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Effect of changing lumbar stiffness by single facet joint dysfunction on the responsiveness of lumbar muscle spindles to vertebral movement

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Objective: *Individuals experiencing low back pain often present clinically with intervertebral joint dysfunction. The purpose of this study was to determine whether relative changes in stiffness at a single spinal joint alters neural responsiveness of lumbar muscle spindles to either vertebral movement or position.*

Methods: *Muscle spindle discharge was recorded in response to 1mm L_6 ramp and hold movements (0.5mm/s) in the same animal for lumbar laminectomy-only (n=23), laminectomy & $L_{5/6}$ facet screw (n=19), laminectomy & $L_{5/6}$ facetectomy (n=5) conditions. Mean instantaneous frequency (MIF) was calculated for the ramp-up, hold, ramp-down and post-ramp phases during each joint condition.*

Objectif : *La lombalgie se manifeste souvent cliniquement sous forme de dysfonction articulaire intervertébrale. Cette étude a pour objet de déterminer si des changements relatifs dans la rigidité d'une seule articulation vertébrale modifieraient la réactivité des fuseaux musculaires lombaires envers le mouvement ou la position des vertèbres.*

Méthodologie : *Les décharges des fuseaux musculaires ont été notées en réponse à des mouvements de rampe et de maintien de 1 mm à L_6 (0,5 mm/s) chez le même animal pour le groupe laminectomie lombaire seulement (n=23), laminectomie et vis translaminofacettaire $L_{5/6}$ (n=19), laminectomie et facettectomie $L_{5/6}$ (n=5). La fréquence instantanée moyenne (FIM) a été calculée pour les phases d'intensification, de maintien, d'atténuation et post-rampe pour chacun des groupes.*

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Results: *Mean MIFs were not significantly different between the laminectomy-only and the other two types of joint dysfunction for the ramp-up, hold, ramp-down, or post-ramp phases.*

Conclusion: *Stiffness changes caused by single facet joint dysfunction failed to alter spindle responses during slow 1mm ramp and hold movements of the L_6 vertebra.*

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KEY WORDS: stiffness, joint, muscle spindle, chiropractic

Résultats : *Les FIM n'étaient pas significativement différentes entre le groupe laminectomie seule et les deux autres types de dysfonction articulaires pour les phases d'intensification, de maintien, d'atténuation et post-rampe.*

Conclusion : *Les changements de rigidité causés par une dysfonction articulaire à facette unique n'ont pas réussi à modifier la réponse des fuseaux au cours de mouvements lents de rampe et de maintien de 1 mm de la vertèbre L_6.*

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MOTS CLÉS : rigidité, articulation, fuseau musculaire, chiropratique.

Introduction

Aberrant neuromuscular control of the trunk along with the inability of individuals with LBP to adopt optimal postural control strategies is thought to be involved in the etiology of low back pain (LBP).[1-10] Individuals with LBP demonstrate reduced lumbar muscle activation or earlier onsets of muscle activation following predictable and unpredictable trunk loading.[6] It has been reported that individuals experiencing an active episode of LBP demonstrate inadequate trunk muscle activation or inappropriate trunk muscle co-activation in response to rapid and/or unexpected perturbation.[11-13] In addition, LBP patients exhibit altered movement patterns between recurrent episodes but it is unclear whether the patterns develop prior to or following the first LBP episode.[10] These altered neuromuscular responses that accompany LBP have been attributed to a number of mechanisms including segmental neural circuitry and cognitive responses due to stress, pain avoidance and/or anticipation of pain.[14,15]

Muscle spindles are proprioceptors which provide a continuous sensory input to the central nervous system related to muscle length and rate of change in muscle length, and thereby potentially supply information regarding joint position and movement. This sensory input may help to optimize neuromuscular control of the trunk and intervertebral motion during intended movement trajectories. Compared to muscle spindles in appendicular muscles, much less is known about the functional characteristics of these proprioceptors in trunk musculature. However differences in structural complexity, organization and response to changes in muscle length have been described in muscle spindles of the trunk relative to appendicular muscles.[16-21] For example, we have recently shown that measures of dynamic responsiveness in trunk muscles are 5-10x higher than values reported for appendicular muscles.[18] Table 1 provides an abbreviated summary of recent findings regarding the responses of paraspinal muscle spindles to changes in both vertebral position and movement as well as to high velocity low amplitude spinal manipulation using variations of the experimental model employed in the present study.

Impaired spinal biomechanics are thought to have adverse physiological consequences by producing less than optimal neuromuscular control of the trunk. Individuals experiencing acute or chronic LBP episodes often present clinically with intervertebral joint dysfunction.[29-31] The relationship between intervertebral joint mobility and alterations in trunk mechanoreception has received little direct investigation but is of clinical interest due to the frequent assessment of intervertebral joint mobility by manual therapy practitioners during their clinical decision making process when treating patients experiencing LBP.

There is evidence suggesting that clinical identification of spinal joint hypo- and hypermobility subgroups along with correspondingly tailored manual therapy treatment approaches can lead to more successful therapeutic out-

Table 1

Muscle spindle response to vertebral position, movement, & spinal manipulation in an animal model

I. Lumbar Vertebral Position and Movement	
The history of vertebral position can change the responsiveness of muscle spindles. Static postures that changed lumbar vertebra position by as little as 0.07mm for as little as 4sec altered muscle spindle responsiveness to passive movement.	Cao and Pickar 2011[22] Ge and Pickar 2012[24]
Dynamic responsiveness of paraspinal muscle spindles are at least 5-10x higher compared to values reported for appendicular muscles.	Cao et al. 2009[18]
Muscle spindle responsiveness to lumbar vertebral movement and to a new position did not change in response to HVLA-SM regardless of thrust force, displacement, or duration.	Cao et al. 2013[23]
II. High Velocity Low Amplitude Spinal Manipulation (HVLA-SM)	
As HVLA-SM thrust duration approaches those used clinically, discharge frequency greatly increases and the increase depends more upon the amplitude of the thrust opposed to the thrust force.	Reed et al. 2013[25] Pickar & Kang 2006[27] Pickar et al. 2007[28]
Lumbar muscle spindles show more sensitivity to smaller HVLA-SM thrust displacements (1 vs 2mm).	Pickar et al. 2007[28]
HVLA-SM thrust duration effects baseline spindle discharge at 1, 2, 3mm displacements and 25, 55, 85% body weight thrust force.	Cao et al. 2013[23]
Intersegmental mobility changes at a single facet joint alters spindle response to clinically relevant HVLA-SM thrust durations (≤ 150ms).	Reed et al. 2013[26]

comes.[32-34] In a randomized clinical trial categorizing 131 LBP patients with respect to the clinical determination of spinal joint hypo- and hypermobility, it was reported that individuals with spinal joint hypomobility had greater improvement with spinal manipulation than individuals with spinal joint hypermobility.[33] This clinical study highlights the need not only to understand the underlying biological mechanisms of manual therapy intervention but suggests that the physiological response to the same therapeutic intervention differs based on the clinically identified types of spinal joint dysfunction (hypo- or hypermobility).

Motivated by the lack of knowledge regarding how different types of spinal joint dysfunction affect trunk mechanoreceptor activity and possibly clinical outcomes to the same manual therapeutic intervention, we undertook a series of basic science experiments investigating the effect of spinal joint dysfunction on sensory input related to vertebral movement and spinal manipulation. We previously reported the effects that single facet joint dysfunction has on sensory input during spinal manipulation.[26] The purpose of this paper is to report the effects that single facet joint dysfunction have on the mean instantaneous frequency of muscle spindles located in trunk musculature during 1mm ramp and hold movements of the L_6 lumbar vertebra derived from secondary analyses of the previous study involving facet joint dysfunction and spinal manipulation.[26]

Methods

Electrophysiological recordings were made from lumbar paraspinal muscle spindles in 23 Nembutal-anesthesized male cats weighing an average of 4.46kg (SD 0.31). All experiments were reviewed and approved by the Institutional Animal Care and Use Committee and comply with the Canadian Council on Animal Care. One neuron was investigated per animal because of the irreversible nature of the $L_{5/6}$ facetectomy surgical procedure. The experi-

Table 2

	Laminectomy Only	Laminectomy & Facet Screw	Laminectomy & Facetectomy
Experimental Order	1st →	2nd →	3rd
Vertebra Movement	L6	L6	L6
Number of L6 Neurons Analyzed	20	19	5

mental approach has been described previously in detail[25,26,35] and is presented only briefly.

A mixture of O_2 and isoflurane was delivered through a facemask (2L/min and 2%) in order to place catheters in a common carotid artery and an external jugular vein to monitor blood pressure and introduce fluids respectively. Following catheterization, deep anesthesia was maintained throughout the experiment with Nembutal (35 mg/kg, iv). Deep anesthesia was identified by absence of withdrawal reflex to noxious pinching of the toe pad, mean arterial pressures less than 120mmHg and the absence of a pressor response to surgical manipulation.

The proximal portion of the L_6 dorsal roots (cats have 7 lumbar vertebrae) was exposed after a bilateral laminectomy at the L_5 vertebra. The musculature on the right side of the spinal column (multifidus, longissimus and iliocostalis muscles) remained intact except for any attachments to the posterior portions of the L_{4-5} vertebrae and for small slit incisions (3mm) on either side of the L_6 spinous process for forceps attachment by which the vertebra was moved. Most of the multifidus muscle remained attached to the L_6 vertebra using this method because it's aponeurotic tendon inserts onto the process's caudal edge.[36] In addition, the L_6 dorsal root enters the spinal cord 1 to 1½ vertebral segments cranial to the L_6 paraspinal soft tissues. The L_6 dorsal root was cut close to its entrance into the spinal cord and placed on a small platform. Thin filaments from the cut proximal dorsal rootlets were teased apart until muscle spindle activity from a single neuron with the most sensitive part of its receptive field being in the low back could be identified. At the end of the experimental protocols several approaches were used to confirm receptor location and its identity as a muscle spindle including: (1) vonFrey filaments (Stoelting, USA) to confirm the most sensitive area for mechanically activating the neuron was in the multifidus or longissimus muscles (the intervening lumbococcygeus muscle innervated by sacral nerves was removed; (2) a sustained increase in discharge response to succinylcholine injection (100 ug/kg, ia); (3) a sustained increase in response to a fast vibratory stimulus and (4) decreased discharge to paraspinal muscle electrically induced muscle twitch.

Ramp and hold movement of the L_6 vertebra was controlled using an electronic feedback control system (Lever System Model 310; Aurora Scientific) under displacement control. Attached to the control system's lever arm was a pair of adjustable tissue forceps which were clamped tightly onto the lateral surfaces of the L_6 spinous process. Ramp and hold movements of 1mm peak amplitude were applied at a rate of 0.5mm/s. Due to the facetectomy, testing order for the three joint conditions in the same animal was fixed. Therefore, determination of muscle spindle responses to the 1mm ramp and hold displacements was conducted in the following order: laminectomy-only, laminectomy & facet screw, laminectomy & facetectomy (Table 2). It should be noted that ramp testing for each spinal joint condition was performed prior to conducting a series of 5 randomized spinal manipulative thrust protocols (time control-0 ms, 75, 100, 150, 250ms) each separated by 5 minute intervals as previously described in detail.[26] In addition, insertion of the facet screw and facetectomy procedure typically required 30-35 minutes to accomplish equating to approximately 1 hour elapsing between ramp and hold testing per spinal joint condition once a paraspinal muscle spindle was isolated.

Creating Spinal Joint Conditions and Determining of Lumbar Stiffness

Changes in spinal stiffness were created by unilateral (left) $L_{5/6}$ facet-fixation (to increase intervertebral stiffness) or $L_{5/6}$ facetectomy (to decrease intervertebral stiffness). The left $L_{5/6}$ facet joint was fixated by inserting a single 10mm titanium endosteally-anchored mini-screw (tomas®-pin; Dentaurum, Germany) through the articular pillars of the $L_{5/6}$ facet joint. For the facetectomy, the left L_5 inferior facet and left L_6 superior facet were removed using bone rongeurs.

Lumbar stiffness testing was first performed in the laminectomy-only condition, as opposed to the intact spine, as this was the spinal condition in which neural recordings were first obtained. To determine lumbar stiffness in each joint condition, a 1mm ramp and hold movement of the L_6 vertebra was applied in the dorsal ventral direction at a rate of 0.5mm/s using the feedback-controlled motor. During the 1mm ramp and hold, forces and displacements were being measured so that force-displacement curves of the ramp portion could be constructed. The slope of the most linear portion of the force-displacement curve (between 2.16 – 8.83N) of the 1mm ramp was calculated and represented the spinal joint stiffness for each condition. Ramp pre-conditioning was not performed in order to minimize the total number of facet screw/bone engagements.

Twenty-three animals were used in this study. As described previously,[26] animals in which the laminectomy & facet screw (n=4) failed to increase ramp stiffness by at least 2 % when compared to the laminectomy-only condition were excluded from further analysis. Similarly, animals in which the laminectomy & facetectomy (n=8) failed to decrease ramp stiffness by at least 2% when compared to laminectomy-only were also excluded. In addition, during the laminectomy & facetectomy condition the neural recording was lost in 10 animals due to facetectomy-associated bleeding. Therefore, of the 23 animals used in this study, 20 neurons were included in the analysis: 4 had data for all 3 conditions (laminectomy-only, laminectomy & facet screw, laminectomy & facetectomy), 15 had data for the laminectomy-only and laminectomy & facet screw conditions, and 1 had data for the laminectomy-only and laminectomy & facetectomy conditions (Table 2).

Data Analysis

Muscle spindle activity was converted to instantaneous frequency (IF) by taking the reciprocal of the time interval between successive action potentials. IFs during the constant velocity ramp movement and hold position were used to obtain the following 5 measures of afferent response: (a) baseline during the 2 seconds that immediately preceded each ramp-up; (b) ramp-up; (c) during the last 2 seconds of the hold phase; (d) ramp-down and (e) post-ramp during 2 seconds that immediately follow the ramp-down (Fig. 1). Mean IF (MIF) was calculated over the durations of baseline, ramp-up, hold, ramp-down and the post-ramp phase.

Changes from baseline MIF due to the laminectomy-only, laminectomy & screw and the laminectomy & facetectomy condition during the 1mm ramp and hold constituted the response measures. All neural activity was reported in impulses per second (imp/s). Data were analyzed in SAS System for Windows (Release 9.2) (SAS Institute Inc., Cary, NC). Statistical significance was set at 0.05. Each response variable was analyzed with a linear mixed effects longitudinal regression model including individual random effects to account for correlation between repeated measurements for an individual neuron based on a compound symmetry covariance structure. Adjusted means and 95% confidence intervals based on this model are reported.

Results

Muscle spindle recordings were analyzed from neurons with receptive fields located in the multifidus muscle (n=3) and longissimus muscle (n=17). In the cat, these lumbar paraspinal muscles are the two most medial to the spinous process.[36] In response to succinylcholine injection, all neurons exhibited long lasting high frequency discharges relative to baseline. In addition, all neurons exhibited a sustained response to vibratory stimulus and were silenced by muscle twitch during bipolar muscle stimulation (amplitude 0.1-0.3mA: 50 μs).

Lumbar stiffness in the laminectomy-only condition was 11.51N/mm (range 6.39 to 18.23N/mm). Compared to the laminectomy-only condition, laminectomy-facet fixation increased spinal stiffness 4.02N/mm (range: 1.08 to 7.75N/mm; 12.56% to 69.45%) while laminectomy-facetectomy decreased spinal stiffness −1.18N/mm

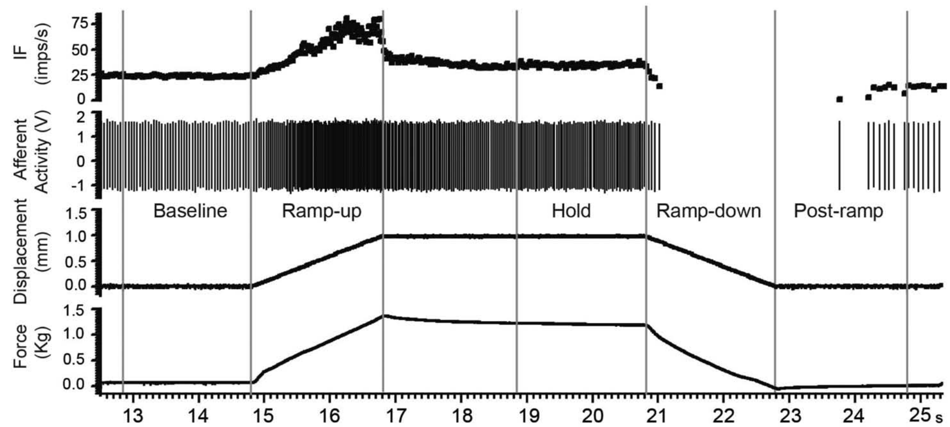

Figure 1.
An example of a 1mm ramp and hold movement of a L6 vertebra in a laminectomy-only preparation. Force, displacement, primary afferent activity and instantaneous frequency recordings are shown. Baseline, ramp-up, hold, ramp-down, and post-ramp regions used to calculate mean instantaneous frequencies are demarcated. Note the increase in afferent activity during the ramp-up and hold phase and the cessation of discharge due to unloading of the muscle spindle during the ramp-down phase.

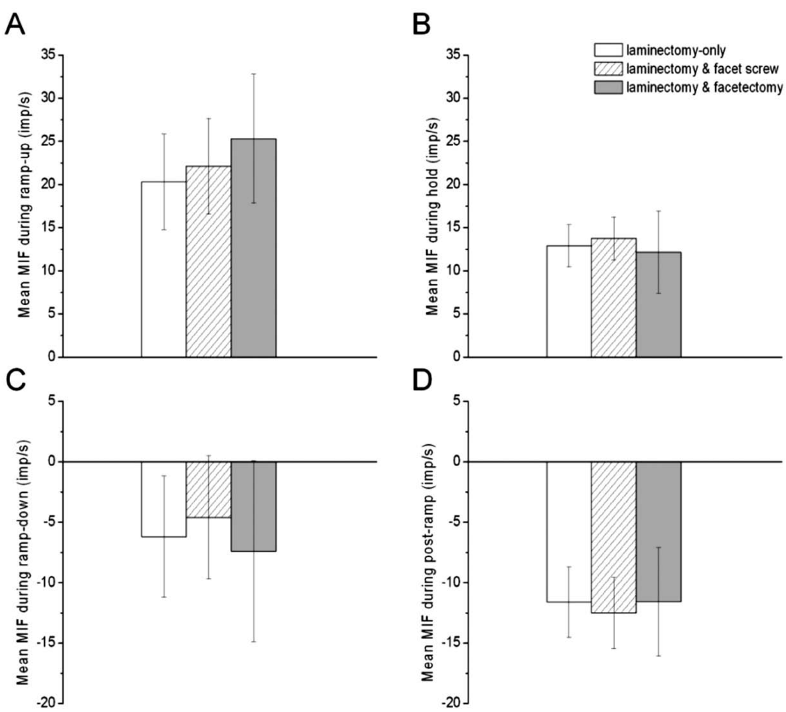

Figure 2.
The mean change in mean instanteous frequency relative to baseline discharge during (A) ramp-up, (B) hold, (C) ramp-down, and (D) post-ramp for laminectomy-only, laminectomy-facet fixation, and lamectomy-facetectomy conditions. There were no significant differences between conditions during any phase of vertebra movement.

(range: −0.69 to −2.26N/mm; −3.25% to −21.09%) as reported previously.[26]

Figure 1 shows an original recording from a muscle spindle with a receptive field in the longissimus muscle during a 1mm ramp and hold experimental protocol in the laminectomy-only condition. There was an increase in neural activity during the ramp-up and hold phases which was typically followed by a cessation of muscle spindle discharge due to spindle unloading and a resumption of resting discharge.

Figure 2 shows the adjusted mean MIF and 95% confidence intervals for each response measure during the ramp and hold movements for each facet joint condition. Mean $MIF_{ramp\text{-}up}$ was not significantly different among the 3 conditions (Fig. 2A; $F_{2,22}$=1.71, p=.20). The adjusted mean difference in $MIF_{ramp\text{-}up}$ between the laminectomy-only and the laminectomy & facet screw condition was 1.82imp/s (-1.61, 11.04) and 4.99imp/s (-1.07, 11.04) between the laminectomy-only condition and the laminectomy & facetectomy condition. Mean MIF_{hold} (Fig. 2B; $F_{2,22}$=0.27, p=.76), $MIF_{ramp\text{-}down}$ (Fig. 2C; $F_{2,22}$=0.56, p=.58) and $MIF_{post\text{-}ramp}$ (Fig. 2D; $F_{2,22}$=0.33, p=.72) were also not significantly different among conditions.

Discussion

The potential for interactive effects between intervertebral joint mobility and sustained changes in sensory signaling from peripheral paraspinal tissues is of fundamental importance to all researchers and clinical practitioners interested in optimizing neuromuscular control of the trunk. Spinal manipulation and/or spinal mobilization are typically delivered to patients at anatomical locations exhibiting signs and symptoms of biomechanical dysfunction.[37-39] The present study is a first step toward investigating the relationship between muscle spindle signaling and acute spinal joint dysfunction during passive movements applied to the lumbar spine.

This study indicated that acute biomechanical dysfunction (laminectomy & facet screw, laminectomy & facetectomy) at a single facet joint failed to alter mechanoreceptive afferent response during slow (0.5mm/s) 1mm dorsal-ventral ramp and hold movements of a lumbar vertebra. These findings mirror results from the recent study investigating the effects spinal manipulation thrust durations under the same spinal joint conditions in which the longest thrust duration (250ms) also failed to demonstrate changes between conditions.[26] Acute spinal joint dysfunction at multiple joints, chronic spinal joint dysfunction, increased vertebral displacement, rotary displacement, and/or a faster ramp rate may be required to affect neuromuscular sensory input from trunk muscle proprioceptors during slow ramp and hold movements and/or longer spinal manipulative thrust durations.

It is interesting to note that in two previous feline studies using the laminectomy-only condition, muscle spindle responses to ramp and hold movements (1, 2, and 3mm; 0.5mm/s), both similar to and greater than the hold amplitude used in the current study (1mm, 0.5mm/s) were not affected by an interposed high velocity low amplitude spinal manipulative thrust;[23] yet the afferents were almost twice as sensitive during the manipulative thrust itself when the peak amplitude was 1mm compared to 2mm.[28] These previous studies along with the present study suggest that mechanoreceptive trunk responses to slow vertebral movements (0.5mm/s) are neither affected by acute single facet joint dysfunction nor by high velocity low amplitude spinal manipulation regardless of ramp amplitude.

Limitations

The present study was limited to the effects of acute spinal joint dysfunction at a single facet joint with all other spinal joints remaining intact. While this was a model investigating the simplest degree of intervertebral joint dysfunction on paraspinal sensory input, a greater degree of joint dysfunction (e.g. involving multiple facet joints and/or the intervertebral disc as often encountered clinically) or the chronic presence of joint dysfunction may be required to affect trunk muscle spindle signaling. There were no differences in mean MIF between the conditions for ramp-up, hold, ramp-down, and post-ramp, but these findings should be confirmed in a powered study with minimal loss of preparations particularly within the laminectomy & facetectomy condition. Additional factors that should be taken into consideration in future studies include: making contact on the paraspinal muscles themselves as opposed to making direct contact with the vertebra itself via forceps attached to the spinous process, a greater degree of vertebra displacement (>1mm), increasing the ramp rate, incorporating a rotary or lateral component to vertebral displacement, chronic spinal joint dysfunction and/or testing in the presence of a musculoskeletal inflammatory milieu that frequently accompanies spinal joint dysfunction clinically. One or more of these factors may be required to physiologically affect changes in sensory input from trunk muscle spindles during slower and/or small intervertebral joint movements.

Failure to create a minimum 2% change in lumbar stiffness in a dozen preparations is likely due to a number of factors including but not limited to the greater inherent flexibility of the feline spinal column, inadequate placement of the facet screw, partial splintering of the facet joint, incomplete facetectomy, and/or lack of a rotary or lateral displacement component of the spine during biomechanical testing. Dorsal-ventral ramp testing was the only direction used in current study due to the increased risk of tearing the afferent fiber off the recording electrode that accompanies rotary or lateral movements in this type of experimental preparation.

Neurophysiological and biomechanical studies using anesthetized animals where measurements from the spinal tissues can be obtained directly are of growing importance in the quest to understanding the underlying mechanisms of spinal manipulation despite certain inherent limitations of this work. Since the chiropractic profession's first basic science white paper was published in 1997,[40] much basic work has been accomplished (see [41-44] for review), and yet there remains a great need for more and better animal models if the goal is to identify the biological mechanisms involved in spinal manipulation intervention. Once mechanisms are identified, this knowledge can then be translated into providing better clinical care for individuals seeking chiropractic services. As shown in Table 1, much information relevant to the practice of chiropractic has been learned over a relatively short period using slight variations of the animal model used in the current study.

Conclusion

Coordination of paraspinal muscles is required to provide optimal neuromuscular control of dynamic intervertebral mobility during intended bodily movements. It is possible that distorted proprioceptive input related to acute or chronic spinal joint dysfunction could result in suboptimal neuromuscular trunk control; however, the results of this study indicate that changes in lumbar stiffness due to dysfunction at a single facet joint fails to alter paraspinal muscle spindle responses during slow (0.5mm/s) 1mm ramp and hold movements. Spinal joint dysfunction at multiple joints, chronic joint dysfunction, and/or more rotary/combinatorial motions in a facet dysfunctional model may be necessary to alter responses of trunk spindle afferents during small slow movements of the lumbar spine.

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