A BIOMECHANICAL MODEL FOR MECHANICALLY EFFICIENT CAVITATION PRODUCTION DURING SPINAL MANIPULATION: PRETHRUST POSITION AND THE NEUTRAL ZONE

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Spinal manipulative therapy (SMT) is the generic term commonly given to a group of manually applied therapeutic interventions.[1] These are usually applied with the aim of inducing intervertebral movement by directing forces to vertebrae.[2,3] There are various theories for mechanisms to how SMT translates into clinical effects, in particular, for the treatment of spinal pain,[4-8] making the selection of techniques difficult to explain or justify.

In statistical terms, the clinical outcomes of SMT for spinal pain are significantly greater than those of placebo or sham.[9-13] Consequently, notwithstanding the importance attached to the magnitude of these outcomes, some form of interface must exist between mechanical events that occur during the delivery of SMT and the clinical outcomes that result. At present, however, the exact location or even nature of this interface is as yet uncertain. Because the precise biomechanics involved in SMT are largely unknown, further exploration of this area would be valuable, if only to assist practitioners to better appreciate the mechanisms underlying their clinical observations and to justify their actions.[14-17]

Spinal manipulative therapy includes both "manipulation" and "mobilization" procedures. Until now, force-time histories measured during spinal manipulation have been described as consisting of 3 distinct phases: the "preload" (or "prethrust") phase, the "thrust phase," and the resolution phase[3] (Fig 1). Most of the force delivered during the prethrust and thrust phases is applied along the same line of action, perpendicular to the skin surface.[18,19] Therefore, a fourth "orientation" phase may be added to describe the period during which the patient is orientated into the appropriate position in preparation for the prethrust phase, as demonstrated in previous studies[20,21] (Fig 1). Forces applied during the orientation phase are likely variable but should gradually increase throughout the phase because restraining tissues provide increasing resistance to further departures from the resting neutral position.

Within the thrust phase of a manipulation, a (usually) high-velocity "thrust" (which, in this context, refers to a rapidly delivered additional force) delivers an impulse (the time integral of applied force, equal to the difference in momentum) to 1 or more "target" vertebra. This impulse is represented in Fig 1 by the area under the curve of the thrust phase, within the limits of ΔF. This impulse is understood to create a very small amplitude movement between the surfaces of a target zygapophyseal joint.[2] Hence, the given term *high-velocity, low-amplitude thrust* is derived from the mechanical characteristics commonly associated with the delivery of this intervention.

Manipulation is usually associated with an audible "pop," "click," or "crack," which is often viewed as signifying success in the technical delivery of the intervention,[15,19,20,22-32] although this has yet to be directly linked to clinical effects.[33] This cracking sound is caused by an event termed *cavitation*, occurring within the synovial fluid (SF) of the joint.[34] *Cavitation* is the term used to describe the formation and activity of bubbles (or cavities) within fluid, formed when tension is applied to the fluid as a result of a local reduction in pressure.[34-36] It can theoretically occur in any diarthrodial synovial joint in the body and is a consequence of certain types of motion between the articular surfaces.[34,37,38] Cavitation can occur during both high- and low-velocity joint motion.[39,40] As such, high-

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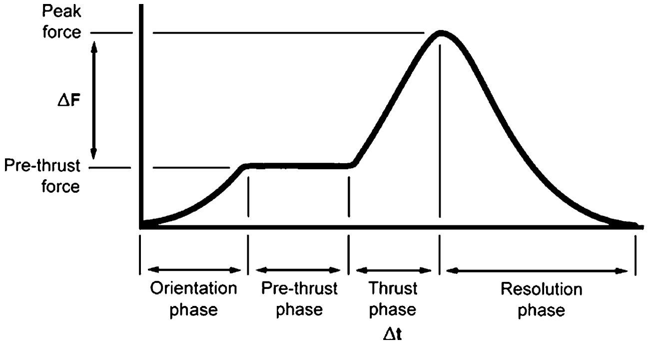

Fig 1. *Typical force-time history of the perpendicular force exerted by a clinician on a patient during spinal manipulation. Adapted from Herzog.*[25] *Copyright 2000, Elsevier Inc.*

velocity motion has to be considered an important yet not absolute requirement for the production of cavitation during spinal manipulation. Thus, it may be argued that cavitation is the only characteristic that truly distinguishes a manipulation from other SMT modalities.

By contrast, mobilization of the spine is associated with relatively slow loading rates, ranging from almost static loading to cyclical (oscillatory) loading rates as high as 5 to 6 Hz.[15] It is generally performed at less than 2 Hz[15]; causes very little, if any, intervertebral motion[41,42]; and does not produce cavitation (the only factor that truly distinguishes it from manipulation). In the case of higher frequencies (5 Hz), the amplitude of oscillation is probably quite small so that tissue strain rates are likely to be small compared with manipulation. In addition, mobilization is usually characterized by a large number of loading cycles and a much longer duration of loading than manipulation.[15] For clarity therefore, in the remainder of this article, the term *manipulation* will specifically refer to high-velocity, low-amplitude thrust manipulation (which, when successfully delivered, produces cavitation).

MECHANISMS OF ACTION

Various theories have been proposed to explain the clinical effects of spinal manipulation. Essentially, 4 main theories emerge from the published literature. These are (1) release of trapped intra-articular material such as synovial folds or meniscoids; (2) relaxation of "hypertonic" muscle by sudden stretching, the "mechanoreceptor-pain gate" or "reflexogenic" theory; (3) disruption of articular or periarticular adhesions; and (4) "unbuckling" of motion segments that have undergone "disproportionate displacements."[6] A recent critical review of these 4 main theories[4] argued that only one theory, namely, the release of trapped intra-articular material such as synovial folds or meniscoids, so far offers a plausible "mechanical" explanation for the measured clinical effects of spinal manipulation on spinal pain. It was also argued that, although cavitation seemed unlikely to be an absolute requirement for these intra-articular mechanical events to occur, it is at the very least an indicator of successful joint surface separation, which would be a requirement.[4] There is also evidence that zygapophyseal joint cavitation, the distinguishing characteristic of spinal manipulation, appears to be associated with certain physiological outcomes.[43,44] To invoke these physiological outcomes, it is therefore reasonable to argue that cavitation is necessary. Hence, it would be useful to have more precise information about biomechanical factors that will facilitate cavitation production. Although previous work has already provided useful biomechanical data for spinal manipulation,[3,15,25,45,46] most have not focused upon factors that facilitate cavitation. This article aims to explore some of these factors.

MANIPULATION KINEMATICS

Kinematics is the branch of mechanics that deals with motion (of an object) without reference to force or mass. With a few notable exceptions,[2,20,21,47-53] most biomechanical studies of spinal manipulation have given scant attention to kinematics. Hence, despite these novel efforts, accurate and complete kinematic data for vertebral movements during all phases of spinal manipulation throughout the spine are currently unavailable. Consideration of this area should reveal biomechanical factors that play an important role in cavitation production.

Joint kinematics are largely determined by the morphology of the bones and the anatomical restraints influencing the articulations that they form. During spinal manipulation, the clinician applies a force to the spine, tending to translate a target vertebra (all points of the bone moving in parallel paths and to the same extent), and a moment, tending to rotate the target vertebra relative to its adjacent neighbors. The rotational movements similar to those created by the muscles are known as *physiological movements*, whereas the translational movements that are not normally produced voluntarily are known as *accessory movements*.[15]

In any diarthrodial synovial joint, including the zygapophyseal joints, translations will produce different types of articular surface motion depending on the line of action of the applied force relative to the morphology of that particular joint. These translations are gliding (a parallel motion of one surface across another), distraction (the separation of articular surfaces in a direction perpendicular to the surfaces), and compression (the apposition of the 2 articular surfaces toward one another to create equal and opposite loading).

Joint movement can be further described in terms of dividing the resultant (total) movement into components of primary and coupled movements. In the spine, reference is usually made to the motion of an entire vertebra with one of its neighbors rather than to motion occurring at individual

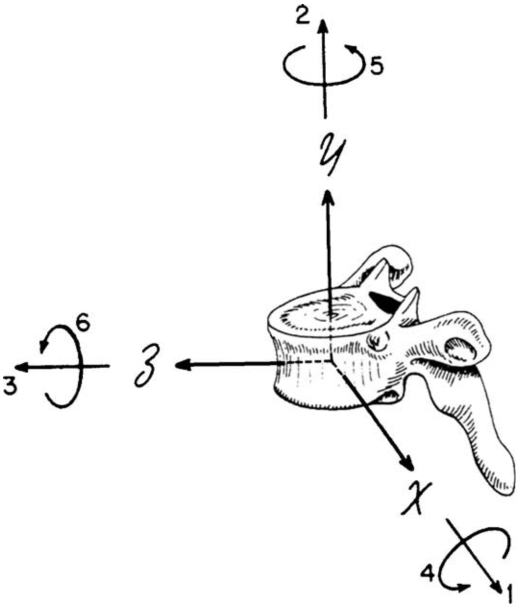

Fig 2. *Coordinate system located at the center of the vertebral body, showing the 6 possible movements in relation to the x-, y-, and z-axes. Reproduced from J Biomech 1976;9:185-92. Copyright 1976, Elsevier Science.*

zygapophyseal joints. Therefore, in terms of spinal manipulation, the primary movement can be viewed as motion of an entire target vertebra that occurs in the same plane as, or rotation about an axis perpendicular to, the line of action of the applied force delivered by the clinician. Vertebral movements that occur concomitantly with the primary movement but in directions other than that expected of the externally applied force are known as *coupled movements*.

Coupling of motion may be defined as the consistent association of rotation along or about an axis, with another translation or rotation along or about a second axis of a 3-dimensional orthogonal coordinate system.[54] Vertebrae have 6 degrees of freedom: rotation about and translation along transverse, sagittal, and longitudinal axes. Fig 2 illustrates the 6 possible movement components: translations in 3 directions (1, 2, 3; the directions of the x-, y-, and z-axes) and rotations in 3 directions (4, 5, 6; about lines parallel to these 3 axes). Hence, in addition to a primary movement, there are 5 possible coupled movement components (Fig 2).

The motion produced during flexion, extension, lateral flexion, and axial rotation between vertebrae is a complex combined motion resulting from simultaneous rotation and translation.[55] An externally applied force such as that delivered during spinal manipulation has the potential to produce various combinations of physiological and accessory vertebral movements. Furthermore, passively generated movements are likely to result in vertebral motion that differs from that which occurs during active physiological movements.[15,24] This is because physiological coupling can be constrained during the application of an external nonphysiological force.[56,57] As such, zygapophyseal articular surface motion, occurring as a result of an externally applied force, may also differ from that which occurs during active movements.

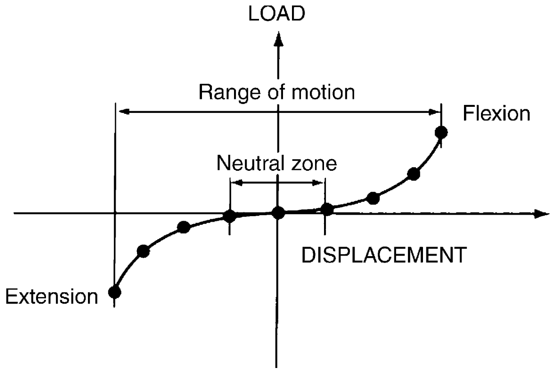

Fig 3. *Load-deformation behavior of the spinal segment (FSU) highlighting the region known as the neutral zone. Reproduced from Curr Orthop 1994;8:100-5. Copyright 1994, Elsevier Science.*

MANIPULATION KINETICS

Kinetics is the branch of mechanics that deals with motion (of an object) under the action of given forces. This includes static (equilibrium) states in which no movement is occurring and dynamic states in which forces may vary as movement occurs.

Most previous biomechanical analyses of spinal manipulation have been concerned with the forces and moments acting upon the bones that form the target joint. It is still not clear how the available kinetic data for spinal manipulation (as summarized in Fig 1) are representative of the forces that actually arrive at the target vertebra. Motion of the target vertebra will be heavily influenced by the morphologies of the intervertebral joints and the restraints offered by the connecting tissues. Indeed, several studies suggest that a substantial proportion of the kinetic energy transferred to the patient is likely to be used on the deformation of both superficial and restraining tissues.[41,42,58] As such, it may be valid to discuss the production of cavitation in terms of the mechanical efficiency of manipulation delivery.

FUNCTIONAL SPINAL UNITS

The bodies of 2 adjacent vertebrae with their strong and intimate connections, including their interconnecting ligaments, the intervertebral disc, and the zygapophyseal joints, form individual fundamental segmental units throughout the spine. Each of these fundamental units is known as a *functional spinal unit* (FSU). An *FSU* is defined as the smallest segment of the spine to exhibit biomechanical characteristics similar to those of the entire spine.[54]

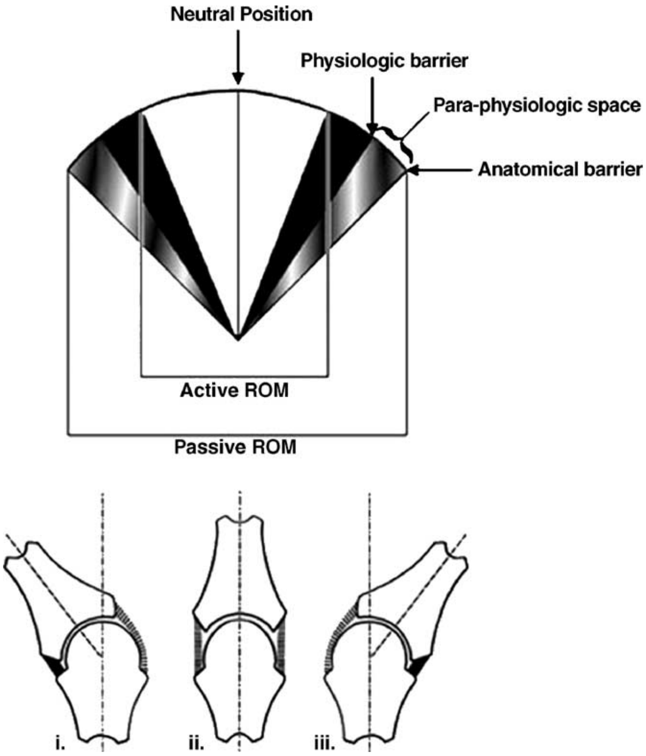

Fig 4. *Schematic representation of the prevailing model of target joint motion during manipulation. The simple anatomy of the MCP joint is used to illustrate the arcuate motion predicted by the model. To preserve the symmetry of the model, frontal plane rotation (abduction-adduction) of the MCP joint is considered. The model predicts that the applied force creates a moment and subsequent rotation of the proximal phalanx in a single movement plane, about a stationary center on the metacarpal bone. During the prethrust phase, the joint rotates to the end of available passive movement until it reaches a "physiological barrier," provided by the viscoelastic SF. During the thrust phase, more force is applied, which if sufficient produces cavitation and "breaks" the physiologic barrier. The corresponding configurations of the MCP joint when at the ends of the range of motion (i and iii) and in the neutral position (ii) are displayed beneath.*

The typical load-displacement behavior of a cadaveric FSU specimen is illustrated in Fig 3. Within the total range of passive motion of any FSU, the typical nonlinear load-displacement curve consists of 2 regions or "zones" that exhibit very different biomechanical behavior.

In the vicinity of the resting neutral position of the FSU, this load-displacement behavior is highly flexible. This is the region known as the *neutral zone*,[59] which may be defined as the motion region of the joint where the passive osteoligamentous stability mechanisms exert little or no influence. During passive physiological movement of the FSU, motion occurs in this region against minimal internal resistance. It is a region in which a small load causes a relatively large displacement. Certainly in the lumbar spine, exactly where the neutral zone motion region is situated (within the total range of motion of an FSU) is largely determined by the zygapophyseal joints.[60] As such, the initial orientation of the zygapophyseal joints at the outset of a movement will have a significant effect on ensuing motion of the FSU.[53,61-64] The "elastic zone" is the remaining region of FSU motion that continues from the end of the neutral zone to the point of maximum resistance (provided by the passive osteoligamentous stability mechanism), thus limiting the range of motion.

Manipulation "Prethrust Position"

As evident in Fig 1, previous kinetic data for spinal manipulation consistently demonstrate a preload force, a relatively constant force that may be applied for several seconds before the thrust phase.[3,18,19,52,65-67] This phase may be more accurately described as the prethrust phase, given that it too involves significant applied force. Similarly, the position achieved at the end of the prethrust phase, upon which the additional thrust impulse will be delivered, may be described as the prethrust position.

The prevailing kinematic model of motion for both the target FSU and target zygapophyseal joint during spinal manipulation[68-70] is based entirely on observations of cavitation produced during distraction of metacarpophalangeal (MCP) joints.[34,71] As a result, this model has limited validity for predicting spinal motion. These studies undoubtedly provide insight into cavitation occurring in zygapophyseal joints. However, care is needed when transferring a model of motion based on a simple joint such as the MCP to a much more complex articular arrangement such as an FSU and its constituent zygapophyseal joints. Although the articulations at a MCP joint and an FSU each involve motion between 2 bones, motion at a MCP joint demands consideration of only one independent synovial joint. It therefore differs markedly from the 3-joint complex of an FSU (the so-called articular triad). Indeed, it was the simple anatomy and accessibility of the MCP joint that lent itself to the early studies of synovial joint cavitation,[34,71] which were not designed to provide models for spinal manipulation. Even so, the prevailing kinematic model fails to make a distinction between kinematics of the target FSU and those of the individual target zygapophyseal joint. The apparent confusion that this has created can be seen in the inconsistency of descriptions and supposed definitions of spinal manipulation throughout the literature.[9,28,72,73]

During spinal manipulation, there is usually a designated target zygapophyseal joint (within the target FSU), in which cavitation is desired.[31] The intent of the clinician is to efficiently deliver a suitable proportion of the thrust impulse to this target joint.[74] As such, when discussing the production of cavitation, kinematics of the target joint must be clearly distinguished from those of the target FSU. Because we are specifically interested in the cavitation event, we will be primarily concerned with kinematics of the target joint for the remainder of this article.

The modern graphical conceptualization of the prevailing kinematic model of manipulation is 2-dimensional and is represented by the area covered by one of the bones of a simple diarthrodial synovial joint as it travels through its entire range of physiological rotation, which is symmetrical and thus idealized (Fig 4).[69] Here, another fundamental problem arises with the model in that inferences made from observations of an accessory movement (distraction) in a joint have been applied to describe a physiological movement (pure rotation about a fixed axis).

As may be seen in Fig 4, the prevailing kinematic model describes the ideal prethrust position of a target joint as being located at the limit of the joint's passive range of motion in a single plane of motion, far into the elastic zone. If this model is used to predict the distribution of the often substantial force applied during the thrust phase,[65,66] most would be seen to pass directly to the restraining tissues surrounding the target zygapophyseal joint. If this occurred, these tissues could easily be damaged.[75-77] Rather conveniently, a concept known as the *physiologic barrier*, which has evolved to account for the resistance provided by SF cohesion as described in studies of MCP joint distraction,[34,71,78] is said to dissipate (in the form of SF cavitation) much of the force that reaches the target joint before it is able to reach the anatomical restraining tissues. The remaining portion of the elastic zone, beyond the physiologic barrier, is generally known as the *paraphysiologic space* (Fig 4).

Some studies suggest that much of the substantial force applied during the thrust phase is unlikely to be transmitted directly to anatomical tissues surrounding the target joint.[58,79,80] In addition, the contact forces applied during the orientation and prethrust phases have 3-dimensional components[19] and create FSU motion in multiple planes,[3,20,21,51] indicating that the prevailing 2-dimensional kinematic model is in need of some revision. In recent years, some attempts have been made at revising this model, acknowledging the likely importance of complex combined FSU movements during the orientation and prethrust phases,[24,81] and problems encountered when transferring the model to clinical scenarios.[82] However, such attempts have so far fallen short of providing a comprehensive revision that is entirely consistent with available empirical data.

Assuming cavitation to be the mechanical goal of manipulation, the target joint must be placed in a prethrust position that facilitates efficient delivery of kinetic energy from the thrust impulse to the SF so that tension is applied to the fluid. For maximum mechanical efficiency, this must occur in a position that results in the minimum loss of kinetic energy (from the thrust impulse) to the surrounding tissues. In biomechanical terms, the motion region of the target joint that most suitably fulfills these requirements is the neutral zone (as defined previously). Therefore, for the safe and efficient delivery of the thrust impulse to the SF, the ideal prethrust position will be equivalent to the neutral zone of the target joint. This argument can be applied to any diarthrodial synovial joint in the body, including, of course, an individual zygapophyseal joint.

Importance of Neutral Zone in Prethrust Position

Conventionally, use of the term *neutral zone* in relation to the spine has been reserved for the description of the motion behavior of 1 or more complete FSU[57,59,83,84] (Fig 3). Even so, it may be argued that, within any individual FSU, each of its 2 constituent zygapophyseal joints will possess an independent motion region where the passive osteoligamentous stability mechanisms (of that individual joint) exert little or no influence. Certainly, the low restraint offered by zygapophyseal joint capsules[85,86] would lend support to this argument, on the condition that the FSU was orientated in such a way as to allow the target joint to exploit such freedom of motion,[2] a concept possibly overlooked in previous investigations.[87]

The neutral zone of an FSU surrounds the resting neutral position of that FSU. There is a degree of preexisting tension that naturally exists in spinal ligaments and tissues surrounding the zygapophyseal joints, even when in this resting neutral position.[88] In this neutral configuration, a perfectly formed FSU possesses reflectional (mirror image) symmetry about the sagittal plane, which divides the body into right and left halves. Indeed, this is the only form of symmetry that the FSU possesses. In this configuration, preexisting tension is uniformly distributed between the 2 constituent zygapophyseal joints, which offer equal restraint to motion. Only motion in the sagittal plane (rotation or translation) will retain this FSU symmetry. Motion in any other plane (such as axial rotation or lateral flexion) will create a departure from symmetry and a consequent nonuniform distribution of tension throughout the FSU, which will undoubtedly influence the restraint offered by each of the 2 zygapophyseal joints. The restraint offered in any one of these joints may increase or decrease, depending on the precise orientation of the FSU. Consequently, the orientation of a given FSU when in its position of overall restraint equilibrium (FSU neutral zone) may differ from its orientation when any one of its constituent zygapophyseal joints is positioned to encounter minimal restraint (target joint neutral zone). It is therefore likely that FSU motion outside the sagittal plane would be required to decrease the restraint offered by any one particular zygapophyseal joint so that it tends toward its neutral zone motion region.

Theoretically, only from within the neutral zone of the target joint may tension be applied to the viscoelastic SF of that joint with minimal resistance from anatomical tissues. If the prethrust position is optimal, the additional force delivered during the thrust phase with the FSU in this position will travel through the path of least possible resistance and arrive at the target joint. Motion is likely to occur between the target joint surfaces in the form of a distraction or gliding translation or a combination of both,[2,38] ultimately transferring kinetic energy to the SF. If this kinetic energy is sufficient, cavitation will ensue.[37]

A New Model

To follow convention, the simple anatomy of the MCP joint can be used to illustrate this concept for a new general model of manipulation (Fig 5). In every study to have studied cavitation in MCP joints, cavitation was achieved by distraction translation in the neutral position (which, in the MCP joint, is the midpoint of the neutral zone). Therefore, just as with the original model (Fig 4), care must be taken when using data from MCP joint motion to predict spinal motion. In particular, when transferring this model to a zygapophyseal joint, restraint provided by all components of the target FSU must be recognized. Furthermore, although, like the original model, this model is represented in Fig 5 by a 2-dimensional motion diagram along a single plane, the concept is actually 3-dimensional in that achieving the neutral zone in every plane would provide the optimal (most efficient) prethrust position.

The further the target joint is positioned from its neutral zone (ie, into its elastic zone), the greater will be the force required, during the thrust phase, in overcoming the resistance provided by the surrounding tissues to achieve cavitation. Thus, cavitation will be more efficiently produced when the target joint is distracted within the neutral zone motion region. In the spine, although spinal manipulation is likely to create strain in the capsules of target zygapophyseal joints that is within physiological parameters, this may account for the observation of larger peak manipulation forces during manipulation regarded by clinicians as "satisfactory" (by way of producing cavitation), yet which possess largely identical kinematic characteristics to those that did not.[52]

What is occurring with the paraphysiologic space? If any extra motion becomes available to the target joint after cavitation occurs, as a result of reduced resistance offered by SF, then it is likely only to be available perpendicular to the joint surface, allowing joint gapping against less resistance[2,34,37,39,71] (Fig 5). The available extra range of motion provided in this paraphysiologic space will then be limited only by the joint's anatomical restraining tissues.

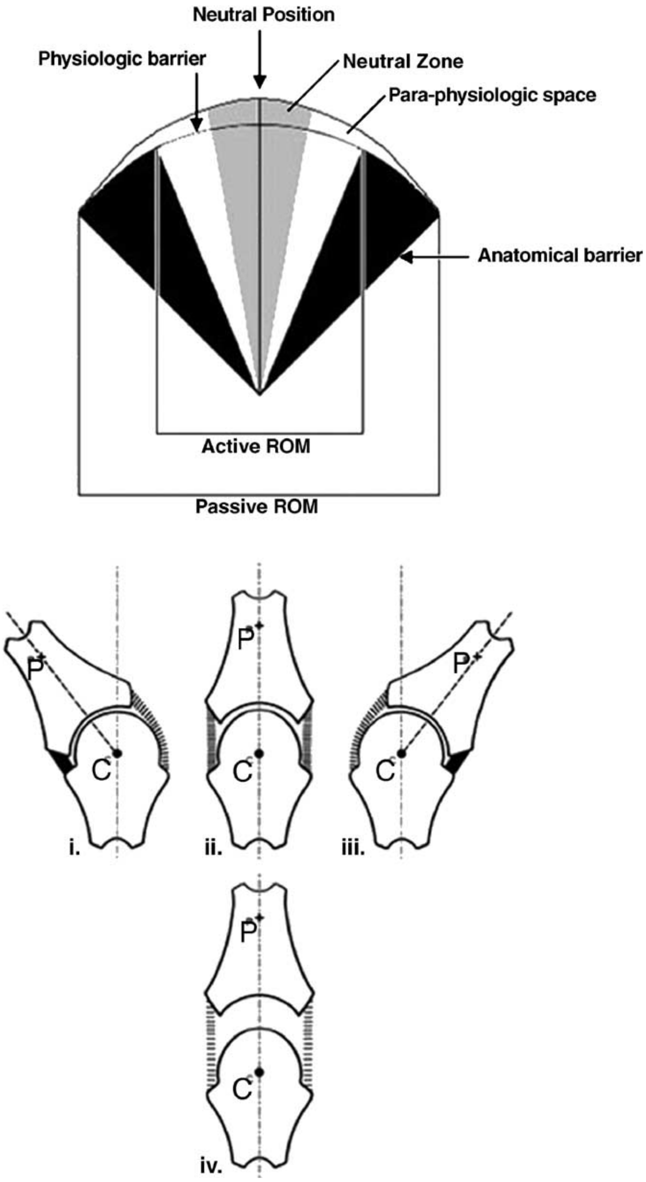

Fig 5. *Schematic representation of cavitation in a synovial joint produced by joint gapping. Frontal plane rotation (abduction-adduction) of the MCP joint is used to illustrate the model. Rotation occurs about a stationary center (C) on the metacarpal bone and point P is a constant location on the proximal phalanx that describes the motion of the joint. Configurations i and iii represent the joint when at the ends of the available range of motion and ii represents the resting, neutral position. In this model, the most efficient prethrust position to facilitate joint gapping is within the neutral zone region, because the comparative laxity of the joints restraining tissues allows the articular surfaces to separate with minimal loss of kinetic energy (iv). Once cavitation occurs, the available extra range of motion provided in the para-physiologic space will be perpendicular to the articular surfaces and limited only by the joints restraining tissues.*

Zygapophyseal joint gapping has been confirmed during manipulation of the spine.[2] For the surfaces of any zygapophyseal joint to separate, the motion of the FSU to which it belongs must depart from normal coupling, which is determined by joint morphology and restraining tissues. The motion of the target FSU that occurs during spinal manipulation must therefore be nonphysiological. Thus, considerable external force is required if the motion of the FSU is to deviate from normal coupling. A significant proportion of the force applied during the orientation phase will be used to overcome the restraint offered by the target FSU and constrain coupled movements that would normally occur. The almost constant force applied during the prethrust phase produces little additional motion and will therefore be primarily used to maintain this FSU orientation. In the case of "long-lever" manipulations, orientating the entire target FSU around the target joint neutral zone position (and sustaining this orientation) will require considerable forces because resistance will be simultaneously provided by several body segments such as the head, thorax, abdomen, pelvis, and extremities.[20,21,53]

Manipulation Accuracy and Specificity

In the context of spinal manipulation, accuracy is achieved when cavitation occurs in the designated target zygapophyseal joint, regardless of whether it also occurs in any other joint(s). On the other hand, specificity is achieved when cavitation does not occur in any joint other than the target joint. Research has shown that accuracy is generally achieved at the cost of specificity.[31]

The resistance offered by tissues of the target joint in the optimal prethrust position should, by definition, be minimal. From this, the thrust impulse will provide the SF with the additional kinetic energy required to produce cavitation.[37] Therefore, if cavitation is intended to be specific to a single target zygapophyseal joint, the target joint would need to be alone in being within its neutral zone motion region. This would apply to all other zygapophyseal joints, including the contralateral joint within the target FSU.

Without obvious exception, all spinal manipulation procedures appear to entail some degree of motion outside the sagittal plane during orientation and prethrust phases, regardless of anatomical level.[2,20,21,47-53] Thus, the distribution of restraint and force transmission between the 2 zygapophyseal joints within a target FSU are intentionally altered during these phases by orientating the FSU further from its resting, neutral, symmetrical configuration.

According to previous authors, motion in joints of neighboring FSUs may be reduced by applying a "short-lever" manipulation toward a target vertebra.[31] In the case of long-lever manipulations, whereby the applied force is delivered to the target FSU through its contiguous neighbors, specificity may be increased during the orientation and prethrust phases by way of approximating articular surfaces of neighboring zygapophyseal joints in such a way as to effectively "lock" their FSU and permit force transmission between joint surfaces[24,89] or by confining them to their elastic zone regions to "saturate the capacity of local damping factors."[45] Failure to do so may mean that the ensuing thrust impulse will be dissipated throughout multiple FSUs and thus be less specific.[31,90]

Without orientation and prethrust phases, the spine would be allowed to freely oscillate during the thrust phase, with its behavior being largely a function of its own resonant frequency and the "thrust-rise time" (Δt in Fig 1).[17,91-93] From this, we may deduce that the prethrust position effectively creates a damping effect, which limits the extent to which force is transmitted to the entire spine during the thrust phase. In doing so, the orientation and prethrust phases increase the likelihood of both accuracy and specificity of joint surface motion at the target zygapophyseal joint. Consequently, it obviates the need for a very high–velocity thrust impulse (short thrust-rise time), as predicted by Solinger[93] for a specific spinal manipulation with no distinct prethrust phase or influence of coupling.

Importantly, these prethrust forces are not unique to short-lever manipulations, in which manipulation forces are applied directly over the target FSU. They also appear during long-lever manipulations, in which forces are applied via limbs and through partial or entire body segments.[3] This damping effect is thus unlikely to be the result of local compression of paraspinal soft tissues from direct contact pressure[41,42] or effects of direct compression on the low-friction skin-fascia interface[94] but the upshot of an optimal prethrust position, produced by the skilful application of forces during the orientation and prethrust phases, that acts to form a path of least resistance for the ensuing thrust impulse.

Clinical Relevance

The existing theories for the mechanisms of action of spinal manipulation[6] and the rationale for its use[14] have been based on the prevailing kinematic model, which continues to inform contemporary opinion and even policy.[9,72,73,82] However, it is hoped that this new model will inform further explanatory work on the production of cavitation during spinal manipulation. In particular, further kinematic investigation should yield valuable information, which is likely to be of clinical relevance. If this model is ultimately verified by empirical research, future definitions of manipulation that give reference to biomechanical characteristics of the intervention should be modified accordingly.

This proposed revision of the conceptual and kinematic model of manipulation is unlikely to have profound impact on the everyday technical delivery of particular spinal manipulation procedures because anecdotal evidence suggests that cavitation is already commonly achieved during current clinical practice. The presented model and the identification of characteristics that potentially facilitate the cavitation event are simply intended to bring explanations of clinical effects and empirical research into closer accord. Nonetheless, the model proposed may offer a starting point for clinicians and researchers alike to develop more mechanically efficient manipulative approaches and techniques.

The presence of pain in the spine has been shown to produce abnormal kinematic behavior,[95-97] which in turn may influence or even limit movements that result from externally applied forces such as those applied during the various phases of spinal manipulation. With the ideal prethrust position described as being equivalent to the neutral zone of the target joint, it is no longer a function of the total range of motion of that joint. Essentially, the location of the neutral zone should be the same for joints with a normal range of motion as with joints with an increased range of motion (hypermobility) or a decreased range of motion (hypomobility). This circumvents some problems identified with the previous model.[82] Previously injured FSUs and peripheral joints are known to be associated with less passive restraint and have been characterized by proportionally larger neutral zones.[59,98,99] If the passive retraining tissues of a particular target joint are influenced in this way, it may explain why cavitation is more easily achieved in some joints than others[100] because the probability of that joint being in its neutral zone region at any particular time will be greater. This may also explain why habitual “knuckle crackers” seem to have lax joints, in which cavitation may be more readily achieved. The opposite may be true (smaller neutral zone) for joints in which cavitation cannot be achieved.

Finally, if cavitation is judged to be the mechanical goal of a manipulation, then maximal mechanoreceptor stimulation will indicate a less mechanically efficient impulse delivery. When the target joint is moved into the elastic zone motion region, there is likely to be increased tissue resistance (to the thrust impulse), which will result in increased high-threshold mechanoreceptor stimulation. Mechanoreceptor stimulation has often been suggested as the most likely route through which spinal manipulation provides clinical effects.[25,27,69,101-111] The mechanoreceptor-pain gate theory thus seems to be mutually exclusive from the notion that cavitation is the goal of manipulation. However, future research is needed to investigate whether either of these factors constitutes the interface between the biomechanics of spinal manipulation and the clinical outcomes that result.

Conclusions

Biomechanical factors that facilitate mechanically efficient cavitation production during manipulation have been explored, and a revision of the conceptual and kinematic model has been proposed. Central to this model, mechanically efficient cavitation production during manipulation requires a prethrust position, in which the target joint is ideally positioned into its own neutral zone motion region, thus maximizing the efficiency of the manipulation. Future research is needed to test this model.

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