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The biomechanics of spinal manipulative treatments

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The purpose of this manuscript is to review the work that has been performed on the biomechanics of spinal manipulative treatments (SMT) over the past three years at The University of Calgary. The forces delivered to different segments of the spine during SMT vary considerably, and so do the treatment forces delivered by one chiropractor to different patients. Also, it was found that the speed of force application during SMT facilitates cavitation and is responsible for eliciting an electromyographical (reflex) response of the back musculature. We also found significant movement of thoracic vertebra T11 relative to thoracic vertebrae T10 and T12 during applications of straight posterior-to-anterior thrusts to the transverse process of T11. The relative movements occurred predominantly in the axial and sagittal rotation directions, and not as expected, in the direction of the primary thrust (posterior to anterior).
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KEY WORDS: spinal manipulative treatments, biomechanics, audible release (cavitation), reflex response, vertebral movements, chiropractic.

Le but de ce manuscrit est d'examiner les travaux accomplis sur la biomécanique des traitements à base de manipulations vertébrales (SMT) au cours des trois dernières années à l'Université de Calgary. Les forces appliquées aux différents segments de la colonne vertébrale pendant les SMT varient considérablement, de même que les forces de traitement appliquées par un chiropracteur à différents patients. Nous avons également remarqué que la vitesse d'application de la force pendant les SMT facilite la cavitation et déclenche une réponse (réflexe) électromyographique de la musculature dorsale. Nous avons également constaté un mouvement significatif de la vertèbre thoracique T11 par rapport aux vertèbres thoraciques T10 et T12 lors de l'application de pressions en ligne droite de l'arrivère vers l'avant sur l'apophyse transverse de la T11. Les mouvements relatifs se produisaient principalement dans les sens de rotation axial et sagittal, et contrairement à ce que nous avions anticipé, dans le sens de la première poussée (de l'arrivère vers l'avant).
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MOTS-CLÉS : traitement à base de manipulations vertébrales, biomécanique, soulagement audible (cavitation), réflexe automatique, mouvements des vertèbres, chiropractie.

Introduction

Biomechanics is the science that investigates the external and internal forces and moments acting on a biological system, and the effects these forces produce. During spinal manipulative treatments (SMTs), a chiropractor exerts an external force on a specific target area on the spinal column of a patient. This external force may reach a considerable magnitude[1] and is typically applied at a very high rate.[2] The location of application, the magnitude, and the precise direction of the treatment forces depend on the patient and the specific problem at hand. The effects that the treatment forces have on the spinal column are not well understood; however, the following effects have been observed, or are hypothesized to occur:

1 Absolute and relative movements of the vertebral bodies in the vicinity of the SMT application;
2 Cavitation of the facet joints;
3 Reflex response of the muscles in the vicinity of the SMT application.

The purpose of this manuscript is to review the work that has been performed on the biomechanics of SMT over the past three years at The University of Calgary. Particularly, I would like to show how much force chiropractors exert on patients at different levels on the spinal column, and what the effects of these forces are in terms of vertebral movements, cavitation, and reflex responses.

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Methods

Most of the procedures relevant to the work described here have been presented elsewhere, and therefore just a brief account will typically be given. More detailed information may be obtained by consulting the references listed.

Force measurements: The forces exerted by chiropractors on patients during SMT were measured using a thin (2 mm), flexible pressure pad (EMED Inc.).[3] The pressure pad is placed between the contact hand of the chiropractor and the treatment area. The pressure pad records the forces applied perpendicularly to its surface; thus, great care was taken to study SMTs that had the direction of force application at right angles to the pressure pad. Force measurements were recorded at a frequency of 100 Hz for several different treatment modalities on the cervical spine,[2] on the thoracic spine,[4] and on the sacroiliac joint.[1,3]

Cavitation measurements: Cavitation measurements were obtained using a uni-axial accelerometer (Dytran 3115A) fixed to the spinous process of the target vertebra with double-sided adhesive tape. Cavitation signals could be distinguished from the accelerations caused by the movements of the spine as a result of SMT by a power spectrum analysis (Fast Fourier Transformation). The cavitation signals, on average, had a frequency content that was approximately ten times larger than the frequency content of the accelerations caused by normal spinal movements.[5] All results of cavitation measurements presented in this manuscript were obtained from SMTs performed on the thoracic spine. The SMTs consisted of a straight posterior-to-anterior thrust to the transverse process of a thoracic vertebra using a reinforced hypothenar contact.

Movement measurements: Measurements of the absolute and relative movements of vertebral bodies were obtained from SMTs applied to unembalmed, post-rigor cadaveric specimens. Movements were measured from a pair of rigid, stainless steel bone pins that were fixed in the bodies of vertebrae T10, T11, and T12. The movements of these bone pins, representing the three-dimensional movement of the corresponding vertebral bodies, were quantified using film digitization of the bone pins from two high-speed cameras (Locam) filming all experimental procedures from a sagittal and a frontal view at a nominal rate of 100 frames/s.[6]

Reflex response: Reflex responses of the back musculature elicited during SMT were measured using bipolar surface electrodes placed exactly on the opposite side of the spine from the point of application of the treatment force. The skin underneath the area of electrode placement was treated in a standard way to reduce skin resistance to levels of less than 2 kOhm.[7] The interelectrode distance was 3.0 cm, the sampling frequency was 5,000 Hz, and all signals were pre-amplified (1000×) no farther than 10 cm from the recording electrodes.

All measurements of reflex responses during SMT presented here were made on the thoracic spine. SMT consisted of a straight posterior-to-anterior thrust to the transverse process of T3, T7, or T9 using a reinforced hypothenar contact. The rate of force application was either fast (i.e., a normal SMT, where peak thrusting forces are reached within about 150 ms from the onset of the thrust) or slow (i.e., peak forces were reached within about 3–5 s).

Results

External forces: The forces exerted by chiropractors on patients during SMT depend strongly on the patient and the spinal level at which the treatment is performed. Figure 1 shows three treatments on the T4 level performed by the same chiropractor using the same technique on three different patients. Obviously, the forces applied on the three patients differ considerably. In fact, the peak thrusting force on subject 1 (P1) is well below the preload force applied to subject 3 just prior to the actual treatment thrust (Pr3). This result, in conjunction with many other observations not shown here, indicates that the forces applied by a chiropractor during SMT are strongly influenced by the patient.

Figure 2 shows mean treatment forces exerted by a number of chiropractors on a number of different patients. Forces exerted on the pelvis (S), lumbar spine (not shown), and thoracic spine (T) appear to be of the same order of magnitude and appear to have a similar time history. In contrast, treatments performed on the cervical spine (C) show a distinctly different force-time history than those performed on the remainder of the spinal column or pelvis; they are executed with little or no preload force, the peak treatment forces are considerably lower than the corresponding values of the sacroiliac joint and the thoracic spine (Figure 2), and treatment thrusts are performed faster than those performed on the sacroiliac joint and the thoracic spine.

Cavitation: During most SMTs a cracking sound is heard. This cracking sound has been associated with cavitation of the spinal facet joints,[4,8] and it has become so much an integral part of the qualitative assessment of an SMT for clinicians that many chiropractors will immediately and spontaneously repeat a treatment that did not result in cavitation.

Cavitation signals typically occur near the peak thrusting force on the rising phase of force production (Figure 3). However, we have also measured cavitation signals after peak thrusting forces had been achieved, indicating that the magnitude of the externally applied force cannot be the only factor responsible for the cavitation response. Further investigation into the factors that may cause cavitation revealed the following two results: first, forces at the instant of cavitation were significantly smaller (t-test, $\alpha = 0.05$) for normal treatment thrusts compared to the corresponding forces obtained during slow SMTs; and second, SMTs not causing cavitation were performed slightly slower and with less force than the corresponding SMTs

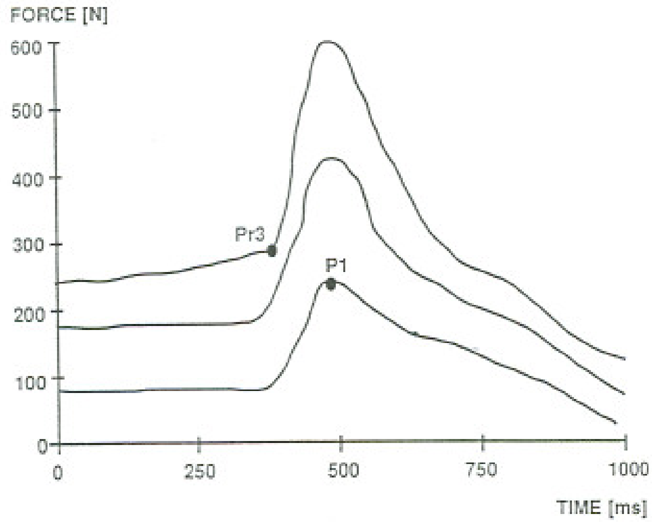

Figure 1 Force-time histories of treatments delivered by one chiropractor to three different patients. All SMTs consisted of a posterior-to-anterior thrust to the transverse process of T4, using a reinforced hypothenar contact. P1 represents the peak force delivered to patient 1; Pr3 represents the preload force delivered to patient 3.

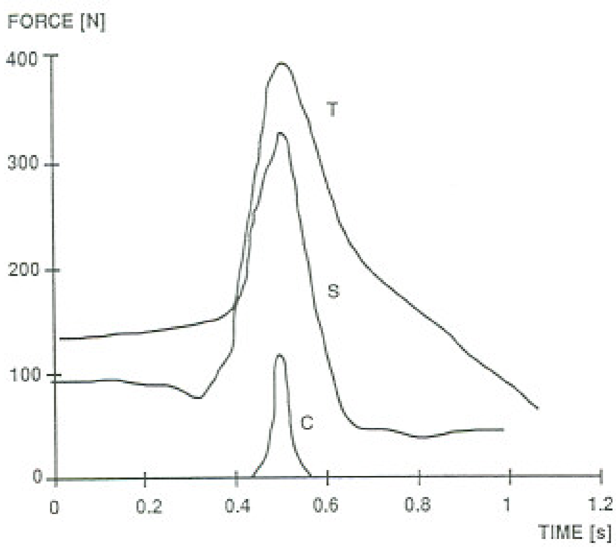

Figure 2 Average force-time histories of treatments delivered to the cervical spine (C), the thoracic spine (T), and the sacroiliac joint (S). Treatment forces were obtained from different chiropractors treating several patients each. (used with permission; Herzog W. et al., Spine 1993; 18:1206–1212.)

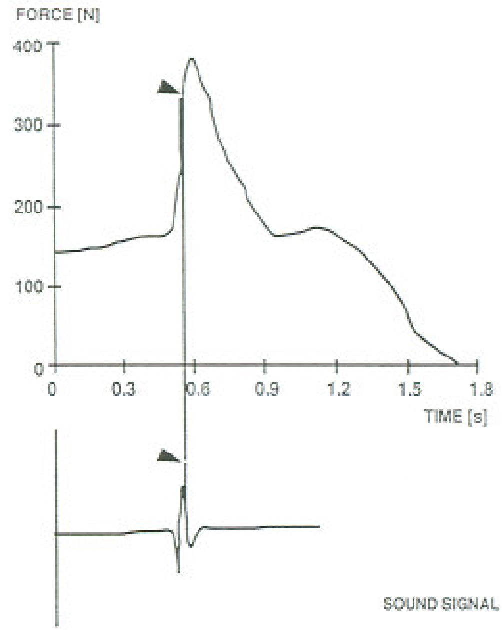

Figure 3 Force-time history and acceleration-time history of a treatment delivered to T4. The arrow on the acceleration trace indicates where cavitation occurred, and the corresponding arrow on the force trace shows the treatment force at the instant of cavitation. (used with permission; Herzog W. JCCA 1991; 35:156–164.)

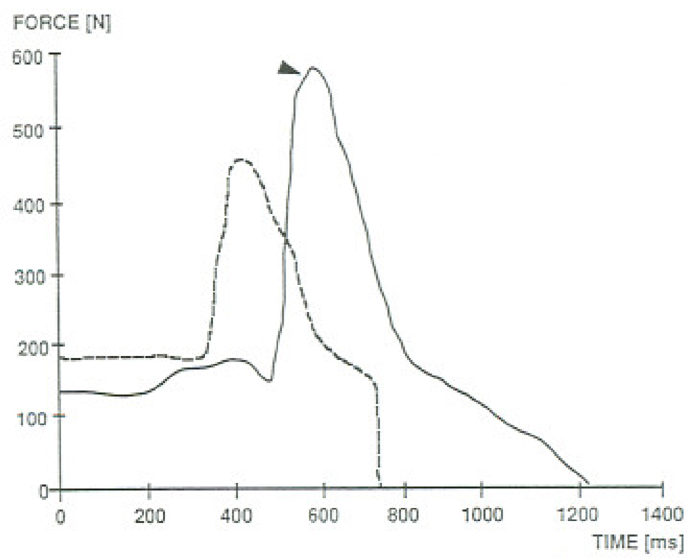

Figure 4 Force-time histories of two treatments delivered to T4. The two treatments were performed by one chiropractor to one patient within about 2–3 secs (the actual delay of the two SMTs is not shown on the graph). The first treatment (intermittent line) did not cause cavitation, whereas the second treatment (sold line) did (arrow). (used with permission; Conway et al., Clin Biomech 1993; 8:210–214.)

that followed (Figure 4). From these results, it was concluded that, aside from the magnitude of the treatment forces applied, the speed of force application appeared to be of major importance for producing cavitations. The higher the speed of force application, the lower the force required to cause cavitation. Therefore, it appears that the speed of SMT may significantly influence the effects of the treatment forces on the spine.

Movements of vertebral bodies: It has been accepted for a long time that SMTs cause temporary deformations of the spinal column; however, there are few (if any) scientific reports on the amount and direction of relative movements of one vertebral body relative to the adjacent vertebrae during SMT. Figure 5 shows the posterior-to-anterior translation of T10, T11, and T12 caused by a posterior-to-anterior thrust to the transverse process of T11; i.e., the primary direction of force application was from posterior-to-anterior. For peak treatment forces ranging from 300–600 N, the average anterior translations of T10, T11, and T12 were approximately 6–12 mm. Interestingly, there was no systematic anterior translation of T11 relative to either T10 or T12. Movements of the three vertebrae in the remaining directions (medial-lateral and proximal-distal translation, as well as axial, sagittal, and frontal rotation) were smaller than the movement in the posterior-to-anterior direction, but they caused movements of T11 relative to T10 and T12 in axial rotation (Figure 6), and movements of T11 relative to T12 in sagittal rotation (Figure 7). From these results it appears that relative movements of vertebral bodies at thoracic levels occur primarily in rotation and not in translation, and that relative movements may not necessarily occur in the direction of the largest absolute movements.

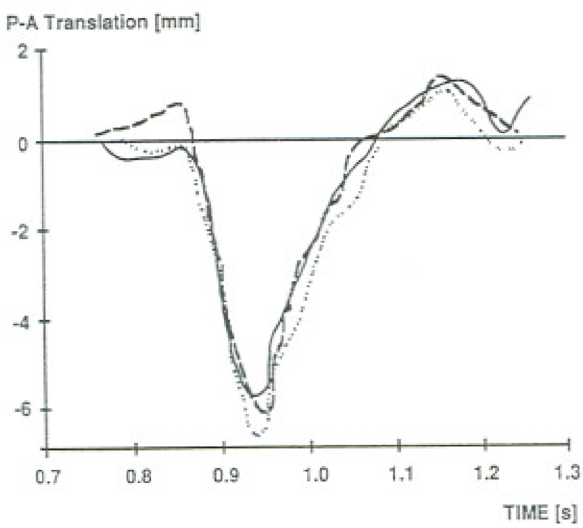

Figure 5 Anterior displacement versus time for T10, T11, and T12 (dashed, dotted, and solid lines, respectively) for a treatment delivered to the transverse process of T11, using a reinforced hypothenar contact.

Reflex responses: Reflex responses associated with SMT were measured for normal (fast) treatment thrusts and for slowly applied forces. It was hypothesized that SMTs which are applied very quickly, would cause a reflex response associated with a stretching of the muscle spindles in the treatment area. This hypothesis was supported by the presence of a reflex response (in the form of an electromyographical signal) for each

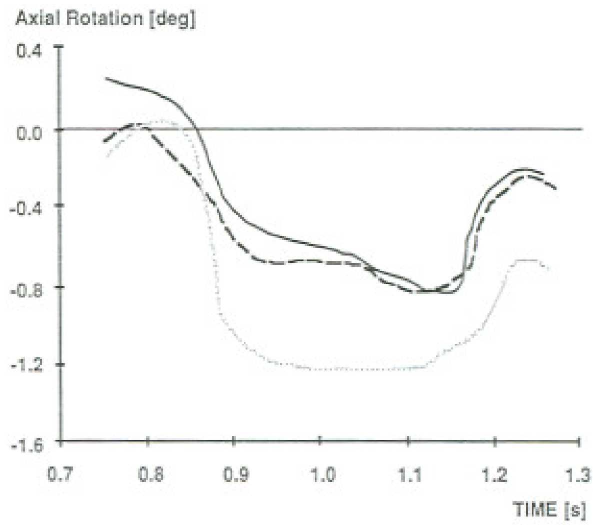

Figure 6 Axial rotation versus time for T10, T11, and T12 (dashed, dotted, and solid lines, respectively) for a treatment delivered to the transverse process of T11, using a reinforced hypothenar contact.

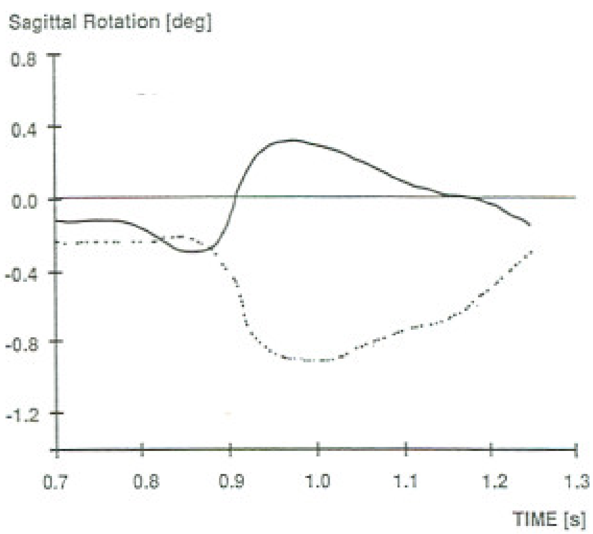

Figure 7 Sagittal rotation versus time for T11 and T12 (dotted and solid lines, respectively) for a treatment delivered to the transverse process of T11, using a reinforced hypothenar conact.

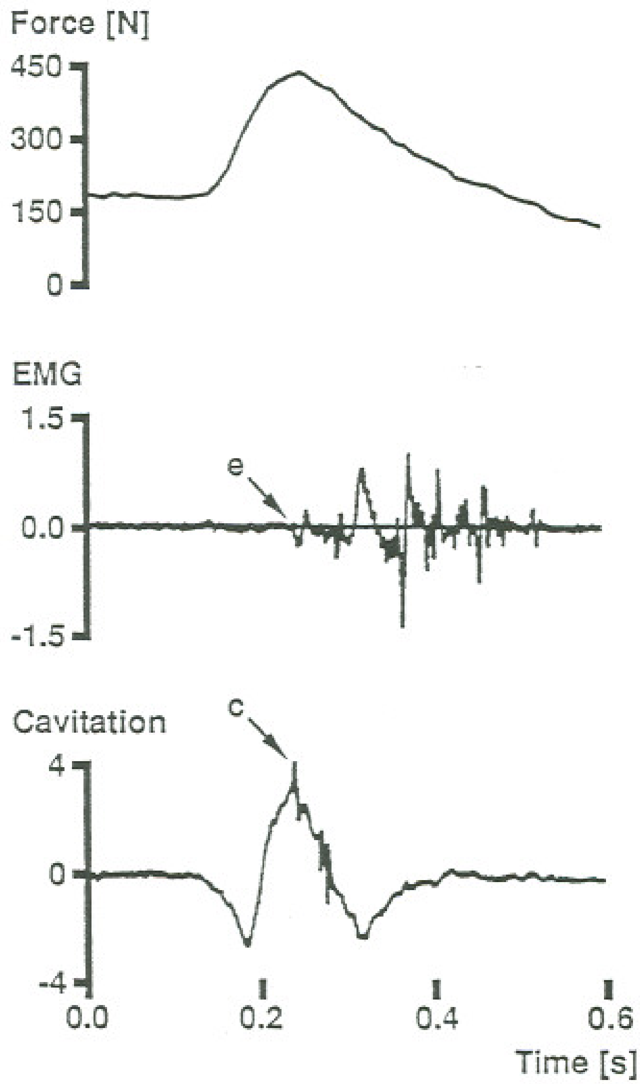

Figure 8 Force-time, EMG-time, and acceleration-time histories of a representative treatment delivered to the transverse process of a thoracic vertebral body. "c" indicates the instant of cavitation, and "e" the onset of the EMG signal (units for the EMG and the cavitation signals are arbitrary).

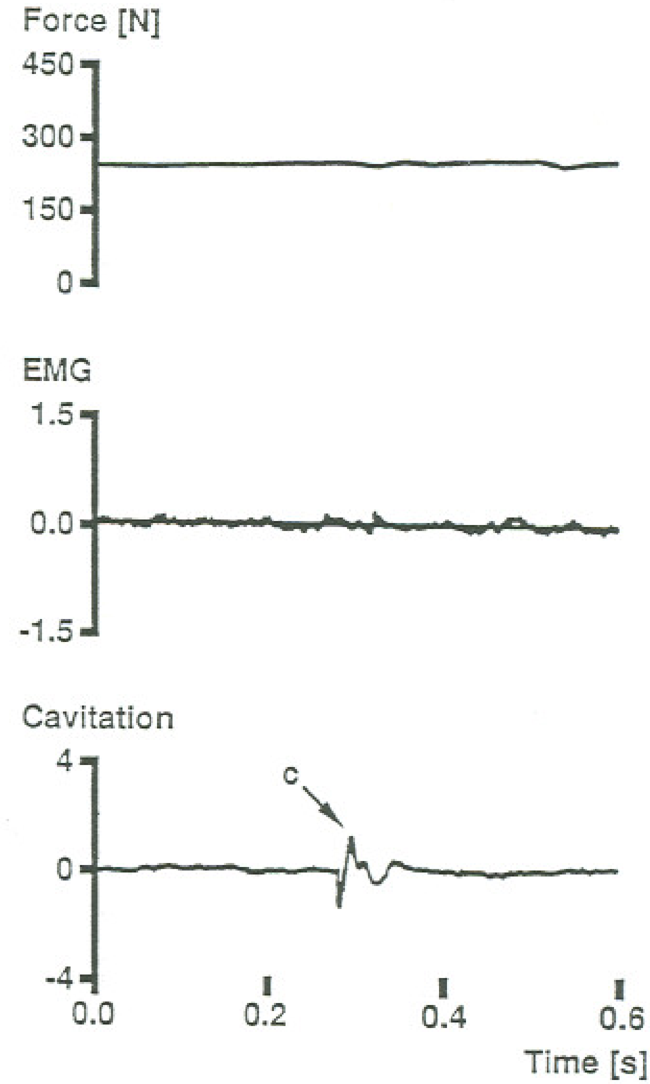

Figure 9 Force-time, EMG-time, and acceleration-time histories of a representative treatment delivered to the transverse process of a thoracic vertebral body. "c" indicates the instant of cavitation (units for the EMG and the cavitation signals are arbitrary).

SMT performed on the thoracic spine (Figure 8), whereas such a response was never observed for slowly applied treatment forces (Figure 9).

It was further hypothesized that cavitation may elicit a reflex response associated with Type II joint capsule proprioceptors. In order to test this hypothesis, a series of slow "treatments" were applied to the thoracic spine causing cavitation. However, cavitation alone (i.e., in the absence of a fast thrusting force) never elicited a measurable reflex response (Figure 9). This result may be because cavitation did not cause a fast distraction of the facet joints, or because a reflex response was elicited but did not manifest itself in the muscles instrumented for recording, or because cavitation simply does not give a sufficient stimulus to joint capsule proprioceptors to trigger a reflex response. The results shown here cannot be used to distinguish between any of these (or other) possibilities. However, as in the case of the factors causing cavitation, it appears that the speed of the applied treatment force is of primary importance in eliciting reflex responses.

Discussion

External forces: The forces applied by a chiropractor to a patient were shown to depend on the level of the spine at which the treatment was performed, and on the patient. Generally, forces applied to the cervical spine were of a much lower magnitude but similar or higher rate than forces applied to the rest of the spinal column and the pelvis. This result may reflect the fact that the cervical spine is easier to adjust than the thoracic or lumbar spine; however, it may also reflect the higher risk of damage to structures in the cervical spine or its vicinity (i.e., the vertebral artery) when high forces are applied to that area compared to when high forces are applied distal to the cervical spine.

A given chiropractor treating different patients on the same spinal level, using the same treatment modality for a given problem, may use treatment forces that differ in magnitude by a factor of three (e.g., Figure 1). Obviously, the clinician will gauge the amount of force administered to a patient very carefully. It is not precisely known what factors will influence the decision about how much force is required for a given patient, but it appears that the force required to move the target vertebra to the end range of passive motion (i.e., the preload force required) influences the thrusting force in a directly proportional way (Figure 1). This finding suggests that the stiffer the motion segments of the treatment area are, the more force will be required to obtain the clinically desired release during SMT.

Cavitation: At this point, it is not known where the audible release during SMT originates. Overwhelming evidence suggests that the audible release is the cavitation sound from (synovial) facet joints,[1,4,8,9] however, the proof for this statement is still required.

The mechanical factors causing cavitation during SMT appear to be the external forces applied and the speed of force application. Evidence from our studies suggests that cavitation may be elicited with lower externally applied forces when the treatment consists of a high velocity thrust, compared to when the forces are applied slowly (i.e., over 3–5 s). Thus, if cavitation is to be achieved with the least amount of treatment force, it is recommended that the treatment be performed with as high a rate of force application (i.e., speed) as possible.

Movements of vertebral bodies: It is easy to observe by eye that SMT causes temporary deformation of the spinal column. However, chiropractors claim that vertebral bodies move relative to one another, and this relative movement cannot be observed by eye, nor can it be measured from surface markers placed on the spinous processes of vertebral bodies. Most scientists agree that relative movements of vertebrae during SMT cannot even be measured using videofluoroscopy. Probably the only method to quantify relative movements of vertebrae accurately is through the use of external markers fixed by bone pins directly to the vertebral bodies. Presently, human ethics committees at Canadian universities will not allow the placement of bone pins in vertebral bodies of patients for the purpose of movement measurements; however, this procedure is straightforward using cadaveric specimens. For straight posterior-to-anterior thrusts to the transverse process of T11, the primary movement that occurs in T10, T11, and T12 is in the anterior direction. Interestingly, we could not detect any systematic relative movements of T11 to T10 or T12 in the anterior direction.

A posterior-to-anterior thrust to a transverse process will always cause an axial rotation of the target vertebra. This axial rotation was most pronounced for the target vertebra (i.e., T11) thus causing relative axial rotations of T11 to T10 and T12 (Figure 6).

A posterior-to-anterior force, anywhere on the spine of a prone patient, may not cause sagittal rotation of the target vertebra, but in order to accommodate the graded anterior translations of the spine observed in this situation, it appears necessary that the vertebral body just distal to the target vertebra rotates sagittally, such that its proximal end moves further anteriorly than its distal end; and similarly, the vertebral body just proximal to the target vertebra is expected to rotate such that its distal end moves further anteriorly than its proximal end. Therefore, vertebral bodies might be expected to rotate in opposite directions in this specific situation. This expectation was supported through our studies. Not only was this opposite sagittal rotation observed (Figure 7), it typically caused the largest relative movements between the target and the adjacent vertebral bodies.

Reflex responses: The most commonly known reflex response is the patellar tendon reflex. Tapping the patellar tendon causes a quick stretch of the muscle spindles of the knee extensor muscles. The spindle afferents will signal the stretch of the spindles to the appropriate spinal level, where the spindle afferents make a monosynaptic connection with the α -motor neurons innervating the knee extensor muscles, causing the knee extensor muscles to contract briefly. It was hypothesized that a fast SMT would cause a stretch to some of the spindles in the back musculature because of the movements of the spine and the relative movements of the vertebrae during SMT. It was further speculated that, if such a stretching of the spindles did occur, a reflex contraction of the appropriate muscles should follow, and this contraction could be seen using electromyographical techniques. In accordance with the delay of spindle reflexes, it was expected that the electromyographical signal must occur clearly after the onset of the treatment force, but not later than about 100 ms, and that the signal would disappear shortly after the end of the treatment thrust. All of these expectations were satisified in our experiments, thus leading to the conclusion that fast SMTs will cause a reflex activation of the back musculature, which is likely associated with the spindle proprioceptors. The fact that no EMG signal was ever observed during a slow (3–5 s) application of the treatment force further supports the idea that fast treatment thrusts elicit a spindle reflex contraction of the back musculature in the vicinity of the application of the treatment force.

We had further hypothesized that a slow SMT causing cavitation may also elicit a reflex response caused by the Type II proprioceptors located in the capsules of the spinal facet joints. However, such a response was not observed. It is not clear at this moment if the lack of observation of a Type II proprioceptor reflex response is associated with the real absence of such a response, or if the response was actually elicited but was not measured with our specific experimental design. Of course, there also exists the possibility that spinal joint cavitation does indeed elicit a Type II proprioceptive reflex response; however, the SMTs performed by us never caused a "true" facet joint cavitation.

Acknowledgments

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References

1 Herzog W, Conway PJW, Kawchuk GN, Zhang Y, Hasler EM. Forces exerted during spinal manipulative therapy. Spine 1993; 18:1206–1212.

2 Kawchuk GN, Herzog W. Biomechanical characterization (fingerprinting) of five novel methods of cervical spinal manipulation. J Manipulative Physiol Ther 1993; 16:573–577.

3 Hessel BW, Herzog W, Conway PJW, McEwen MC. Experimental measurement of the force exerted during spinal manipulation using the Thompson Technique. J Manipulative Physiol Ther 1990; 13:448–453.

4 Conway PJW, Herzog W, Zhang Y, Hasler EM, Ladly K. Forces required to cause cavitation during spinal manipulation in the thoracic spine. Clin Biomech 1993; 8:210–214.

5 Herzog W, Zhang YT, Conway PJ, Kawchuk GN. Cavitation sounds during spinal manipulative treatments. J Manipulative Physiol Ther 1993; 16:523–526.

6 Gál JM, Herzog W, Kawchuk GN, Conway PJ, Zhang YT. Movements of vertebrae during manipulative thrusts to unembalmed human cadavers. Submitted to Spine, January 1994.

7 Basmajian JV, de Luca CJ. Muscles Alive 5th ed. Los Angeles: Williams & Wilkins, 1985: 22–25.

8 Sandoz R. The significance of the manipulative crack and of other articular noises. Ann Swiss Chiro Assoc 1969; 4:47–68.

9 Conway PJW, Zhang YT, Herzog W, Kawchuk GN. The use of an external acoustic microphone to confirm joint cavitation signals obtained from skin-mounted accelerometers placed at the metacarpophalangeal joint. Submitted to Clin Biomech, February 1994.