 1995. Responses of mechanosensitive afferents to manipulation of the lumbar facet in the cat. Spine 20, 2379–2385.

Pickar, J.G., Wheeler, J.D., 2001. Response of muscle proprioceptors to spinal manipulative-like loads in the anesthetized cat. J. Manipulat. Physiol. Ther. 24, 2–11.

Reeves, N.P., Cholewicki, J., Milner, T.E., 2005. Muscle reflex classification of low-back pain. J. Electromyogr. Kinesiol. 15, 53–60.

Solomonow, M., Krogsgaard, M., 2002. The sensory function of ligaments. J. Electromyogr. Kinesiol. 12, 165.

Stubbs, M., Harris, M., Solomonow, M., Zhou, B., Lu, Y., Baratta, R.V., 1998. Ligamento-muscular protective reflex in the lumbar spine of the feline. J. Electromyogr. Kinesiol. 8, 197–204.

Sung, P.S., Kang, Y.M., Pickar, J.G., 2005. Effect of spinal manipulation duration on low threshold mechanoreceptors in lumbar paraspinal muscles: a preliminary report. Spine 30, 115–122.

Symons, B.P., Herzog, W., Leonard, T., Nguyen, H., 2000. Reflex responses associated with activator treatment. J. Manipulat. Physiol. Ther. 23, 155–159.

Triano, J., Schultz, A.B., 1997. Loads transmitted during lumbosacral spinal manipulative therapy. Spine 22, 1955–1964.

Wood, T.G., Colloca, C.J., Matthews, R., 2001. A pilot randomized clinical trial on the relative effect of instrumental (MFMA) versus manual (HVLA) manipulation in the treatment of cervical spine dysfunction. J. Manipulat. Physiol. Ther. 24, 260–271.

Yurkiw, D., Mior, S., 1996. Comparison of two chiropractic techniques on pain and lateral flexion in neck pain patients: a pilot study. Chiropr. Tech. 8, 155–162.