Joint Manipulation: Toward a General Theory of High-Velocity, Low-Amplitude Thrust Techniques

Andrew S. Harwich, DO

ABSTRACT

Objective: The objective of this study was to describe the initial stage of a generalized theory of high-velocity, low-amplitude thrust (HVLAT) techniques for joint manipulation.

Methods: This study examined the movements described by authors from the fields of osteopathy, chiropractic, and physical therapy to produce joint cavitation in both the metacarpophalangeal (MCP) joint and the cervical spine apophysial joint. This study qualitatively compared the kinetics, the similarities, and the differences between MCP cavitation and cervical facet joint cavitation. A qualitative vector analysis of forces and movements was undertaken by constructing computer-generated, simplified graphical models of the MCP joint and a typical cervical apophysial joint and imposing the motions dictated by the clinical technique.

Results: Comparing the path to cavitation of 2 modes of HVLAT for the MCP joint, namely, distraction and hyperflexion, it was found that the hyperflexion method requires an axis of rotation, the hinge axis, which is also required for cervical HVLAT. These results show that there is an analogue of cervical HVLAT in one of the MCP joint HVLATs.

Conclusions: The study demonstrated that in a theoretical model, the path to joint cavitation is the same for asymmetric separation of the joint surfaces in the cervical spine and the MCP joints. (J Chiropr Humanit 2017;24:15-23)

Key Indexing Terms: *Manipulation, Chiropractic; Manipulation, Osteopathic; Biomechanical Phenomena*

INTRODUCTION

High-velocity, low-amplitude thrust (HVLAT) techniques are widely used in manual therapies and nearly always produce a “cracking” noise. This is considered a cavitation event^{1,2} for the metacarpophalangeal (MCP) joint and is produced by the sudden separation, or “gapping,” of the joint surfaces. In clinical practice, the force to do this is applied manually. It is assumed that the event is the same mechanism in both spinal and peripheral joints, as it involves the same types of structures. For example, similar characteristics were found for joint noises (ie, “cracks”) in both the MCP joint and the cervical apophysial joint.³ In addition, it was found that gapping occurred in lumbar adjusting procedures.⁴ Various terms have been used for the lesion that is treated with HVLAT.⁵ In this paper, the term “joint dysfunction” will be used.

One way to try to better understand the joint dysfunction that is treated with HVLAT is to analyze in detail the kinematics of the thrust procedure used in clinical practice that produces joint gapping. Following the reverse path of those kinematics should then reveal the path to the lesioned state.

There appear to be problems with describing the manipulative technique unambiguously: one description of the spinal manipulative thrust technique⁶ focused on “end feel” for what has been called the *preload phase* of the maneuver produced by combinations of applied movements.⁷ However, these combinations are only hypothesized, and the numerous variations of the positioning prior to delivery of the thrust (eg, it is not agreed whether the target joint should be in flexion or extension) are based on a prescriptive rationale that has not been verified by proper testing. For example, the direction of the thrust on a target joint would appear to depend on the therapist’s desire to either increase or decrease tension on unspecified joint structures. Hing et al⁸ stated that HVLAT can be performed on the same joint in at least 3 directions following the methods described in the literature.⁹ The authors failed to explain how the target joint is gapped in 2 of these directions (ie, “upslope” and “downslope”), if that is an immediate aim of the manipulation, since the thrust is parallel to the joint plane.

Private Practice, London, United Kingdom.

Corresponding author: Andrew S. Harwich, DO, The Bridge House Practice, 154 Caledonian Road, Kings Cross, London, UK, N1 9RD. Tel.: +44 207 833 3748. (e-mail: thebhp@btconnect.com). Paper submitted August 15, 2016; accepted January 24, 2017. 1556-3499

© 2017 by National University of Health Sciences.

<http://dx.doi.org/10.1016/j.echu.2017.01.001>

Evans and Breen¹⁰ used the chart attributed to Sandoz¹¹ to find the position of minimum energy to perform the HVLAT, although there is no particular requirement to do that. They decided that the neutral position is the appropriate position, but if the technique is not restricted to distraction HVLAT and causes a hinge separation on the MCP joint in adduction or abduction, the efficiency of the technique is doubled. By using a 2-dimensional example to which a symmetric gapping force is applied, the parallel with normal spinal manipulation is rendered false, whether or not other planes of movement are considered.

Klein et al,¹² using a method of HVLAT to the cervical spine in which the patient is in the sitting position, showed that movement may be blocked at the contralateral joint to the one targeted by placing a finger over the joint. It is also not clear how cephalad axial traction can be easily and simultaneously applied by using this method.

In trying to assess the accuracy and specificity of lumbar and thoracic manipulation, Ross et al¹³ offer 4 different modes of manipulation of the lumbar spine. In 2 of these, “spinous push” and “spinous pull,” which are possibly opposite forces of axial rotation, are applied to the same target joint. It is not clear from their description whether this implies that gapping of the same zygapophysial joint can occur in several different ways. A quite different prescription for cervical HVLAT from that suggested by other therapists has also been given.¹⁴ This method employs a contact point on the inferior vertebra, and the thrust is applied to the inferior vertebra in the same direction as recommended by other authors, keeping the patient’s head and cephalad spine still, but moving the inferior vertebra. Kinematically, it is not equivalent to the consensus method outlined in this paper.

There appears to be general agreement on the process of applying HVLAT techniques. This is to be expected from the long empirical tradition of using the HVLAT in clinical practice.¹⁵ Nevertheless, as described here, there are variations and nuances of technique that are deemed necessary for success with the maneuver but that do not lead to a consistent view of either the pathophysiology or the therapeutic benefit of HVLAT techniques. However, without sufficiently detailed kinematics, it is impossible to describe the kinetics accurately, and the physiology of joints with lesions therefore remains unclear.

Except for the simplest case of distraction HVLAT of the MCP joint, the kinematics of HVLAT techniques have not yet been rigorously evaluated. Therefore, the objective of this study was to describe the initial stage of a generalized theory of HVLAT techniques for joint manipulation. This study examined the movements described by different authors to produce joint cavitation in both the MCP joint and the cervical apophysial joint, and the similarities and differences between MCP cavitation and cervical facet joint cavitation were investigated by comparing the kinetics qualitatively.

METHODS

To visualize the motion segments, graphical models were drawn by using engineering drawing software (SmartSketch, Intergraph Corporation, Madison, Alabama). The bones with their articular surfaces are regarded as rigid bodies, but the joint capsule is elastic and deformable; the capsular attachments are fixed but are regarded as pin joints (when modeled as individual fibers). Only the relevant structures are shown. The topologic relationships between elements are emphasized over numerical measures, since the vector analysis is qualitative; therefore, the models are not to scale, and forces have direction but no given magnitude. Keeping 1 bone fixed, incremental movement is made on the other bone in accordance with the generally agreed prescription to produce articular gapping.

Using data on joint contour from Chao,¹⁶ Minami,¹⁷ and Unsworth,² a typical MCP joint was drawn in lateral view cross-section (Fig 1). This single view suffices, since nowhere in the literature has it been suggested that movement occurs out of this plane to produce the 2 methods of HVLAT to the joint, as discussed below. The proximal phalanx (PP) could then be moved, but the metacarpal (MC) bone was taken as fixed. The changes in capsule length (and hence tension) are illustrative, although we ensured that the relative changes were within acceptable parameters (ie, less than failure strain: ~100% at MCP, ~100% at C4-C5^{18,19}). This was done by measuring differences in length after movement had been imposed on the model and normal rotations constrained by maintaining contact of articular surfaces until articular gapping occurred.

We did not find any reports providing a detailed description of hyperflexion HVLAT of the MCP joint. However, it is a widespread practice to crack the knuckle joints in this way. *Hyperflexion* is defined as flexion taken beyond the range possible through voluntary muscle contraction by an external force. The overall sequence is that the MCP joint is palmar flexed to a point of tension by an external force applied to the proximal phalanx and, similar to distraction HVLAT, a further impulse is given to the phalanx to produce the crack.

A similar construct was used to visualize a midcervical segment (Fig 2).

The positioning and movements for cervical HVLAT are listed in Table 1.²⁰⁻²⁵ They are fairly consistent among

Fig 1. The metacarpophalangeal joint in neutral position. MC, metacarpal; PP, proximal phalanx.

Fig 2. A cervical segment in neutral position.

several authors from different disciplines. The lower vertebra is fixed in space so that motion occurs at the upper vertebra. The models were graphically manipulated to produce the facet separation needed for cavitation according to these descriptions. By comparing the mech-

anisms of MCP HVLAT with C4-5 HVLAT, and since cavitation is the same phenomenon for both, we explored whether there are specific similarities between the methods of manipulation of the 2 regions and, qualitatively, what forces are needed to bring this about.

Table 1. Techniques of Cervical HVLAT (to Manipulate C4-5 Right)

Technique	Author					
	Gibbons and Tehan ²¹	Maitland ²⁵	Haldeman ²⁴	DiGiovanna et al ²²	Kuchera and Kuchera ²³	Bergman and Peterson ²⁰
Lesion	Somatic dysfunction	Movement restriction	Rotary fixation	Somatic dysfunction	Somatic dysfunction	Movement restriction rotation, lateral flexion, extension
P initial position	Supine	Supine	Supine	Supine	(Supine)	Supine, but various listed
Neck position	Neutral	Neutral	N/A	Extension	Flexion (flatten sagittal plane)	Neutral
Contact point	AP C4	AP C4 posterolateral	SP C4 / AP C4	AP C4?	N/A	AP C4, lateral SP C4(alt)
Applicator	Index finger	Index finger	Index finger	Index finger (MCP joint)	N/A	Index finger, and various (alt)
Leverage 1	Rotation left	Rotation left	Rotation left	Rotation left	Rotation left	Rotation left
Leverage 2	Sidebend right	Lateral flexion (alt)	Sidebend right	Sidebend right	Sidebend right (minimal)	Sidebend right
Leverage 3	N/A	N/A	Traction occasionally	Head kept midline	N/A	Extension if desired
Thrust 1	Up + midline + rotary	Rotary	Caudally + medially	Rotary	Rotary in rotation plane	Rotary, plane of joint
Thrust 2	Sidebend + down + midline (alt)	Lateral flexion (alt)	N/A	Sidebend (alt)	Sidebend (alt)	Sidebend (alt)
Thrust 3	Plane of joint	Plane of joint	N/A	Vary with level treated	N/A	N/A

(alt), alternative method; AP, articular pillar; MCP, metacarpophalangeal; N/A, not available; SP, spinous process. Information was drawn from the fields of osteopathy,²¹⁻²³ chiropractic,^{20,24} and physical therapy.²⁵

Fig 3. Stages to distraction and hyperflexion high-velocity, low-amplification thrust (HVLAT) of metacarpophalangeal joint. MC, metacarpal; PP, proximal phalanx.

RESULTS

By applying the prescribed motions for HVLAT on the moving bone, the stages to the cavitation event are shown for each joint and mode. This event, that is, gapping, is represented by a marked change in the intra-articular space and is symmetric across the articular surface for traction techniques and asymmetric for the remainder. A vector analysis of the forces producing the HVLAT is given.

Metacarpophalangeal Joint

Axial distraction has been the preferred HVLAT technique for the MCP joint in research (Fig 3, Distraction). This consists of (1) the phase of preliminary separation, as termed by Roston and Wheeler-Haines,¹ in which the groove where the capsule is “sucked in” is shown; and (2) “the crack” produced by a further impulse through the applied force on the proximal phalanx.

In Figure 3, hyperflexion, stage 1 is initial flexion of the joint, and the capsule will be relatively slack, and the volar plate slides proximally; in stage 2, as the joint further flexes, the dorsal capsule starts to come under tension, and the volar plate slides further proximally, the attached (relatively thin) capsule folds back; and in stage 3, the immediate prethrust position is at approximately 90-degree flexion. We could not find any data on the behavior of the joint capsule on the palmar aspect in flexion–hyperflexion movement. Youm et al²⁶ stated that in palmar flexion, the contact point moves to the palmar end of the phalangeal base, implying that a degree of sliding takes place, as described by Zatsiorsky.²⁷ However, compression must

occur because a synovial recess is present²⁸ and because of the fibrous nature of the volar plate intracapsular fat. This is known to occur in the lumbar apophysial joints, according to McFadden and Taylor²⁹ and Giles.³⁰

For gapping, and hence cavitation, to occur as shown in stage 4, an axis of rotation must exist, as indicated by point H (Fig 3). This point, termed the *hinge point* or *hinge axis*, lies in a plane orthogonal to the plane of view. H, in Figure 4, is created by forces acting in the immediate prethrust equilibrium position. First, the applied force on the shaft of the proximal phalanx produces a torque countered by increasing tension in the dorsal capsule F_{dc} . Compression of the capsule and intracapsular fat from approximation of the

Fig 4. Prethrust equilibrium at hinge point.

Fig 5. Vectors of facet separation. LV, lower vertebra; UV, upper vertebra.

volar aspect of the proximal phalanx with the MC bone and reaction of the (fixed) MC F_{pp} and F_{mc} also occur. Tension in the volar capsule, F_{vc} , arises from a component of the applied force proximally translating the phalanx. The much more rapid movement associated with the thrust event may be resisted by the viscosity of the compressed soft tissues as well as further increased tension in the volar capsule.

Cervical Apophysial Joints

The cervical analogue of axial distraction HVLAT to the MCP joint would be a distraction force, E , acting on the superior vertebra, as shown in Figure 5. Direct distraction is difficult to apply clinically because of lack of friction between the dermal layers and the bone to be moved and would need to be applied to both right and left facet joints.^{31,32} Traction is used therapeutically but not with the aim of specific joint manipulation. This does not exclude the occurrence of spontaneous cavitation.

If the facet separation vector is resolved into component parts, e_2 , e_3 , e_4 , and e_5 , such that $E = e_2 + e_3$ in the frontal plane, and $E = e_4 + e_5$ in the sagittal plane, looking first at the frontal plane in Figure 5 and the blue component vectors, to achieve facet separation an ipsilateral translation, supplied by e_2 , has to take place; this cannot be applied manually, since it needs the upper vertebra to be pulled. With the red vectors, the more the e_2 is directed lateromedially, the more e_3 would have to supply not only the distraction component but also a force medial to lateral, which is again not possible manually. In the sagittal plane, red e_4 and blue e_5 can be regarded as pulling forces, and these are not performed clinically, nor is it possible to see how they could occur with the “point” application of force.

Positioning for HVLAT to Cervical Apophysial Joint

As a typical example, the following movements are to manipulate C4-C5 on the right side.

Based on information from Table 1, there are 4 stages for the most commonly described HVLAT to cervical apophysial joints:

- 1 The start position is neutral (Fig 2).
- 2 Force is applied by the right hand to the right articular pillar of the upper vertebra.
- 3 Rotate vertebra to the left.
- 4 Sidebend vertebra to the right.

Although asymmetry of position is often cited as one of the criteria for determining manipulable midcervical facet lesions, no consistent asymmetry has been reported to be associated with this. Moreover, nowhere in these published sources is it mentioned that HVLAT cannot be achieved starting from the neutral position. It is also assumed in the methods listed in Table 1 that the prescribed movements are possible. The neutral position was thus chosen as the starting position.

There appears to be no fixed order in applying forces, but the initial (firm) contact of the operator’s hand or finger with the articular pillar, represented by F acting in the positive x direction in Figure 6, supplies a force tending to shift the upper vertebra contralaterally. This movement is usually not explicitly stated to be done. Clinically, incremental steps are followed with each type of movement (translation, rotation, sidebend, extension, etc) to achieve the prethrust position.

Fig 6. Side shift of upper vertebra.

Fig 7. Side shift + left rotation of upper vertebra.

The position after left rotation has been added to the left shift of the upper vertebra, as shown in Figure 7. The lateral border of the left articular pillar shows the capsule, LC, superimposed to demonstrate the tension increase as a result of lengthening of the fiber.

The Hinge Point

To gap the joint surfaces on the ipsilateral (right) side and given that symmetric distraction is not the method used, an axis of rotation must exist on the contralateral side. It will lie approximately parallel to the oblique plane of the contralateral facet. The creation of this IAR—the hinge point H in Figure 7—results from the combination of movements produced by the applied force, F , taking the capsule LC near the limit of elastic stretch. Figure 8 shows how the contralateral shift force, F_x , resolves into a component F_s acting along the capsule and a component F_T acting orthogonal to the capsular fiber. F_s will at least maintain capsular tension allowing F_T to produce torque at C. The glide of the superior facet and the absence of a force in the positive y direction establish the position of a hinge point or axis of rotation beyond the lateral margin of the articular surface. Any IAR is a point of least resistance to torsion but of greatest resistance to translation.

Sidebending of the cervical spine in a direction ipsilateral to the joint being manipulated is often cited as a component of

manipulation (Table 1). However, looking at the frontal view and in line with Bogduk and Mercer,³³ true sidebending as rotation about an axis in the $+z$ direction cannot occur but would be a glide “down slope” on the right facet (counter to the rotation previously imposed) plus right translation of the upper vertebra. This would reduce capsule tension at the segment, and thus no gapping could occur with the thrust movement.

Figure 9 illustrates the final stage of an HVLAT—gapping of the ipsilateral joint by a force, F , applied to the right articular pillar of C4. The directions of F are supposed to be the same for both pre-HVLAT and on-HVLAT, implying that the gapping force thus always has at least 1 of the component directions of the positioning force. In Figure 9, it can be seen that F_x is the component of the F that produces gapping. This is a contralateral shift that converts to a torque at the hinge point H.

DISCUSSION

There is still uncertainty about the place of thrust techniques in the treatment of musculoskeletal problems. The reason could be that the mechanism of HVLAT is not well understood. This study employed for the first time computer-generated, graphic models of thrust kinematics of 2 quite different joints that relate to the clinical descriptions of the technique. In addition, this study revealed for the first time, at least theoretically, the detailed stages of the thrust procedure.

Fig 8. The hinge point at the left facet.

Fig 9. High-velocity, low-amplification thrust to a cervical apophyseal joint on the right.

The study showed that symmetric distraction methods cannot be the common ground for spinal and peripheral joint manipulations. However, there is some similarity between cervical apophysial HVLAT and hyperflexion MCP HVLAT. The difference, however, is that distraction HVLAT has no axis of rotation, as it is a translatory movement, but the second type has an axis—the hinge point—around which the moving bone can rotate.

Onan et al³⁴ demonstrated large ranges of movement when testing isolated cervical facets. However, pre-HVLAT positioning must create tension in some portion of the capsule, since cavitation implies gas bubble formation in a closed environment, perhaps through the mechanism of tribonucleation,^{35,36} and the major limiting factor of the HVLAT motion must be capsular tension.

Combining this capsular tension with a reduction in the intracapsular, extra-articular joint space, fat in the intracapsular space will be compressed. There is communication through the capsule between extra- and intracapsular fat, assumed to be present in cervical joints as they are in the lumbar region^{28,29}; but a sharp force may not allow fast passage of the fat and, thus, on a fast movement, act as a cushion to the lateral shift of the superior vertebra, taking the hinge point away from the capsule insertion (point C in Fig 9) of the fixed inferior body.

It has been shown in the foregoing kinematic analysis that rotary forces in the transverse or oblique transverse plane cannot produce the gapping movement deemed necessary for successful cervical thrust techniques. The purpose of these forces is to help bring capsular tension to the right level to create the hinge point. The sidebending element common to all thrusts described is likely to only reduce overall muscle tension on the same side as the target joint, as well as pretensioning the opposite joint, to allow better focused access. In addition, small flexion or extension movements do not seem critical to achieving a thrust, but it is possible that small extension of the segment, at least in the neck, may act in a similar fashion as sidebending.

The left and right paired apophysial articular surfaces could be regarded as a single kinematic entity, and so the various ligaments and also the intervertebral disc would act as constraints to motion but not fundamentally alter it. The comparison of an asymmetric HVLAT to the cervical apophysial joints with hyperflexion HVLAT to the MCP joints then becomes clearer. Both need to establish a hinge axis and do so by tensioning a particular part of the capsule in a similar way by a “sideways” translation for the cervical joint and a proximal translation for the MCP joint. The possible effect of intracapsular fat is to cushion the compression from the rapidly applied force.

It is suggested here that any asymmetric HVLAT technique applied either spinally or to peripheral joints follow the sequence of movement set out above—namely, the establishment of a hinge axis by the tension built up from initial positioning and the final thrust in a direction that creates a moment about the axis. By the definition of

asymmetry and through geometric considerations a center of rotation for cavitation must exist just beyond the articular surface margins.

If there is a consistently present joint dysfunction that requires HVLAT to correct it, it is necessary to show the potential existence of hinge axes for every manipulable joint that relate to the particular geometry of the joint. The MCP joint shows that a hinge axis for producing joint gapping may not be unique for each joint, but this does not mean that the joint lesions addressed by HVLAT are as varied. Differences exist, for example, between lumbar and cervical HVLATs, as described in clinical practice. In general, in the cervical HVLAT technique, the upper vertebra is moved and the lower vertebra fixed, whereas in the lumbar HVLAT technique, the lower vertebra is moved and the upper vertebra fixed. Support for the hinge axis hypothesis and asymmetry of the cavitation technique is given by Cramer et al³⁷ who found that, albeit in the lumbar zygapophysial joints, “upside” joints gapped more than the “downside” joints in side-posture HVLAT.

Shear forces were not present in the MCP joint testing.² So, given the assumption of equivalence of MCP joint cracking and cervical joint cracking, gapping (separation) of the joint surfaces is an integral part of the HVLAT phenomenon. However, the magnitude of the gapping necessary for successful HVLAT is unknown, as is the velocity of the joint separation.

A full description of joint dysfunction is the subject of ongoing research. If HVLAT has therapeutic value, then it must be correcting a physiological dysfunction common to all manipulable joints. There appears to be no need to posit tissue damage or trauma for this to occur. Indeed, the phase of the HVLAT mechanism described here implies intact, normal elasticity of the ligaments and capsule. Cohesive forces between the articular surfaces are unlikely to be the condition “cracked” by HVLAT, since an increased joint gap was observed in the prethrust phase.^{1,38}

Limitations

The clinical procedure of cervical HVLAT has not been verified by real-time imaging; hence it is not known whether the path described is what is followed clinically, although it has consensus among various sources (Table 1) despite many apparent variations. This is also true for hyperflexion HVLAT of the MCP joint. Measurement of capsule tension as related to crack force and the cavitation event has not yet been done and would help validate the ligament strains proposed in the model.

Although it is believed that other spinal and peripheral joints probably behave similarly (ie, have same requirements to achieve gapping and thus point the way to a general theory), the analysis needs to be extended to these. Thus, by using descriptions of commonly practiced techniques of HVLAT

and generating computer models as was done in this study, the theoretic existence of those joints' hinge axes could be shown.

CONCLUSIONS

The model tested in this study showed the necessity for the hinge point for gapping of the 2 types of synovial joint investigated. This study has revealed a model to describe the initial stage of HVLAT procedures to restore normal joint function.

FUNDING SOURCES AND CONFLICTS OF INTEREST

No funding sources or conflicts of interest were reported for this study.

CONTRIBUTORSHIP INFORMATION

Concept development (provided idea for the research): A.S.H.

Design (planned the methods to generate the results): A.S.H.

Supervision (provided oversight, responsible for organization and implementation, writing of the manuscript): A.S.H.

Data collection/processing (responsible for experiments, patient management, organization, or reporting data): A.S.H.

Analysis/interpretation (responsible for statistical analysis, evaluation, and presentation of the results): A.S.H.

Literature search (performed the literature search): A.S.H.

Writing (responsible for writing a substantive part of the manuscript): A.S.H.

Critical review (revised manuscript for intellectual content, this does not relate to spelling and grammar checking): A.S.H.

Practical Applications

- The study showed the need for precision in application of joint manipulation by HVLAT techniques.
- The contact point of the applied force has to stay as close to the moving bone as possible.
- The final direction of the thrust force to achieve a successful outcome is translatory rather than rotary.
- The mechanism as described invites generalization to nearly all synovial joints.

REFERENCES

1. Roston JB, Wheeler-Haines R. Cracking in the metacarpophalangeal joint. *J Anat.* 1947;81(Pt 2):165-173.
2. Unsworth A, Dowson D, Wright V. Cracking joints. *Ann Rheum Dis.* 1971;30(4):348-358.
3. Meal GM, Scott RA. Analysis of the joint crack by simultaneous recording of sound and tension. *J Manipulat Physiol Ther.* 1986;9(3):189-195.
4. Cramer GD, Gregerson DM, Knudsen JT, Hubbard BB, Ustas LM, Cantu JA. The effects of side-posture positioning and spinal adjusting on the lumbar Z joints: a randomized controlled trial with sixty-four subjects. *Spine (Phila Pa 1976).* 2002;27(22):2459-2466.
5. Gatterman MI. Foundations of Chiropractic: Subluxation. St. Louis, MO: Mosby-Year Book Inc.; 1995.
6. McCarthy CJ. Spinal manipulative thrust technique using combined movement theory. *Man Ther.* 2001;6(4):197-204.
7. Herzog W. The mechanical, neuromuscular, and physiologic effects produced by spinal manipulation. In: Herzog W, editor. *Clinical Biomechanics of Spinal Manipulation.* Philadelphia, PA: Churchill Livingstone; 2000. p. 191-207.
8. Hing WA, Reid DA, Monaghan M. Manipulation of the cervical spine. *Man Ther.* 2003;8(1):2-9.
9. Gibbons P, Tehan P. Manipulation of the Spine, Thorax and Pelvis. 1st ed. Edinburgh, UK: Churchill Livingstone; 2001.
10. Evans DW, Breen AC. A biomechanical model for mechanically efficient cavitation production during spinal manipulation: prethrust position and the neutral zone. *J Man Physiol Ther.* 2006;29(1):72-82.
11. Sandoz R. Some physical mechanisms and effects of spinal adjustments. *Ann Swiss Chiropract Assoc.* 1976;6:91-141.
12. Klein P, Broers C, Feipel V, et al. Global 3D head-trunk kinematics during cervical spine manipulation at different levels. *Clin Biomech.* 2003;18(9):827-831.
13. Ross JK, Bereznic DE, McGill SM. Determining cavitation location during lumbar and thoracic spinal manipulation: is spinal manipulation accurate and specific? *Spine (Phila Pa 1976).* 2004;29(13):1452-1457.
14. Reggars JW, Pollard HP. Analysis of zygapophyseal joint cracking during chiropractic manipulation. *J Manip Physiol Ther.* 1995;18(2):65-71.
15. Cramer G, Budgell B, Henderson C, Khalsa P, Pickar J. Basic science research related to chiropractic spinal adjusting: the state of the art and recommendations revisited. *J Manip Physiol Ther.* 2006;29(9):726-761.
16. Chao EYS. Biomechanics of the Hand. Singapore: World Scientific Publishing Co. Pte. Ltd.; 1989.
17. Minami A, An KN, Cooney III WP, Linscheid RL, Chao EY. Ligamentous structures of the metacarpophalangeal joint: A quantitative anatomic study. *J Orthop Res.* 1983;1(4):361-368.
18. Winkelstein BA, Nightingale RW, Richardson WJ, Myers BS. The cervical facet capsule and its role in whiplash injury: a biomechanical investigation. *Spine (Phila Pa 1976).* 2000;25(10):1238-1246.
19. Yoganandan N, Kumaresan S, Pintar FA. Geometric and mechanical properties of human cervical spine ligaments. *J Biomech Eng.* 2000;122(6):623-629.
20. Bergman TF, Peterson DH. Chiropractic Technique Principles and Procedures. 3rd ed. St. Louis, MO: Mosby, Elsevier; 2011.
21. Gibbons P, Tehan P. Manipulation of the Spine, Thorax and Pelvis. 2nd ed. Edinburgh, UK: Churchill Livingstone; 2007.
22. DiGiovanna EL, Schiowitz S, Dowling DJ. An Osteopathic Approach to Diagnosis and Treatment. 3rd ed. Philadelphia, PA: Lippincott Williams & Wilkins; 2005.

23. Kuchera WA, Kuchera ML. Osteopathic Principles in Practice. 2nd ed. Columbus, OH: Greyden Press – Original Works Books; 1991.
24. Haldeman S. Principles and Practice of Chiropractic. Norwalk, CT: Appleton & Lange; 1992.
25. Maitland GD. Vertebral Manipulation. 4th ed. London, UK: Butterworths; 1977.
26. Youm Y, Gillespie TE, Flatt AE, Sprague BL. Kinematic investigation of normal MCP joint. *J Biomech.* 1978;11(3): 109-118.
27. Zatsiorsky V. Kinematics of Human Motion. Champaign, IL: Human Kinetics; 1998.
28. Gad P. The anatomy of the volar parts of the capsules of the finger joints. *J Bone Joint Surg (Am).* 1967;49 B(2):362-367.
29. McFadden KD, Taylor JR. Axial rotation in the lumbar spine and gapping of the lumbar zygapophysial joints. *Spine (Phila Pa 1976).* 1990;15:295-299.
30. Giles L. Anatomical Basis of Low Back Pain. Baltimore, MD: Williams and Wilkins; 1989.
31. Bereznick DE, Ross JK, McGill SM. The frictional properties at the thoracic skin-fascia interface: implications in spine manipulation. *Clin Biomech (Bristol, Avon).* 2002;17(4):297-303.
32. Kawchuk GN, Perle SM. The relation between the application angle of spinal manipulative therapy (SMT) and resultant vertebral accelerations in an in situ porcine model. *Man Ther.* 2009;14(5):480-483.
33. Bogduk N, Mercer S. Biomechanics of the cervical spine. I: Normal kinematics. *Clin Biomech (Bristol, Avon).* 2000; 15(9):633-648.
34. Onan OA, Heggeness MH, Hipp JA. A motion analysis of the cervical facet joint. *Spine (Phila Pa 1976).* 1998;24(4): 430-439.
35. Kawchuk GN, Fryer J, Jaremko JL, Zeng H, Rowe L, Thompson R. Real-time visualization of joint cavitation. *PLoS One.* 2015;10(4):e0119470.
36. Chen YL, Kuhl T, Israelachvili J. Mechanism of cavitation damage in thin liquid films: collapse damage vs. inception damage. *Wear.* 1992;153:31-51.
37. Cramer GD, Ross K, Raju PK, et al. Quantification of cavitation and gapping of lumbar zygapophyseal joints during spinal manipulative therapy. *J Manip Physiol Ther.* 2012; 35(8):614-621.
38. Nordheim Y. Eine neue methode, den gelenkknorpel, besonders die kniegelenkmenisken, rontgenologisch darzustellen (ohne zuhilfenahme eingespritzten kontrastmittels). *Fortschr Rontgenstr.* 1938;57:479-495 [in German].