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Spinal Manipulative Therapy and Somatosensory Activation

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Abstract

Manually-applied movement and mobilisation of body parts as a healing activity has been used for centuries. A relatively high velocity, low amplitude force applied to the vertebral column with therapeutic intent, referred to as spinal manipulative therapy (SMT), is one such activity. It is most commonly used by chiropractors, but other healthcare practitioners including osteopaths and physiotherapists also perform SMT. The mechanisms responsible for the therapeutic effects of SMT remain unclear. Early theories proposed that the nervous system mediates the effects of SMT. The goal of this article is to briefly update our knowledge regarding several physical characteristics of an applied SMT, and review what is known about the signalling characteristics of sensory neurons innervating the vertebral column in response to spinal manipulation. Based upon the experimental literature, we propose that SMT may produce a sustained change in the synaptic efficacy of central neurons by evoking a high frequency, bursting discharge from several types of dynamically-sensitive, mechanosensitive paraspinal primary afferent neurons.

INTRODUCTION

Manually-applied movement and mobilisation of body parts as a healing activity has been used for centuries (Wiese & Callender, 2005). A relatively high velocity, low amplitude force applied to the vertebral column with therapeutic intent, referred to as spinal manipulative therapy (SMT), is one such activity. It is most commonly used by chiropractors, but other healthcare practitioners including osteopaths and physiotherapists use it as well. Although SMT has been advocated for a wide range of health problems (Ernst & Gilbey, 2010), currently available best evidence suggests it has a therapeutic effect on people suffering some forms of acute neck and back pain particularly when it is used in combination with other therapies (Brønfort et al, 2004; Brønfort et al, 2010; Dagenais et al, 2010; Miller et al 2010; Walker et al 2010; Lau et al 2011). Its effect on chronic low back pain is less clear (Rubinstein et al 2011; Walker et al 2010).

SMT is typically applied when dysfunctional areas of the vertebral column are found. Clinicians identify these areas based upon palpatory changes in the texture and tone of paraspinal soft tissues, the ability to elicit pain and/or tenderness from these tissues,

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asymmetries in hard or soft tissue landmarks, and restrictions in spinal joint motion (Kuchers & Kappler 2002; Sportelli et al 2005). The clinician's goal in applying a spinal manipulation is to restore normal motion and normalize physiology of the neuromusculoskeletal system in particular and potentially other physiological systems affected by the dysfunction.

The mechanisms responsible for the therapeutic effects of SMT remain unclear. Early theories proposed that the nervous system likely mediates the effects of SMT. For example, Korr (1975) proposed that SMT alters or modulates proprioceptive afferent input to the central nervous system. Twelve years later Gillette (1987) provided a speculative description of all afferent input likely to arise from SMT of the lumbar spine. The force-time profile of SMT, based upon the one study available at the time, was trapezoidal in shape, reaching a peak force of nearly 200N and lasting nearly 400ms before returning to pre-SMT levels. Identification of afferents likely activated by SMT was based upon a review of the experimental evidence describing the response characteristics of all known somatic mechanosensitive receptors to the mechanical features of the stimuli that activated them (eg, force magnitude, rate of force application). Much of the data concerning receptor-type and response characteristics were derived from studies involving the appendicular somatosensory system since little was known at the time about the axial somatosensory system. Consequently Gillette's description (Gillette, 1987) provided a hypothetical profile of the afferent activity arising during SMT.

Since Gillette's (1987) benchmark paper, considerably more is known about the morphology of the vertebral column's somatosensory system (for example see Giles & Taylor 1987; Richmond et al 1988; Groen et al 1990; McLain 1994; Jiang et al 1995; Bolton 1998). Table 1 summarises receptor types that have been found in paravertebral tissues. Similarly, more is now known about the mechanical characteristics of SMT. Additionally, in vivo and cadaveric studies have better informed us about the kinematics of vertebral motion segments produced by SMT. Together these new data provide a more informed basis for modelling SMT activation of the axial somatosensory system.

The goals of this article are to briefly update our knowledge regarding several physical characteristics of an applied SMT and to review what is known about the signalling characteristics of sensory neurons innervating the vertebral column in response to spinal manipulation. Then based upon this data, we describe neurophysiological events that may contribute to the therapeutic effects of spinal manipulation.

PHYSICAL CHARACTERISTICS OF SMT

Mechanical parameters and forces associated with SMT

The biomechanical characteristics (i.e. force or displacement versus time curves) of a number of SMT techniques involving either manual or instrument-assisted protocols have been determined in studies performed directly on human subjects (for reviews see Lee et al, 2000; Herzog, 2010) or with the use of patient simulation devices (Kawchuk et al 2006; Graham et al, 2010). Figure 1 shows examples from both types of studies. As described by Herzog (2010), the profiles may be characterized by a pre-load phase, a thrust phase which rapidly rises to a peak force, and a resolution phase (see Fig. 1A).

The characteristics of these profiles appear to vary depending upon region of the vertebral column to which they are applied (e.g., see Fig 1B). In human studies the kinematic parameters of SMT have been obtained using a flexible force-sensitive mat interposed between the clinician's hands and the patient to record the force and duration of an SMT. SMT in the cervical region has relatively little pre-load ranging from 0 to 39.5N (Herzog et

al 1993, Kawchuk et al 1992, Kawchuk & Herzog 1993). In contrast, the average pre-load forces during SMT in the thoracic region ($139 \text{ N} \pm 46$, SD) and sacroiliac region (mean $88 \text{ N} \pm 78 \text{ N}$) are substantially higher than in the cervical region and are potentially different from each other (Herzog et al, 1993). From the beginning of the thrust to end of the resolution phase, SMT duration varies between 90-120ms (mean = 102 ms). The time to peak force during the thrust phase ranges from 30-65ms (mean = 48 ms). Peak applied forces range from 99-140 N (mean = 118N, n= 6 treatments) (Herzog et al 1993). In the same study with SMT directed at the thoracic (T4) region and applied to three different patients by the same practitioner, the mean ($\pm$ SD) time to peak force was $150 \text{ ms} \pm 77 \text{ ms}$ and mean peak force reached $399 \text{ N} \pm 119 \text{ N}$. During the resolution phase, force returned to pre-SMT levels over durations up to 2 times longer than that of the thrust phase. When SMT was applied to the sacroiliac joint, mean applied peak forces reached $328 \text{ N} \pm 78 \text{ N}$ (Herzog et al 1993), with the thrust and resolution phases having similar durations (~100ms). The peak force during manipulation of the lumbar spine measured by Triano and Schultz (1997) tended to be higher than during the thoracic or sacroiliac manipulation measured by Herzog et al (1993) and the force-time profiles looked like half-sine waves with the time to and from peak taking approximately 200ms. Peak impulse forces during thoracic manipulation measured by Suter et al (1994) approximated the >400N peak impulse force measured by Triano and Schultz (1997).

The physical characteristics of an SMT may vary based upon the technique being used and the individual practitioner. While instrument assisted SMT may apply preload forces on the order of 20N, peak forces vary from approximately 50N to 380N depending on the instrument being used and selection of the instrument's settings (Colloca et al 2005). Up to 38% of the instrument assisted thrusts were reported to produce absolute forces significantly different ($P < 0.05$) from each other (Kawchuk et al 2006). In addition, the difference in applied force duration between 2 operators using instrument-assisted SMT can be as much as 75% (Kawchuk et al 2006). Similarly, measurements of SMT forces and displacements applied to a non-biological device simulating the SMT's contact site also show variability. In a study measuring force and displacement over the duration of a Toggle Recoil SMT both force and displacement varied by 50% when performed by an individual practitioner while, between practitioners, force varied by up to 100% and displacement by up to 50% (Graham et al 2010). These findings presumably identify practitioner-related variability since neither the instruments nor the simulator's mechanical properties change. During a non-instrument-assisted, predominately rotatory manipulative procedure applied to the neck, practitioners did not consistently perform the procedure in that peak thrust velocities were different. However, better inter-practitioner than intra-practitioner consistency was observed for thrust duration (Ngan et al 2005). Interestingly, a spinal mobilisation (low velocity) manual technique (cervical lateral glide) performed on the neck demonstrated very small intra-practitioner variability (Vicenzino et al, 1999).

It is clear that the mechanical parameters of SMT vary significantly depending on the manipulated region of the vertebral column, the type of procedure being performed, and characteristics of the individual practitioner. Nevertheless the force parameters are sufficiently described to allow modelling of the applied force to in vivo animal studies (see section below entitled STUDIES OF PARAVERTEBRAL SOMATOSENSORY AFFERENT ACTIVATION DURING SMT-LIKE MOTION).

Vertebral Motion with SMT

Less is known about the vertebral motion that occurs during SMT. Studies have been undertaken in unembalmed human cadavers to determine thoracic and lumbar vertebral motion induced by manual SMT. Absolute and relative linear (in mm) and angular (in degrees) vertebral motions have been studied in the thoracic spine (Gál et al 1997a, 1997b).

Caudo-cranial and postero-anterior vertebral accelerations, and intra-intervertebral disc pressures have been studied in the lumbar spine (Maigne & Guillon, 2000). Although the number of subjects and datasets are small, these cadaveric studies indicate that vertebral kinematics following posterior to anterior thrusts involves biphasic and in some planes triphasic (pseudo-oscillatory) accelerations and rotations. Ianuzzi & Khalsa (2005a; 2005b) using an actuator to impose physiological rotations or simulated spinal manipulation loads to prosected human lumbar vertebral columns (T₁₂-sacrum) investigated vertebral motion with 6 degrees of freedom. They demonstrated in the lumbar region that vertebral translation occurs primarily in the direction of the manipulative thrust and that vertebral rotations are relatively small (< 2°). Interestingly they also found that strain in the facet joint capsule did not vary either from side to side or between capsules of vertebrae adjacent to the vertebra receiving the thrust. From this, they hypothesized that mechanosensitive afferents in facet joint capsules both at the level of the applied thrust and at levels immediately adjacent would be activated.

Studies of vertebral motion associated with instrument-based SMT have been undertaken in anaesthetized humans (Keller et al 2003) and sheep (Colloca et al 2006; Keller et al 2006a, 2006b). More recently porcine prosected specimens of vertebral column were used to study vertebral motion (acceleration) occurring with instrument-induced SMT applied perpendicular and oblique to the SMT's contact area (Kawchuk & Perle, 2009). Together these studies indicate that instrument-delivered SMT thrusts induce transient oscillatory (lasting 100-150ms), coupled (multiple axis) vertebral motions that vary depending on the subject being tested, and the location and magnitude of the applied force. The sheep preparation also demonstrates that, as might be expected, changing the force-time characteristics also changes the displacements and accelerations of both the target and adjacent vertebrae (Colloca et al 2006; Keller et al 2006a, 2006b).

STUDIES OF PARAVERTEBRAL SOMATOSENSORY AFFERENT ACTIVATION DURING SMT-LIKE MOTION

Despite the significant ethical and technical challenges, Colloca and colleagues performed electrophysiological recordings from the S1 nerve root and multifidus muscle in anaesthetised humans while simultaneously applying an instrument based SMT directed posterior to anterior in the lumbar region (Colloca et al, 2000, 2003; Keller et al 2003). For the nerve root, they reported the occurrence of electrical activity with a mean onset latency ranging from 8.2 to 10.7 ms following the thrust. For the multifidus muscle, they reported electromyographic activity (EMG) with a mean onset latency ranging from 5.5 to 18.3 ms. While these studies indicate nerve and muscle activity may be modulated by a spinal manipulative thrust, they provide limited information regarding the type of neurons affected or the neurophysiological mechanisms involved.

Two quite different in-vivo experimental preparations using the anesthetized cat have been developed for investigating the neurophysiological effects of force-time or displacement-time profiles that simulate SMT when applied to the vertebral column. In one preparation defined angular motions can be imposed upon a cervical vertebra (Bolton & Holland, 1998). In the second preparation, defined loads can be applied to a lumbar vertebra under either force or displacement control (Pickar, 1999).

The first preparation has been used to emulate the force-time profile of an SMT's thrust phase by imposing rotational displacements of the C₂ vertebra about the neck's longitudinal axis (Bolton & Holland 1998). Asymmetric tri-phasic (sine wave with dampened 2nd ½ cycle sine wave) displacements have also been used to emulate the acceleration profile and vertebral movements reported to occur during high velocity low amplitude thrusts in human

cadavers (Gal et al, 1997a,b) and during instrument based spinal manipulation (Keller et al, 2003). Simultaneous with the rotational displacements, electrophysiological recordings from ipsilateral or contralateral projecting primary afferents have been made.

The second preparation utilizing a computer-driven, feedback motor was first used to emulate the force-time profile of high velocity low amplitude manipulations given by clinicians to the lumbar spine (Pickar & Wheeler, 2001). Loads were applied at the L₆ spinous process (cat's have 7 lumbar vertebrae) and directed cranially in the coronal plane using a ramp and hold (0.3s) force profile representing the manipulation's pre-load phase followed by a force profile rising in 100ms to a peak load of 100% of the cat's body weight representing the thrust phase. Simultaneously, electrophysiological recordings were obtained from individual primary afferents innervating the L₆ paraspinal tissues. In subsequent experiments, manipulative loads have been applied to the L₆ vertebra and directed ventrally in the transverse plane (Sung et al 2005; Pickar & Kang 2006; Pickar et al, 2007). Peak displacements of 1 and 2 mm and peak forces proportional to 33%, 66%, or 100% of the cat's bodyweight were used. The three forces induced L₆ displacements of 1.2 ($\pm$ 0.2), 2.0 ($\pm$ 0.5), and 3.3 ($\pm$ 1.1) mm, respectively. These displacements are comparable to the translation and rotational displacements (1.5 ± 0.5 mm and 2^0 - 3.5^0 , respectively) occurring in human cadaveric lumbar spine when high velocity low amplitude thrusts are performed (Ianuzzi & Khalsa, 2005a).

Muscle spindle afferent responses

Activity of individual sensory neurons with a spontaneous resting discharge (15-98 impulses/s) have been studied during the application of spinal manipulative-like loads. (Pickar & Wheeler, 2001; Pickar & Kang, 2006; Pickar et al, 2007). Recordings were obtained from the L₆ dorsal rootlets. Afferents were identified as arising from muscle spindles located in lumbar multifidus or longissimus muscles on the basis of their receptive field's location, their responses to intra-arterial infusion of succinylcholine and/or to electrically-induced muscle twitch. The spindle afferents were further characterized as primary (group Ia) or secondary (group II) based upon their responses to ramp and hold movement of the L₆ vertebra. These studies have shown that the spinal manipulation's thrust phase significantly increases the discharge rate of muscle spindles in the deep lumbar paraspinal muscles ($201\% \pm 57\%$) compared to the pre-load phase ($29\% \pm 20\%$) (see Fig 2A) (Pickar & Wheeler, 2001). Recovery of the spindle's firing rate following the resolution phase may be immediate or take some time (range 100ms - 21.2 s). Furthermore, changing the direction of the applied thrust changes the magnitude of the response.

Many afferents from muscle spindles in the lumbar region demonstrate a graded increase in mean instantaneous frequency when tested across a range of thrust phase durations from 12.5 to 400 ms (see Fig 2B) (Pickar & Kang 2006). In general, group Ia afferents appear more responsive to the spinal manipulative thrust than the group II spindle afferents. Some afferents exhibit an increase only at specific thrust durations. Discharge rate increases by 110-520 impulses/s during a 100ms thrust duration whereas it only increases between 28-88Hz impulses/s during a 800 ms thrust duration (Pickar & Kang 2006). The graded increase in spindle discharge as thrust duration shortens (i.e., as the manipulation's speed becomes faster) is non-linear, with an inflection occurring at thrust durations less than 150ms. This duration represents one that practitioners often achieve when applying a spinal manipulation clinically to either the lumbar or cervical region (see section above, PHYSICAL CHARACTERISTICS OF SMT). The spindle's silent period following the resolution phase, which primarily occurs in group Ia afferents, becomes shorter as the duration of the impulse load becomes shorter. Group II spindle afferents do not become silent but it should be noted that their firing interval (inverse of the firing rate) is greater than the silent period of the Group Ia afferents.

Afferent activity in cervical spinal nerves (dorsal rootlets) has been characterised as arising from neck muscle spindles on the basis of it being spontaneous, its receptive field location being confined to a single neck muscle, and an increase in its firing rate in response to an intra-arterial infusion of succinylcholine. However, in contrast to afferents innervating tissues of the low back, afferents innervating the neck are too short in the cat to allow accurate classification as Group I, II, III or IV on the basis of conduction velocity. Nevertheless, it has been possible to study putative muscle spindle activity in the cervical spine. As can be seen in Figure 3, displacement of the C₂ vertebra can induce a decrease (Fig 3A) or increase (Fig 3B) in the spontaneous firing of a neck muscle spindle afferents depending on the direction of the displacement. Figure 3 also shows that C₂ displacement can induce either an initial pause and then an increase (Fig 3C) or an initial increase followed by a decrease (Fig 3D) in spontaneous discharge. In each case, the spindle's spontaneous firing rate rapidly returns to the level of the pre-manipulative-like vertebral displacement.

Golgi Tendon Organ afferent responses

Afferents with receptive fields in lumbar paravertebral tissues of the cat were deemed to arise from Golgi Tendon Organs (GTO) if 1) they did not exhibit spontaneous activity, but 2) responded to loads with short-lasting, low-frequency activity, 3) had irregular discharge rates in response to an intra-arterial injection of succinylcholine and, 4) had conduction velocities in the group I range (Pickar & Wheeler, 2001). These afferents exhibited responses to SMT-like loading quite different from that of muscle spindles. In particular, GTO afferents were rarely activated by the pre-load phase (with increases in firing rate by >10Hz occurring on only 3 of 15 occasions) and were mildly activated by the thrust phase, increasing their firing frequency by only 21 ± 4 impulses/s during the thrust phase relative to the control and by only 19 ± 4 impulses/s relative to the pre-load phase. Also in contrast to muscle spindle afferents, GTOs responded even when the direction of the SMT was changed (cranial, caudal or 45° to the spine's long axis). With few exceptions GTO afferents became silent immediately following the thrust phase and they remained silent. In a second study using a manipulative-like load of 33% body weight (Sung et al 2005), one putative GTO afferent showed a pattern of behavior similar to the muscle spindle afferents when tested over a range of thrust durations but its mean instantaneous firing rate during the thrust phase was substantially less than that of spindle afferents.

Putative Pacinian corpuscles afferents

Pickar & Wheeler (2001) reported the response of one afferent that was inactive at rest and rapidly adapted when the lumbar paraspinal tissues were probed. It responded to an SMT-like thrust (duration: 200ms; peak force: 6.4N) that distracted the facet joint, but it did not respond at loading rates ~10 times slower than the thrust rate nor with peak loads that were up to 4 times higher than the peak thrust force. If this afferent belonged to a GTO it would likely have been activated by the increasing load (Stuart et al, 1970). Because it responded to rate of mechanical loading, it was likely a Pacinian corpuscle (Sato, 1961).

Other Afferents

Afferents from the cervical paravertebral tissues are difficult to accurately characterize because they cannot be identified on the basis of their conduction velocity and their receptive fields are difficult to isolate due to the extensive coupled movements of the cervical vertebra when mechanical forces are applied to determine mechanical thresholds. For example, Bolton and Holland (1996) have noted that an afferent responding to a large mechanical force may not in fact represent a high threshold mechanoreceptor such as a GTO located at the site of the applied force, but represent a low threshold mechanoreceptor lying distantly and responding to the dampened mechanical force. It has also been difficult to

classify afferents that respond to movement of the C₂ vertebra but do not have spontaneous activity and do not respond to intra-arterial injection of succinylcholine (Bolton & Holland, 1996). In this study, some (2/8) afferents had receptive fields in the ipsilateral semispinalis cervicis or semispinalis dorsalis muscles and were activated during movements of the C₂ vertebra that lengthened these muscles but not when they were shortened. The responses were rapidly adapting, showing a burst of 3-5 spikes, suggesting they were afferents from either Golgi Tendon Organs or paciniform corpuscles. However, this could not be confirmed. Interestingly, seventy-five percent of the afferents (6/8) were only activated by firm (noxious) pinching of the ipsilateral C₂₋₃ zygapophyseal joint capsule with half (3/6) demonstrating an after-discharge suggesting they conveyed nociceptive information.

Common Features

It is clear from these studies in the lumbar and cervical regions that impulse loads with force time profiles similar to that of manually delivered high velocity low amplitude thrusts evoke a relatively high-frequency discharge from afferents innervating muscle spindles, GTO's and high threshold mechanoreceptors. There are currently no unequivocal data regarding whether SMT activates nociceptors.

NEUROPHYSIOLOGICAL CONSEQUENCES OF SMT THAT MAY UNDERLIE THE EFFECTS OF SMT

The biomechanical findings reviewed above indicate that the nature of the SMT thrust is a dynamic mechanical event. During the manipulation, tissue displacements and forces clearly change rapidly, with no static component, and last only a short time-interval. How could this dynamic, very short-lasting (<150ms) mechanical stimulus change the behaviour of the nervous system in a way that outlasts the intervention itself? The neurophysiological findings reviewed above provide an opportunity to consider a contributory mechanism. It has been suggested that a manipulation's long-lasting influence on the nervous system can be regarded as a primary and/or secondary event (for example, Pickar, 2002; Leach, 2004; Henderson, 2005; Bialsoky, 2009a). By primary we refer to any long-lasting neural response that arises as a direct consequence of short-lasting neural activity occurring during the manipulation. By secondary we refer to a long-lasting neural response arising as a consequence of (i.e., secondary to) a long-lasting change in spinal biomechanics caused by the manipulation.

Spinal Biomechanics

A number of sustained changes in spinal biomechanics have been hypothesized to occur as a result of SMT. For example, the impulsive thrust may alter segmental biomechanics by releasing trapped meniscoids, releasing adhesions, or by diminishing distortion in the intervertebral disc (Farfan, 1980; Giles 1989; Lewit, 1991; Haldeman, 1978; Vernon, 1997). Also, individual motion segments are thought capable of buckling thereby producing relatively large vertebral motions that achieve a new position of stable equilibrium (Wilder et al., 1988). The manipulative impulse may provide sufficient energy to restore a buckled segment to a lower energy level thus reducing mechanical stress or strain on soft and hard spinal tissues (Triano, 2001).

Neural responses arising secondary to the long-lasting biomechanical changes may be broadly conceptualized as resulting from neurophysiological changes occurring at either the receptive endings of primary afferents and/or along transmission pathways from these receptive endings. Mechanically-sensitive primary afferents with receptive endings embedded in deep paraspinal tissues respond to mechanical stresses and strains in their local environment (Ianuzzi & Khalsa, 2005a). Long-lasting changes in their mechanical

environment could modify the mechanosensory information received by the spinal cord and brain. Signals from chemoreceptors may also be altered to the extent that inflammatory conditions are altered by the manipulation (e.g. see Song et al, 2006). Transmission pathways on the other hand include both peripheral nerves and ganglia where they pass through or lie in the intervertebral foramen, and the spinal cord and brainstem where the latter extends through the foramen magnum into the neural canal. Sustained compressive force on neural tissue at these sites can affect both impulse-based activity (action potential frequency) and non-impulse-based activity (axoplasmic transport) (see Korr, 1978). It has been hypothesized that spinal manipulation can relieve mechanical compression on these transmission pathways and induce beneficial changes in the chemical milieu of these neurons (see Leach, 2004; Henderson, 2005 for a more thorough discussion of this topic).

Activation of Somatosensory Receptors

In 1987, Gillette (Gillette, 1987) proposed that spinal manipulation activates all known mechanosensitive, somatosensory receptors because they all possess mechanical thresholds lower than the peak force delivered during a manipulation and because the 40 in toto receptor-types are responsive to dynamic and/or static components of a mechanical stimulus. The rationale was based upon the one load-time profile for a spinal manipulation that had been recorded at that time (see Gillette, 1987). More recent biomechanical data (see section above, PHYSICAL CHARACTERISTICS OF SMT) indicate a revision to this load-time profile is needed. A high-velocity, low amplitude spinal manipulation, which over 90% of chiropractic patients receive as part of their care (Christensen, 2005), is purely dynamic, with a short rise-time to its peak amplitude, and with no static component (see Figure 1). Based upon these features, the proposed receptor population responsive to a spinal manipulation can be reduced by more than half, to only those that have a substantial dynamic component. Thresholds of these afferents are less than 20-30N (see Table 2 of Gillette, 1987), and represent magnitudes less than a manipulation's peak force. Thus, all four classes of primary afferents neurons, [Group Ia, Ib, and II (A β), III (A δ) IV (C) fibers] would be expected to respond during the manipulation. However, vertebral tissues could act as low-pass mechanical filters, reducing the stimulus's dynamic component. In the extreme, the applied load may dissipate and its magnitude become insufficient to activate these sensory receptors. Nevertheless, recordings of multi-unit and single-unit activity in paraspinal primary afferents show that spinal manipulation does indeed stimulate paraspinal afferents (see section above, STUDIES OF PARAVERTEBRAL SOMATOSENSORY AFFERENT ACTIVATION DURING SMT-LIKE MOTION).

To date, only muscle spindle afferents in the low back have been systematically studied and their response to spinal manipulation characterized (see section above, **Muscle spindle afferent responses**). Their non-linear behaviour in response to the duration of the manipulation's thrust phase might not be considered surprising based upon the long-known velocity sensitivity of spindles studied in limb muscles. Like limb muscle spindle afferents (e.g. see Figure 10 in Matthews 1963), paravertebral Group Ia spindle endings show a response inflection. This inflection represents a threshold for higher spindle discharge frequencies than would otherwise be predicted from their discharge frequencies evoked by slower stretch rates. Most interestingly, this threshold stretch rate (~10mm/s) is comparable to the rate at which a spinal manipulation imparts movement to a vertebra, translating it less than 3 mm in less than 150 ms (see above **Vertebral Motion with SMT**).

Muscle spindles also demonstrate another type of dynamic threshold when their sensitivity has been studied using sinusoidal stretch-shortening cycles. In the limbs, both Group Ia and Group II muscle spindle afferents show a non-linear increase in sensitivity at sinusoidal loading rates of 1.5 cycles/s (e.g. see Figure 5 in Matthews & Stein 1969). It can be seen in

Figure 2B that when a spinal manipulation is modelled as a half-sine wave the manipulative thrust represents one-quarter cycle. A thrust duration of 150ms would represent a loading rate of 6.7 cycles/s and would be faster than the sinusoidal rate threshold for augmented spindle sensitivity. Together, these findings suggest that one consequence of a spinal manipulation is that it creates a higher frequency sensory input from muscle spindles than otherwise occurs during daily spinal motion. The sensory barrage from the population would be relatively synchronous in time, occurring over the time interval of the thrust (< 150ms) and vertebral motion that accompanies it. The sensory inputs would likely arrive at the central nervous system from a relatively localized area of the spine (see above, *Vertebral Motion with SMT*).

By comparison with muscle spindles, the relationship between the velocity of an applied mechanical stimulus and the discharge pattern of mechanosensitive, non-spindle afferents in either the vertebral column or the limbs is virtually unknown. For example in the finger, Edin et al. (1995) showed that discharge rates of dynamically-sensitive, cutaneous Group II mechanoreceptors increased as the velocity of skin indentation increased. The formal relationship between the two was not characterized. Similarly, A- δ and C-fiber mechanonociceptors are known to fire an initial high burst during a dynamic mechanical stimulus application (Mense, 1986; White & Levine, 1991) but how the duration of the their discharge frequency is formally related to either the magnitude or velocity of the stimulus is not known. If paraspinal non-spindle afferents are also activated by a spinal manipulation (see above, Other Afferents), it seems reasonable to think that they too present a burst of high frequency activity to the central nervous in a synchronous manner and from a localized area of the spine.

Knowledge that SMT-like movements produce a short-lasting, high frequency barrage of action potentials (see above) raises the possibility that SMT may induce longer term effects by modulating the central nervous system. Nearly 3 decades ago studies showed that synaptic efficacy is affected by the history of high frequency bursting from group Ia and group II muscle afferents (Davis et al, 1985, Lüscher et al., 1983; Collins et al., 1984). The effect lasted beyond the duration of the burst itself. In α -motoneurons, bursts of action potentials with short interspike intervals affected the magnitude of post-synaptic potentials differently from longer interspike intervals. In addition, α -motoneurons are bi-stable and can sustain plateau potentials. Brief periods of excitation can switch them into a period of self-sustained firing (Hounsgaard et al, 1986). Such a state appears to have consequences for the normal production of muscle force (Collins et al, 2002). Such processes may underlie experimental findings showing changes in parameters related to increased muscle excitability following SMT (Suter et al, 2000; Dishman et al, 2002; Keller and Colloca, 2000; Koppenhagen et al, 2011).

High frequency stimulation of small diameter A- δ and C-fibers also affects synaptic efficacy. Both long-term potentiation as well as depression have been produced (Randic et al., 1993). The change in behaviour of second order neurons lasts up to 1 hour following the initial sensory barrage (Randic et al., 1993, Ikeda et al, 2000). In these experiments, a peripheral nerve was electrically stimulated thereby synchronously activating the afferent population. The whole nerve was stimulated at 100 Hz over a short lasting interval (~1s) and was given several times at ~10s intervals. The physiological relevance of such a stimulus has been questioned because C- and perhaps A- δ fibers do not typically discharge at such high rates, but stimulation using more intermediate frequencies (20Hz) also produces long-lasting changes (3-6 hours) in synaptic efficacy (Liu & Sandkühler, 1997). The stimulus durations are clearly longer than a manipulative stimulus (< 150ms) however, we currently lack knowledge regarding how short a duration is capable of eliciting a change in synaptic efficacy. In addition, it is not known what discharge rates are evoked in paraspinal C- and A-

8 fibers by spinal manipulation. While changes in synaptic efficacy produced by high frequency stimulation paradigms have been applied toward understanding cellular mechanisms underlying hyperalgesia (Sandkuhler, 2009), they also provide a reasonable basis for considering how the short-lasting, dynamic mechanical input of a spinal manipulation produces a neural response that outlasts the intervention itself. This neurophysiological process may underlie findings from clinically-oriented basic science studies showing that spinal manipulation reduces temporal summation of thermal stimuli delivered to the periphery (George et al, 2006; Bialosky et al, 2009b; Bishop et al. 2011).

Conclusions

In conclusion, spinal manipulation could affect the nervous system by activating paraspinal sensory neurons during the maneuver itself and/or by altering spinal biomechanics. Biomechanical changes which follow the manipulation would, in turn, modulate paravertebral sensory neuron signals. As a short-lasting, dynamic mechanical stimulus, spinal manipulation may take advantage of two signalling characteristics of the nervous system: 1) inherent high frequency signalling properties of dynamically-sensitive primary afferent neurons and 2) response properties of post-synaptic neurons. Experimental studies reveal that spinal manipulation evokes a high frequency discharge in some primary afferents. In experimental studies not using spinal manipulation, spatial and/or temporal summation of high frequency input produces sustained changes in synaptic efficacy. Future studies directed at understanding how central neurons are affected by high frequency sensory input from paraspinal tissues during the manipulation are warranted based upon the literature and should contribute to our understanding of the mechanisms for spinal manipulation's action.

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BIOSKETCH

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References

- Amonoo-Kuofi HS. The density of muscle spindles in the medial, intermediate and lateral columns of human intrinsic postvertebral muscles. *Journal of Anatomy*. 1983; 136(3):509–19. [PubMed: 6224767]
- Bialosky JE, Bishop MD, Price DD, Robinson ME, George SZ. The mechanisms of manual therapy in the treatment of musculoskeletal pain: A comprehensive model. *Manual Therapy*. 2009; 14:531–38. [PubMed: 19027342]
- Bialosky JE, Bishop MD, Robinson ME, Zeppieri G Jr. George SZ. Spinal manipulative therapy has an immediate effect on thermal pain sensitivity in people with low back pain: a randomized controlled trial. *Physical Therapy*. 2009; 89:1292–1303. [PubMed: 19797305]
- Bishop MD, Beneciuk JM, George SZ. Immediate reduction in temporal sensory summation after thoracic spinal manipulation. *The Spine Journal*. 2011; 11:440–46. [PubMed: 21463970]
- Bolton PS. The somatosensory system of the neck and its effects on the central nervous system. *Journal of Manipulative Physiological and Therapeutics*. 1998; 21(8):553–63.
- Bolton PS, Holland CT. Afferent signalling of vertebral displacement in the neck of the cat. *Society for Neuroscience, Abstracts*. 1996; 22:1802.
- Bolton PS, Holland CT. An in vivo method for studying afferent fibre activity from cervical paravertebral tissue during vertebral motion in anaesthetised cats. *Journal of Neuroscience Methods*. 1998; 85:211–8. [PubMed: 9874157]
- Boyd-Clark LC, Briggs CA, Galea MP. Muscle spindle distribution, morphology and density in longus colli and multifidus muscles of the cervical spine. *Spine*. 2002; 27:694–701. [PubMed: 11923661]
- Brønfort G, Haas M, Evans R, Bouter LM. Efficacy of spinal manipulation and mobilization for low back pain and neck pain: a systematic review and best evidence synthesis. *The Spine Journal*. 2004; 4:335–56. [PubMed: 15125860]
- Brønfort G, Haas M, Evans R, Leininger B, Triano J. Effectiveness of manual therapies: the UK evidence report. *Chiropractic & Osteopathy*. 2010; 18:3, 1–33. (doi:10.1186/1746-1340-18-3). [PubMed: 20184717]
- Cao D-Y, Pickar JG, Ge W, Ianuzzi A, Khalsa PS. Position sensitivity of feline paraspinal muscle spindles to vertebral movement in the lumbar spine. *Journal of Neurophysiology*. 2009; 101(4): 1722–9. [PubMed: 19164108]
- Christensen, MG.; Kerkhoff, D.; Kollasch, MW.; Cohn, L. *Job Analysis of Chiropractic*. National Board of Chiropractic Examiners; CO: 2005.
- Collins WF III, Honig MG, Mendell LM. Heterogeneity of group Ia synapses on homonymous alpha-motoneurons as revealed by high-frequency stimulation of Ia afferent fibers. *Journal of Neurophysiology*. 1984; 52(5):980–93.
- Collins DF, Burke D, Gandevia SC. Sustained contractions produced by plateau-like behaviour in human motoneurons. *Journal of Physiology*. 2002; 538:289–301. [PubMed: 11773336]
- Colloca CJ, Keller TS, Black P, Normand MC, Harrison DE, Harrison DD. Comparison of mechanical force of manually assisted chiropractic adjusting instruments. *Journal of Manipulative and Physiological Therapeutics*. 2005; 28(6):414–22. [PubMed: 16096041]

- Colloca CJ, Keller TS, Gunzburg R, Vandeputte K, Fuhr AW. Neurophysiologic response to intraoperative lumbosacral spinal manipulation. *Journal of Manipulative Physiological and Therapeutics*. 2000; 23(7):447–57.
- Colloca CJ, Keller TS, Gunzburg R. Neuromechanical characterization of in vivo lumbar spinal manipulation. Part II. Neurophysiological response. *Journal of Manipulative Physiological and Therapeutics*. 2003; 26(9):579–91.
- Colloca CJ, Keller TS, Harrison DE, Moore RJ, Gunzburg R, Harrison DD. Spinal manipulation force and duration affect vertebral movement and neuromuscular responses. *Clinical Biomechanics*. 2006; 21:254–62. [PubMed: 16378668]
- Dagenais S, Gay RE, Tricco AC, Freeman MD, Mayer JM. NASS contemporary concepts in spine care: Spinal manipulation therapy for acute low back pain. *The Spine Journal*. 2010; 10:918–40. [PubMed: 20869008]
- Davis BM, Collins WF, Mendell LM. Potentiation of transmission at Ia-motoneuron connections induced by repeated short bursts of afferent activity. *J of Neurophysiology*. 1985; 54(6):1541–52.
- Dishman JD, Ball KA, Burke J. Central motor excitability changes after spinal manipulation, a transcranial magnetic stimulation study. *Journal of Manipulative Physiological and Therapeutics*. 2002; 25(1):1–9.
- Edin BB, Essick GK, Trulsson M, Olsson KA. Receptor encoding of moving tactile stimuli in humans. I. Temporal pattern of discharge of individual low-threshold mechanoreceptors. *J of Neuroscience*. 1995; 15(1):830–47.
- Ernst E, Gilbey A. Chiropractic claims in the English-speaking world. *The New Zealand Medical Journal*. 2010; 123(1312):36–44. [PubMed: 20389316]
- Farfan, HF. The scientific basis of manipulation procedures. In: Buchanan, WW.; Kahn, MF.; Laine, V.; Rodnan, GP.; Scott, JT.; Zvaifler, NJ.; Grahame, R., editors. *Clinics in rheumatic diseases*. W.B. Saunders Company Ltd.; London: 1980. p. 159-77.
- Gál J, Herzog W, Kawchuk G, Conway PJ, Zhang Y-T. Movements of vertebrae during manipulative thrusts to unembalmed human cadavers. *Journal of Manipulative Physiological and Therapeutics*. 1997a; 20(1):30–40.
- Gál J, Herzog W, Kawchuk G, Conway PJ, Zhang Y-T. Measurements of vertebral translations using bone pins, surface markers and accelerometers. *Clinical Biomechanics*. 1997b; 12(5):337–340.
- George SZ, Bishop MD, Bialosky JE, Zeppieri G Jr, Robinson ME. Immediate effects of spinal manipulation on thermal pain sensitivity: an experimental study. *BMC Musculoskeletal Disorders*. 2006; 7:68. [PubMed: 16911795]
- Giles, LGF. *Anatomical basis of low back pain*. Williams & Wilkins; Baltimore: 1989.
- Giles LG, Taylor JR. Human zygapophyseal joint capsule and synovial fold innervations. *British Journal of Rheumatology*. 1987; 26(2):93–8. [PubMed: 2435355]
- Gillette RG. A speculative argument for the coactivation of diverse somatic receptor populations by forceful chiropractic adjustments. *Manual Medicine*. 1987; 3:1–14.
- Graham BA, Clausen P, Bolton PS. A descriptive study of the force and displacement profiles of the toggle-recoil spinal manipulative procedure (adjustment) as performed by chiropractors. *Manual Therapy*. 2010; 15:74–9. [PubMed: 19679503]
- Groen GJ, Baljet B, Drukker J. Nerves and nerve plexuses of the human vertebral column. *American Journal of Anatomy*. 1990; 188:282–96. [PubMed: 2371968]
- Haldeman, S. The clinical basis for discussion of mechanisms of manipulative therapy. In: Korr, IM., editor. *The neurobiologic mechanisms in manipulative therapy*. Plenum; New York: 1978. p. 53-75.
- Henderson, CNR. Three neurophysiologic theories on the chiropractic subluxation. In: Gatterman, MI., editor. *Foundations of chiropractic: subluxation*. Elsevier Mosby; St. Louis: 2005. p. 296-303.
- Herzog W. The biomechanics of spinal manipulation. *Journal of Bodywork and Movement Therapies*. 2010; 14:280–6. [PubMed: 20538226]
- Herzog W, Conway PJ, Kawchuk GN, Zhang Y, Hasler EM. Forces exerted during spinal manipulative therapy. *Spine*. 1993; 18(9):1206–12. [PubMed: 8362328]

- Hounsgaard J, Hultborn H, Kiehn O. Transmitter-controlled properties of alpha-motoneurons causing long-lasting motor discharge to brief excitatory inputs. *Progress in Brain Research*. 1986; 64:39–49. [PubMed: 2873622]
- Ianuzzi A, Khalsa PS. Comparison of human lumbar facet joint capsule strains during simulated high-velocity, low-amplitude spinal manipulation versus physiological motions. *The Spine Journal*. 2005a; 5:277–90. [PubMed: 15863084]
- Ianuzzi A, Khalsa PS. High loading rate during spinal manipulation produces unique facet capsule strain patterns compared with axial rotations. *Journal of Manipulative and Physiological Therapeutics*. 2005b; 28(9):673–87. [PubMed: 16326237]
- Ikeda H, Asai T, Murase K. Robust changes of afferent-induced excitation in the rat spinal dorsal horn after conditioning high-frequency stimulation. *Journal of Neurophysiology*. 2000; 83:2412–20. [PubMed: 10758142]
- Jackson HC, Winkelmann RK, Bickel WH. Nerve endings in the human lumbar spinal column and related structures. *Journal of Bone and Joint Surgery*. 1966; 48-A(7):1272–81. [PubMed: 5921784]
- Jiang H, Russell G, Raso J, Moreau MJ, Hill DL, Bagnall KM. The nature and distribution of the innervations of human supraspinal and interspinal ligaments. *Spine*. 1995; 20(80):869–76. [PubMed: 7644951]
- Kawchuk GN, Herzog W, Hasler EM. Forces generated during spinal manipulative therapy of the cervical spine: A pilot study. *Journal of Manipulative and Physiological Therapeutics*. 1992; 15(5):275–8. [PubMed: 1613409]
- Kawchuk GN, Herzog W. Biomechanical characterization (Fingerprinting) of five novel methods of cervical spine manipulation. *Journal of Manipulative and Physiological Therapeutics*. 1993; 16(9):573–7. [PubMed: 8133191]
- Kawchuk GN, Prasad N, McLeod RC, Liddle T, Li T, Zhu Q. Variability of force magnitude and force duration in manual and instrument-based manipulation techniques. *Journal of Manipulative and Physiological Therapeutics*. 2006; 29(8):611–18. [PubMed: 17045094]
- Kawchuk GN, Perle SM. The relation between the application angle of spinal manipulative therapy (SMT) and resultant vertebral accelerations in an in vivo porcine model. *Manual Therapy*. 2009; 14:480–3. [PubMed: 19144558]
- Keller TS, Colloca CJ. Mechanical force spinal manipulation increases trunk muscle strength assessed by electromyography: a comparative clinical trial. *Journal of Manipulative and Physiological Therapeutics*. 2000; 23(9):585–95. [PubMed: 11145798]
- Keller TS, Colloca CJ, Gunzburg R. Neuromechanical characterization of in vivo lumbar spinal manipulation. Part 1. Vertebral motion. *Journal of Manipulative and Physiological Therapeutics*. 2003; 26:567–78. [PubMed: 14673406]
- Keller TS, Colloca CJ, Moore RJ, Gunzburg R, Harrison DH. Increased multiaxial lumbar motion responses during multiple-impulse mechanical force manually assisted spinal manipulation. *Chiropractic & Osteopathy*. 2006a; 14:6. doi:10.1186/1746-1340-14-6. [PubMed: 16597343]
- Keller ST, Colloca CJ, Moore RJ, Gunzburg R, Harrison DE, Harrison DD. Three-dimensional vertebral motions produced by mechanical force spinal manipulation. *Journal of Manipulative and Physiological Therapeutics*. 2006b; 29(6):425–36. [PubMed: 16904488]
- Koppenhaver SL, Fritz JM, Hebert JJ, Kawchuk GN, Childs JD, Parent EC, Gill NW, Teyhen DS. Association between changes in abdominal and lumbar multifidus muscle thickness and clinical improvement after spinal manipulation. *J Orthopaedic and Sports Physical Therapy*. 2011; 41:389–99.
- Korr IM. The Neurobiologic mechanisms in manipulative therapy. Plenum Press; New York: 1978.
- Korr IM. Proprioceptors and somatic dysfunction. *Journal of American Osteopathic Association*. 1975; 74:638–50.
- Kuchera, WA.; Kappler, RE. Musculoskeletal examination for somatic dysfunction. In: Ward, RC.; Hruby, RJ.; Jerome, JA.; Jones, JM.; Kappler, RE., editors. *Foundations for osteopathic Medicine*. Lippincott Williams & Wilkins; 2002. p. 633–59.
- Lau HMC, Chiu TTW, Lam TH. The effectiveness of thoracic manipulation on patients with chronic mechanical neck pain – a randomized control trial. *Manual Therapy*. 2011; 16:141–7. [PubMed: 20813577]

- Leach, RA. The chiropractic theories. Lippincott Williams & Wilkins; Philadelphia: 2004.
- Lee, M.; Gal, J.; Herzog, W. Biomechanics of manual therapy. In: Dvir, Z., editor. Clinical biomechanics. Churchill Livingstone; New York: 2000. p. 209-38.
- Lewit, K. Manipulative therapy in rehabilitation of the locomotor system. Butterworth-Heinemann; Oxford: 1991.
- Liu X, Sandkühler J. Characterization of long-term potentiation of C-fiber-evoked potentials in spinal dorsal horn of adult rat: essential role of NK1 and NK2 receptors. *Journal of Neurophysiology*. 1997; 78(4):1973–82. [PubMed: 9325365]
- Luscher HR, Ruenzel PW, Henneman E. Effects of impulse frequency, PTP, and temperature on responses elicited in large populations of motoneurons by impulses in single Ia-fibers. *Journal of Neurophysiology*. 1983; 50(5):1045–58. [PubMed: 6315900]
- Maigne J-Y, Guillon F. Highlighting of intervertebral movements and variations of intradiskal pressure during lumbar spinal manipulation: a feasibility study. *Journal of Manipulative and Physiological Therapeutics*. 2000; 23(8):531–5. [PubMed: 11050609]
- Matthews PBC. The response of de-efferented muscle spindle receptors to stretching at different velocities. *Journal of Physiology*. 1963; 168:660–78. [PubMed: 14067950]
- Matthews PBC, Stein RB. The sensitivity of muscle spindle afferents to small sinusoidal changes of length. *Journal of Physiology*. 1969; 200:723–43. [PubMed: 4237132]
- McLain RF. Mechanoreceptor endings in human cervical facet joints. *Spine*. 1994; 19(5):495–501. [PubMed: 8184340]
- Mendel T, Wink C, Zimny M. Neural elements in human cervical intervertebral discs. *Spine*. 1992; 17(2):132–5. [PubMed: 1372767]
- Mense, S. Slowly conducting afferent fibers from deep tissues: Neurobiological properties and central nervous actions. In: Autrum, H.; Ottoson, D.; Perl, ER.; Schmidt, RF.; Shimazu, H.; Willis, WD., editors. *Progress in sensory physiology*. Springer-Verlag; New York: 1986. p. 139-217.
- Miller J, Gross A, D'Sylva J, Burnie SJ, Goldsmith CH, Graham N, Haines T, Brønfort G, Hoving JL. Manual therapy and exercise for neck pain: A systematic review. *Manual Therapy*. 2010; 15:334–54. [PubMed: 20593537]
- Nakamura S, Takahashi K, Takahashi Y, Morinaga T, Shimada Y, Moriya H. Origin of nerves supplying the posterior portion of lumbar intervertebral discs in the rat. *Spine*. 1996; 21:917–24. [PubMed: 8726193]
- Ngan JMW, Chow DHK, Holmes AD. The kinematics and intra-and inter-therapist consistencies of lower cervical rotational manipulation. *Medical Engineering and Physics*. 2005; 27:395–401. [PubMed: 15863348]
- Pickar JG. Neurophysiological effects of spinal manipulation. *The Spine Journal*. 2002; 2:357–71. [PubMed: 14589467]
- Pickar JG. An in vivo preparation for investigating neural responses to controlled loading of a lumbar vertebra in the anesthetized cat. *Journal of Neuroscience Methods*. 1999; 89:87–96. [PubMed: 10491938]
- Pickar JG, Wheeler JD. Response of muscle proprioceptors to spinal manipulative-like loads in the anesthetized cat. *Journal of Manipulative Physiological Therapeutics*. 2001; 24(1):2–11.
- Pickar JG, Kang YM. Paraspinal muscle spindle responses to the duration of a spinal manipulation under force control. *Journal of Manipulative and Physiological Therapeutics*. 2006; 29:22–31. [PubMed: 16396726]
- Pickar JG, Sung PS, Kang YM, Ge W. Response of lumbar paraspinal muscle spindles is greater to spinal manipulative loading compared with slower loading under length control. *The Spine Journal*. 2007; 7:583–95. [PubMed: 17905321]
- Randic M, Jiang MC, Cerne R. Long-term potentiation and long-term depression of primary afferent neurotransmission in the rat spinal cord. *Journal of Neuroscience*. 1993; 13(12):5228–41. [PubMed: 8254370]
- Richmond FJR, Abrahams VC. Physiological properties of muscle spindles in dorsal neck muscles of the cat. *Journal of Neurophysiology*. 1979; 42(20):604–16. [PubMed: 154558]

- Richmond FRJ, Bakker DA. Anatomical organisation and sensory receptor content of soft tissues surrounding upper cervical vertebrae in the cat. *Journal of Neurophysiology*. 1982; 48(1):49–61. [PubMed: 6214617]
- Richmond, FJR.; Bakker, DA.; Stacey, MJ. The Sensorium: receptors of the neck muscles and joints. In: Peterson, BW.; Richmond, FJ., editors. *Control of head movement*. Oxford University Press; New York: 1988. p. 49-62.
- Roberts S, Eisenstein SM, Menage J, Evans EH, Ashton IK. Mechanoreceptors in intervertebral discs morphology, distribution and neuropeptides. *Spine*. 1995; 20:2645–51. [PubMed: 8747242]
- Rose PK, Keirstead SA. Segmental projection from muscle spindles: a perspective from the upper cervical spinal cord. *Canadian Journal of Physiology and Pharmacology*. 1986; 64:505–8.
- Rubinstein SM, van Middelkoop M, Assendelft WJJ, de Boer MR, van Tulder MW. Spinal manipulative therapy for chronic low-back pain. *Cochrane Database of Systematic Reviews*. 2011; (Issue 2) Art. No.: CD008112. DOI:10.1002/14651858.CD008112.pub2.
- Sato M. Response of Pacinian corpuscles to sinusoidal vibration. *Journal of Physiology*. 1961; 159:391–409. [PubMed: 14497425]
- Sandkühler, J. Long-term potentiation in pain pathways. In: Basbaum, AI.; Bushnell, MC., editors. *Science of pain*. Elsevier; Amsterdam: 2009. p. 401-6.
- Song X-J, Gan Q, Cao J-L, Wang Z-B. Spinal manipulation reduces pain and hyperalgesia after lumbar intervertebral foramen inflammation in the rat. *Journal of Manipulative and Physiological Therapeutics*. 2006; 29(1):5–13. [PubMed: 16396724]
- Sportelli, L.; Tarola, G. Documentation and record keeping. In: Haldeman, S.; Dagenais, S.; Budgell, B.; Grunnet-Nilsson, N.; Hooper, PD.; Meeker, WC.; Triano, J., editors. *Principles and practice of chiropractic*. 3rd edition. McGraw-Hill; New York: 2005. p. 725-41.
- Stilwell DL. The nerve supply of the vertebral column and its associated structures in the monkey. *The Anatomical Record*. 1956; 125(20):139–64. [PubMed: 13354975]
- Stuart DG, Goslow GE, Mosher CG, Reinking RM. Stretch responsiveness of Golgi tendon organs. *Experimental Brain Research*. 1970; 10:463–476.
- Sung PS, Kang YM, Pickar JG. Effect of spinal manipulation duration on low threshold mechanoreceptors in lumbar paraspinal muscles: a preliminary report. *Spine*. 2005; 30:115–22. [PubMed: 15626991]
- Suter E, Herzog W, Conway PJ, Zhang YT. Reflex response associated with manipulative treatment of the thoracic spine. *Journal of Neuromusculoskeletal System*. 1994; 2:124–30.
- Suter E, McMorland G, Herzog W, Bray R. Conservative lower back treatment reduces inhibition in knee-extensor muscles: a randomized controlled trial. *Journal of Manipulative and Physiological Therapeutics*. 2000; 23(2):76–80. [PubMed: 10714531]
- Triano, J. The mechanics of spinal manipulation. In: Herzog, W., editor. *Clinical biomechanics of spinal manipulation*. Churchill Livingstone; New York: 2001. p. 92-190.
- Triano J, Schultz AB. Loads transmitted during lumbosacral spinal manipulative therapy. *Spine*. 1997; 22:1955–64. [PubMed: 9306523]
- Vernon, H. Biological rationale for possible benefits of spinal manipulation. In: Cherkin, DC.; Mootz, RD., editors. *Chiropractic in the United States: Training, Practice and Research*. 1997. p. 105-115. AHCPR Publication No. 98-N002
- Vicenzino B, Neal R, Collins D, Wright A. The displacement, velocity and frequency profile of the frontal plane motion produced by lateral glide treatment technique. *Clinical Biomechanics*. 1999; 14:515–21. [PubMed: 10521635]
- Walker BF, French SD, Grant W, Green S. Combined chiropractic interventions for low-back pain. *Cochrane Database of Systematic Reviews*. 2010; (Issue 4) Art. No.: CD005427. DOI: 10.1002/14651858.CD005427.pub2.
- White DM, Levine JD. Different mechanical transduction mechanisms for the immediate and delayed responses of rat C-fiber nociceptors. *Journal of Neurophysiology*. 1991; 66(2):363–8. [PubMed: 1774578]
- Wiese, G.; Callender. A history of spinal manipulation. In: Haldeman, S., editor. *Principles and practice of chiropractic*. 3rd Edition. McGraw-Hill; New York: 2005. p. 5-22.

Wilder DG, Pope MH, Frymoyer JW. The biomechanics of lumbar disc herniation and the effect of overload and instability. *Journal of Spinal Disorders*. 1988; 1:16–32. [PubMed: 2980059]

Figure 1.

Force time curves derived from high velocity, low amplitude spinal manipulations applied to humans (**A & B**) and to a simulation device (**C**). **A** shows the phases and relative force occurring during the maneuver. (Modified from Fig 1, Herzog W J. *Bodywork & Movement Therapies* 2010;14:280-6) **B** shows the mean force-time curves of manipulations applied to the cervical thoracic, and sacroiliac regions. Modified from Fig 9 Herzog W, et al. *Spine* 1993;18(9):1206-12. **C** shows the force-time curves of a toggle recoil manipulation performed with a left hand contact (left panel) and a right hand contact (right panel). Modified from Fig 2 Graham BA, et al. *Manual Therapy* 2010; 15:74-9

Figure 2.

Lumbar paraspinal muscle spindle response to a high velocity, low amplitude spinal manipulative-like load. **A** shows an original tracing of a spindle's response to the manipulation. Inset shows the spindle's discharge on an expanded time scale. (Adapted from Journal of Manipulative and Physiological Therapeutics. 24(2):2-11, Pickar J & Wheeler JD, Response of muscle proprioceptors to spinal manipulative-like loads in the anesthetized cat, p6, 2001, with permission from Elsevier) **B** shows original tracings of a muscle spindle afferent's response to 6 different thrust durations (400, 200, 100, 50, 25, and 12.5 ms) using a half-sine waveform. (Adapted from Journal of Manipulative and Physiological Therapeutics. 29(1):22-31, Pickar JG & Kang Y-M, Paraspinal muscle spindle responses to the duration of a spinal manipulation under force control p26, 2006, with permission from Elsevier)

Figure 3.

Cervical muscle spindle afferent response to rapid rotation of the C₂ vertebra simulating the thrust phase of a high velocity, low amplitude spinal manipulation. In each panel (**A**, **B**, **C**, **D**) top trace shows an original recording of spindle activity, middle trace shows the instantaneous discharge frequency (bin width 0.125s) and lower trace shows the C₂ vertebra's relative position. Panel **A** shows a decrease in the muscle spindle afferent activity during the thrust and panel **B** shows an increase in its frequency during displacement to the right. The bottom two panels show a muscle spindle's response to vertebral displacement initially to the left and then right and back to the midline (**C**) and then with displacement

initially to the right and then left and back to the midline (**D**). Note the DC shift (movement artefact) in the tracing of the original muscle spindle recordings (Raw Unit Activity) is greater when the vertebra is displaced contralaterally to the short dorsal rootlet being recorded. (Bolton PS and Holland CT 1998 unpublished data).

Table 1

This table lists the receptors that have been identified in paravertebral tissues of the Cervical (C), Thoracic (T), Lumbar (L), or Coccygeal (Cx) regions of the vertebral column using morphological (M) or physiological (P) studies. The species in which the respective receptors have been studied is listed together with one reference to a study involving the species and study type.

Receptor	Region	Study Type	Species	Evidence (see for example)
Muscle Spindle	C	P	Cat	Richmond & Abrahams 1979
		M	Cat	Richmond & Bakker 1982
		M	Human	Boyd-Clarke et al 2002
	C,T,L	M	Human	Amonoo-Kuofi 1983
	L	P	Cat	Cao et al 2009
Golgi Tendon Organ	C	P	Cat	Richmond & Abrahams 1979
		M	Cat	Richmond & Abrahams 1982
		M	Human	Mendel et al 1992
	L	M	Human	Roberts et al 1995
	Cx	M	Bovine	Roberts et al 1995
Paciniform	C	M	Cat	Richmond & Abrahams 1982
Corpuscle		M	Human	McLain 1994
	L	M	Human Fetus	Jackson et al 1966
		M	Human	Jackson et al 1966
	Cx	M	Bovine	Roberts et al 1995
Ruffini	L	M	Human	Roberts et al 1995
Ending				Jiang et al 1995
Unencapsulated	C	M	Human	Mendel et al 1992
Nerve Endings	C,T,L	M	Monkey	Stilwell 1956
		M	Human Fetus	Groen et al 1990
	L	M	Rat	Nakamura et al 1996
		M	Human Fetus	Jackson et al 1966
		M	Human	Jackson et al 1966