

Assessment of Lumbar Spine Kinematics Using Dynamic MRI: A Proposed Mechanism of Sagittal Plane Motion Induced by Manual Posterior-to-Anterior Mobilization

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Study Design: Descriptive study.

Objective: The purpose of this study was to describe the segmental motion of the lumbar spine during a posterior-to-anterior (PA) mobilization procedure using dynamic magnetic resonance imaging and to propose a mechanism of the lumbar spine's motion as a result of a PA force to a lumbar spinous process.

Background: Studies reporting kinematic descriptions of PA mobilization are in agreement that motion takes place at all lumbar vertebrae. However, these studies differ in the reported direction of motion.

Methods and Measures: Twenty asymptomatic subjects (mean age \pm SD, 31.1 \pm 7.0 years) participated in this study. For each subject, a PA mobilization force was manually applied at each lumbar spinous process while sagittal plane magnetic resonance images were simultaneously obtained. Intervertebral motion was defined as the change in the intervertebral angle between the resting and end range vertebral positions imparted by the PA pressure.

Results: PA force applied at 1 spinous process caused motion at the target vertebra and this motion was propagated caudally and cranially. Motion at the target segment was always into extension.

Conclusions: A PA force applied at a single lumbar spinous process caused motion of the entire lumbar region. The magnitude and direction of intervertebral motions varied with the segment at which the PA force was applied. We postulated that the intervertebral motion induced by a PA force on a spinous process could be in part explained by the morphology of the lumbar spine. *J Orthop Sports Phys Ther* 2004;34:57-64.

Key Words: lumbar segmental mobility, lumbar zygapophyseal joints, manual therapy, spine mobilization

The use of passive intervertebral mobilization has been advocated as a method for assessing spinal stiffness as well as for treating spinal disorders.^{1,2,4,10,12,16} Posterior-to-anterior (PA) mobilization is frequently employed to assess spinal mobility, and involves applying a force to a single vertebral spinous process with the individual lying in the prone position. This technique evaluates passive segmental mobility, which is an indirect reflection of the integrity of periarticular structures (ie, disc, capsule, and ligaments). Even though this and other manual therapy methods have been used with varying levels of success to reduce pain and improve mobility,^{1,2,7,9,13,15,16} it is unclear how this particular manual technique influences intervertebral motion of the lumbar spine.

Recently, it has been suggested that a sustained PA mobilization results in linear PA displacement of the corresponding vertebra and only minimal sagittal plane rotation of the lumbar segments.⁸ Keller and colleagues⁸ used a 15-

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FIGURE 1. Subject and examiner positioned within the magnetic resonance imaging system. Each subject was situated such that the spine and torso were within the opening between the vertical magnets. The examiner is shown applying a posterior-to-anterior force to the subject's lumbar spinous process during imaging.

segment model to mathematically explore the impact of applying a static PA force to the L3 vertebra. The model included the thorax, pelvis, 5 lumbar vertebrae, and 8 flexible joint structures. The model predicted that a static PA force (100 N) applied to the L3 vertebra would result in extension at L3-L4 (1.4°) and flexion at the L1-L2 and L2-L3 segments, while the peak arc of motion in extension would occur caudally at the L5-S1 segment. Using static radiographic technology while mechanically applying a PA force at L4 in healthy male subjects, Lee and Evans¹¹ measured less extension at the L3-L4 and L4-L5 segments (1.2°) and more extension at the L2-L3 segment (2.4°), 2 segments cranial to the force application (target vertebra).¹¹ The similarity between the predicted kinematics by Keller et al⁸ and the measured kinematics of Lee and Evans¹¹ was that

force applied at 1 spinous process influenced motion at the targeted and adjacent segments. The difference between these 2 studies was that the direction of motion between the nontargeted vertebrae was reversed.

The data by Keller et al⁸ and Lee and Evans¹¹ are surprising in light of these authors' comments suggesting that 3-point bending (a single force applied on 1 side of a beam and 2 counteracting forces on the other side acting in the opposite direction) governs the PA mobilization maneuver. If this were correct, the greatest amount of motion should have occurred at the targeted motion segment with less motion at adjacent segments. This was not the case in the studies by Keller et al⁸ and Lee and Evans.¹¹ One possible explanation for this discrepancy was that spine kinematics in these 2 studies were not evaluated dynamically during the PA procedure, and that the force was applied perpendicular to the supporting surface as opposed to perpendicular to the targeted lumbar vertebra.

A better understanding of in vivo responses to a PA force applied to the lumbar spine can now be achieved by using emerging imaging technology. A recently published feasibility study has provided assurance that this clinical technique can be studied quantitatively using dynamic magnetic resonance imaging (MRI).¹⁴ The purpose of the current study was, therefore, to describe the segmental motion of the lumbar spine during a PA mobilization procedure using dynamic imaging techniques and to propose a mechanism of the lumbar spine's motion as a result of a PA force to a lumbar spinous process. We postulated that the unique structure of the lumbar spine would dictate the intervertebral responses to a PA force on a single spinous process.

MATERIALS AND METHODS

Subjects

Twenty healthy individuals (12 male, 8 female) between the ages of 22 and 43 years, with no history of back pain lasting more than 3 days, participated in this study (Table 1). Based on a self-report questionnaire, subjects were excluded from participation if they reported any of the following: (1) spinal malignancy, (2) cardiovascular disease, (3) evidence of spinal cord compression, (4) aortic aneurysm, (5) hiatal hernia, (6) uncontrolled hypertension, (7) spinal infection, (8) severe respiratory disease, (9) pregnancy, (10) abdominal hernia, (11) prior low back surgery, (12) gross spinal deformity, (13) spondylolisthesis, (14) rheumatic joint disease, and (15) implanted biological devices that could interact with the magnetic field (ie, pacemakers, cochlear implants, or ferromagnetic cerebral aneurysm clips). In addition to the above exclusion criteria, subjects

TABLE 1. Anthropometric sex and age characteristic of subjects participating in this study. Data are means \pm SD.

	Male (n = 12)	Female (n = 8)
Age (y)	30.9 \pm 6.4	31.3 \pm 7.6
Body mass (kg)	82.2 \pm 13.6	57.0 \pm 5.5
Body height (cm)	177.5 \pm 8.2	167.3 \pm 4.8

could not have any current pain in the lumbar region or signs or symptoms related to lumbar disc pathology. Therefore, subjects who demonstrated any of the following also were excluded: (1) low back pain or radiating pain below the level of the buttock(s), (2) sensation changes in the lower extremities, (3) diminished reflexes, (4) lower-extremity weakness, (5) urinary or fecal incontinence, and (6) increased peripheral pain with repeated lumbar motions.

Prior to participation all subjects signed an informed consent form approved by The Institutional Review Boards of the University of Southern California and Stanford University.

Instrumentation

Dynamic imaging of the lumbar spine was performed using a vertical (double-donut design) 0.5 Tesla, Signa SP MRI system (General Electric Medical Systems, Milwaukee, WI) with a 56-cm opening that allowed the examiner access to the subject during testing. This system was equipped with a pulse sequence programming environment and real-time interactive MRI capability.

Sagittal-plane imaging of the spine was performed using a receive-only surface coil and an ultrafast spoiled GRASS (gradient recalled acquisition in the steady state) pulse sequence. Images were obtained at a rate of 1 per second using the following parameters: repetition time (TR), 200 milliseconds; echo time (TE), 18 milliseconds; number of excitations, 1.0; matrix, 256 \times 256; field of view (FOV), 28 \times 21 cm; and a 7-mm section thickness with an interslice spacing of 1 mm. Image resolution was 1.37 \times 2.73 mm. The surface coil was flexible and designed such that the examiner could directly palpate the lumbar spinous processes.

Procedure

Subjects were placed in the prone position on a sliding table within the MRI system, such that the spine and torso were within the opening between the vertical magnets (Figure 1). The surface coil was secured to the lumbar region using cloth tape. A small pillow was positioned under the subject's abdomen to avoid end range lumbar extension, thereby mimicking the clinical procedure.

Following subject positioning within the MRI system, a series of sagittal plane "localizers" were obtained to ensure that the image plane captured the vertebral bodies and spinous processes of all lumbar vertebrae. Once the image plane was determined, continuous imaging (at a frequency of 1 Hz) began with a static sagittal view of the lumbar spine in the resting position. This was followed by manual application of a PA force through the spinous process of L5, L4, L3, L2, and L1, in that sequence.

The examiner was standing during the force application. The wrist of the contact hand was positioned in extension and radial deviation. An area of the hand just distal to the pisiform contacted the lumbar spinous process of the subject. To reinforce the symmetrical application of force, the heel of the other hand was placed on the radial side of the carpal bones of the contact hand. The PA force was directed perpendicular to the curve of the lumbar lordosis, because spinal responses have been shown to be altered by the direction of force application.³ The force applied was aimed at reaching the end range of segmental motion and was guided by the examiner's perception of end feel, as comparable in magnitude to that of a grade IV mobilization technique as defined by Maitland.¹²

Each subject was instructed to breathe slowly and rhythmically. The examiner attempted to synchronize the force application with the subject's breathing pattern; that is, the application of force occurred at the transition from inhalation to exhalation, with the goal of reaching end range at the time of full exhalation. The force was applied slowly (approximately 1-2 seconds) and held at end range for at least 5 seconds. Release of the force also occurred slowly (1-2 seconds) before moving to the next vertebral level. Forces were applied at each segment starting caudally at L5 and moving cranially to L1. Therefore, only 1 trial was performed at each level. Once the investigator released the force on L1 and a clear resting position was observed, imaging was terminated.

All PA mobilizations were performed by a physical therapist with 15 years of manual therapy experience. A second investigator viewed the images on the MRI console to assure that the forces were applied to the correct vertebral level. If an error was observed, imaging was repeated.

Data Analysis

Prior to analysis, all images were transferred from the MRI system console to a Macintosh G3 computer (Apple Computer, Cupertino, CA). All electronic data files were assigned a numerical subject code prior to their transfer into the data processing computer. For purposes of this study, only the images of the vertebral segments at rest and at the end range of

segmental motion were analyzed. Sagittal plane intervertebral angles were measured using National Institutes of Health Image software (National Institutes of Health, Bethesda, MD). The intervertebral angle was defined as the angle formed by lines delineating adjacent vertebral endplates (Figure 2). Segmental lumbar motion was defined as the difference between the intervertebral angles measured from the resting and the end range images.¹⁴ An increase in intervertebral angle from the resting to the end range positions was indicative of segmental extension (Figure 2). Conversely, a decrease in the intervertebral angle was indicative of segmental flexion. The superior vertebra was used to define the target segment (ie, between the vertebra to which the PA force was applied and the vertebra immediately caudal to it). For example, the target segment for PA force applied to L4 was L4-L5. Each lumbar segment angular measurement was repeated 3 times and the average measurement was used for statistical analysis.

A single investigator performed all measurements. To establish the intratester reliability of the angle measurements, segmental mobility (as determined from resting and end range images from 5 subjects) was quantified 3 times on 2 separate days. The average of angular displacement value from each evaluation session was used for reliability calculations. Intraclass correlation coefficients (ICC_{3,3}) were found to be excellent, ranging from 0.95 to 0.99. The SEM ranged between 0.40° to 0.66°.

RESULTS

The motion at the target segment was always directed towards extension (Figure 3). In addition to motion at the targeted segment, motion at the

nontargeted lumbar segments was also observed (Figure 3). For example, a PA force applied at the L5 spinous process caused segment-specific (L5-S1) extension (mean ± SD, 3.6° ± 1.1°) as well as extension at all lumbar segments cranial to L5-S1 (Figure 3A). Secondary extension motion decreased gradually from the neighboring segment L4-L5 (mean ± SD, 1.9° ± 0.8°) to the most distant segment L1-L2 (mean ± SD, 1.0° ± 0.7°). This pattern of mean motion was consistent for PA forces applied to the L4 and L3 spinous processes (Figure 3B and 3C). When looking at individual subjects, all subjects demonstrated extension at all lumbar segments during the PA force application at L4 and L5. When the PA force was applied at L3, all subjects demonstrated segmental extension at L3-L4, L2-L3, and L1-L2; while 17 of the 20 subjects extended at L4-L5 and L5-S1 (3 subjects demonstrated a flexion motion at these 2 levels).

A different pattern of intervertebral motion was observed when force was applied at L1 and L2 spinous processes. On average, a PA force applied at L2 resulted in segment-specific (L2-L3) extension (mean ± SD, 3.8° ± 1.5°). The mean (±SD) pattern of secondary motions was such that the immediately adjacent segments (L1-L2 and L3-L4) moved in the same direction (2.5° ± 1.2° and 1.6° ± 1.6° of extension, respectively) while flexion was observed at L4-L5 and L5-S1 segments (mean ± SD, 0.1° ± 1.1° and 1.4° ± 1.6°, respectively) (Figure 3D). With respect to the individual motion pattern when the PA force was applied at L2, all subjects demonstrated segmental extension at L1-L2, L2-L3, and L3-L4. However, 7 subjects did not move or extended (as opposed to flex) at L4-L5, and 4 did not move or extended (as opposed to flex) at L5-S1.

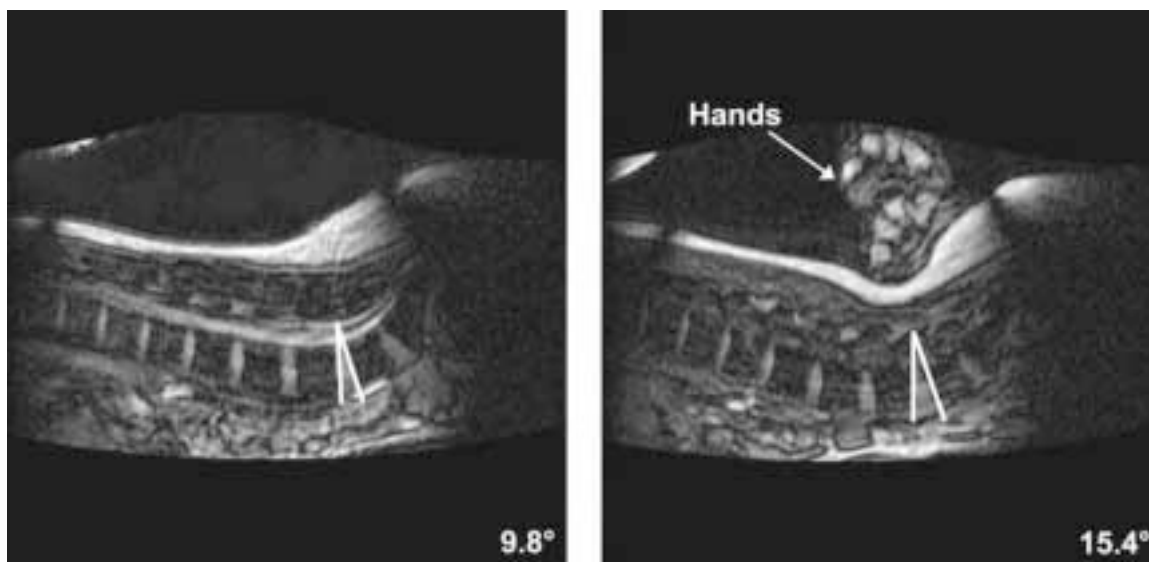


FIGURE 2. The intervertebral angle was measured as the angle formed by lines defining the end plates of adjacent vertebrae. Segmental lumbar motion was defined as the difference in the intervertebral angle between the resting position (left) and intervertebral angle from the end range image (right). The arrow identifies the hands of the examiner.

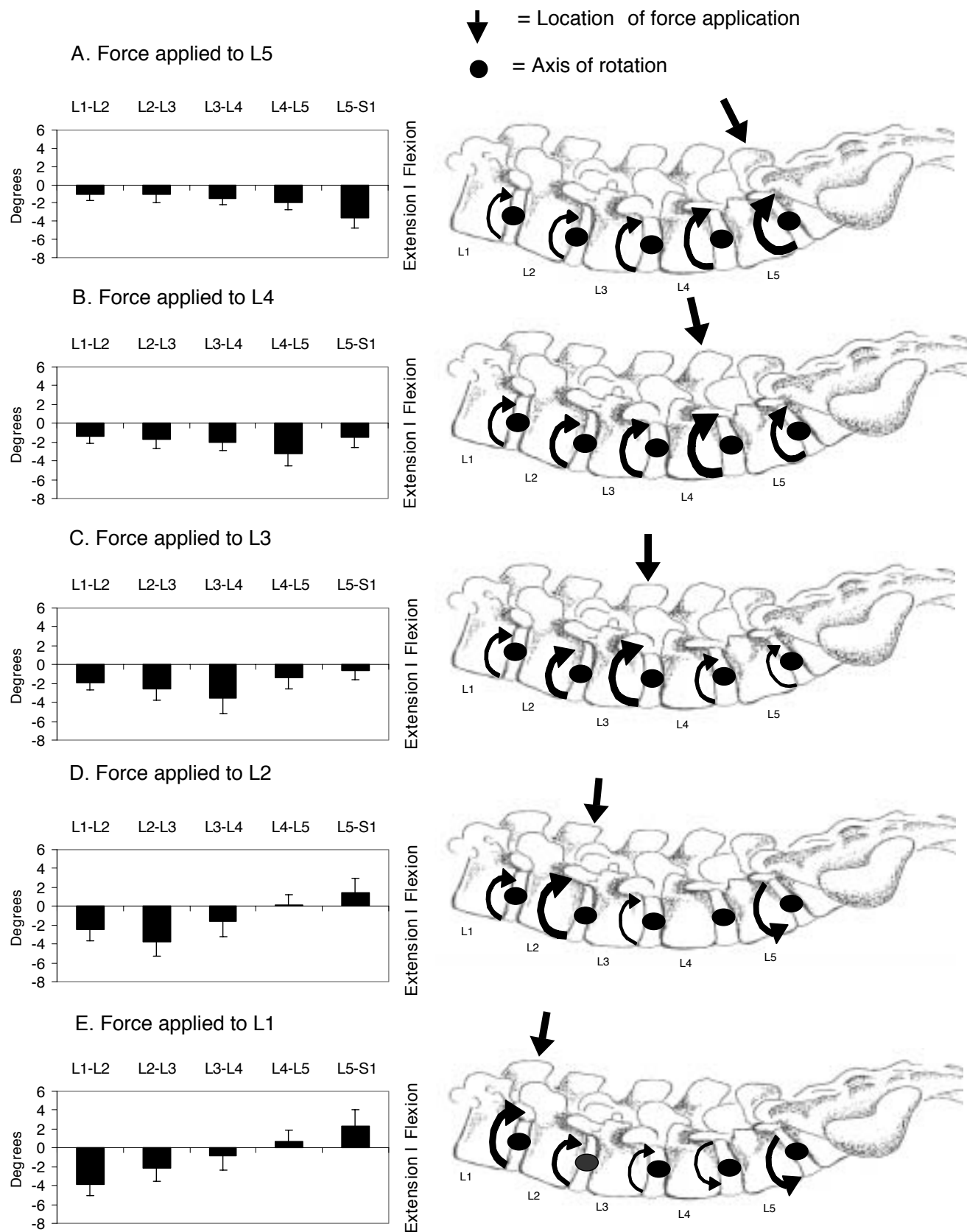


FIGURE 3. (Left column) Mean segmental motion at each lumbar segment during a posterior-to-anterior spine mobilization technique applied to the spinous process of a single vertebra. Error bars represent 1 SD. (Right column) Motion represented graphically. Arrows indicate the vertebra at which the force was applied. Curved arrows show the direction of motion and thickness of the curved arrows indicate relative amount of rotation. Axes of rotation taken from Farrokhi et al.⁵

A similar mean pattern of motion also was observed when the PA force was applied to L1 spinous process (extension at L1-L2, L2-L3, and L3-L4, and flexion at L4-L5 and L5-S1). As with motion pattern when the PA force was applied to L2, all subjects demonstrated extension at L1-L2 and L2-L3. However, 6 of 20 subjects did not move or flexed (as opposed to extend) at L3-L4, 4 did not move or extended (as opposed to flex) at L4-L5, and 2 did not move or extended (as opposed to flex) at L5-S1.

DISCUSSION

The results of this study revealed a consistent pattern of lumbar spine motion during a PA mobilization procedure. Specifically, motion at the targeted segment (the segment below the spinous process where the PA force is applied) was the greatest and was always directed towards extension. Additionally, 2 general patterns of motion were observed at the nontargeted segments. With force applied at L5, L4, or L3, all lumbar segments generally moved towards extension. With force applied at L2 or L1, the 3 most cranial lumbar segments (L1-L2, L2-L3, and L3-L4) moved towards extension while the 2 most caudal segments (L4-L5 and L5-S1) moved towards flexion.

On average, the amount of motion at each tested segment was relatively small (3° - 4°), but larger than previously reported. Lee and Evans¹¹ reported 1.2° to 2.4° of segmental extension during the PA procedure with a force of 150 N applied to the L4 spinous process using a dynamometer plunger mounted on an external frame. The apparatus applied a PA force perpendicularly to the table and not to the curvature of the lumbar spine, as is commonly done in clinical practice. Keller et al⁸ predicted 1.4° of extension at the L3-L4 segment when a 100-N PA force was applied at L3. Their model, however, assumed a straight beam (not a lordotic curvature) composed of 7 segments, and the segments lacked the biofidelity of vertebral bodies such as zygapophyseal joints. Furthermore, the model was likely oversimplified, in that the lumbar spine was assumed to have linear stiffness, which may have contributed to erroneous predictions.

Sagittal Plane Segmental Kinematics: A Proposed Mechanism of Motion Induced by a PA Mobilization

The following discussion proposes a mechanism of lumbar motion in the sagittal plane occurring during a PA mobilization performed on young asymptomatic individuals. Due to the *in vivo* nature of this study, we believe that these data provide a basis for an excellent biofidelity of this motion.

When a PA force is applied to the spinous processes of L3, as during a manual assessment or intervention, the caudal zygapophyseal processes of the tested (L3) vertebra approximate to the cranial zygapophyseal processes of the adjacent caudal (L4) vertebra and impose motion on the L4 vertebra (Figure 4). For example, a force applied to the spinous process of L3 can cause up to 2 mm of anterior glide of the L3 vertebra, causing the inferior zygapophyseal processes of L3 to come to contact with the superior zygapophyseal processes of L4. It is conceivable that this approximation would result in the caudal zygapophyseal process of L3, pushing on its L4 counterpart (bone-on-bone contact), causing a bending moment rotating L4 away from L3 (extension of the L3 on the L4 vertebra) (Figure 4). In addition to causing extension, the force from the L3 zygapophyseal process on L4 likely glides the L4 vertebra anteriorly, causing subsequent approximation at the L4-L5 zygapophyseal processes. This approximation would lead to extension at the L4-L5 segment via a similar mechanism to that described at L3-L4.

At the L2-L3 segment, a different anatomical relationship likely contributes to the observed intervertebral extension. Force applied to the L3 spinous process would glide the superior zygapophyseal processes of L3 away from the inferior zygapophyseal processes of L2, separating the L2-L3 zygapophyseal joint surfaces. This separation would cause the zygapophyseal joint capsule to become taut, pulling the caudal facet of the L2 vertebra anteriorly, causing its vertebra to extend in relation to L3 as a result of a bending moment rotating L2 away from L3 (extension). Despite the same force being transferred from L3 to L2, as it was from L3 to L4 the resulting motion is smaller between L2 and L3 due to yielding joint capsule and a lesser bending moment than that between L3 and L4 (Figure 4). The mechanical interpretation of the PA mechanism is further illustrated by the longer lever arm of the force transferred from L3 to L4, than the lever arm of the same amount of force transferred from L3 to L2 (Figure 4). Ultimately, the bending moment acting on L4 is larger than that acting on L2.

This unique zygapophyseal joint interaction of pushing caudally and pulling cranially takes place in consecutive segments, and the motion is propagated both cranially and caudally, resulting in an increased collective lordosis. The consistently larger amount of extension between the target vertebra (L3 in this example) and the caudal vertebra (L4) than between the target vertebra and the cranial vertebra (L2), is likely caused by bony approximation at L3-L4 versus soft tissue pull at L3-L2. Bony approximation would cause immediate transfer of forces to the adjacent vertebra, while soft tissue pull would occur only after

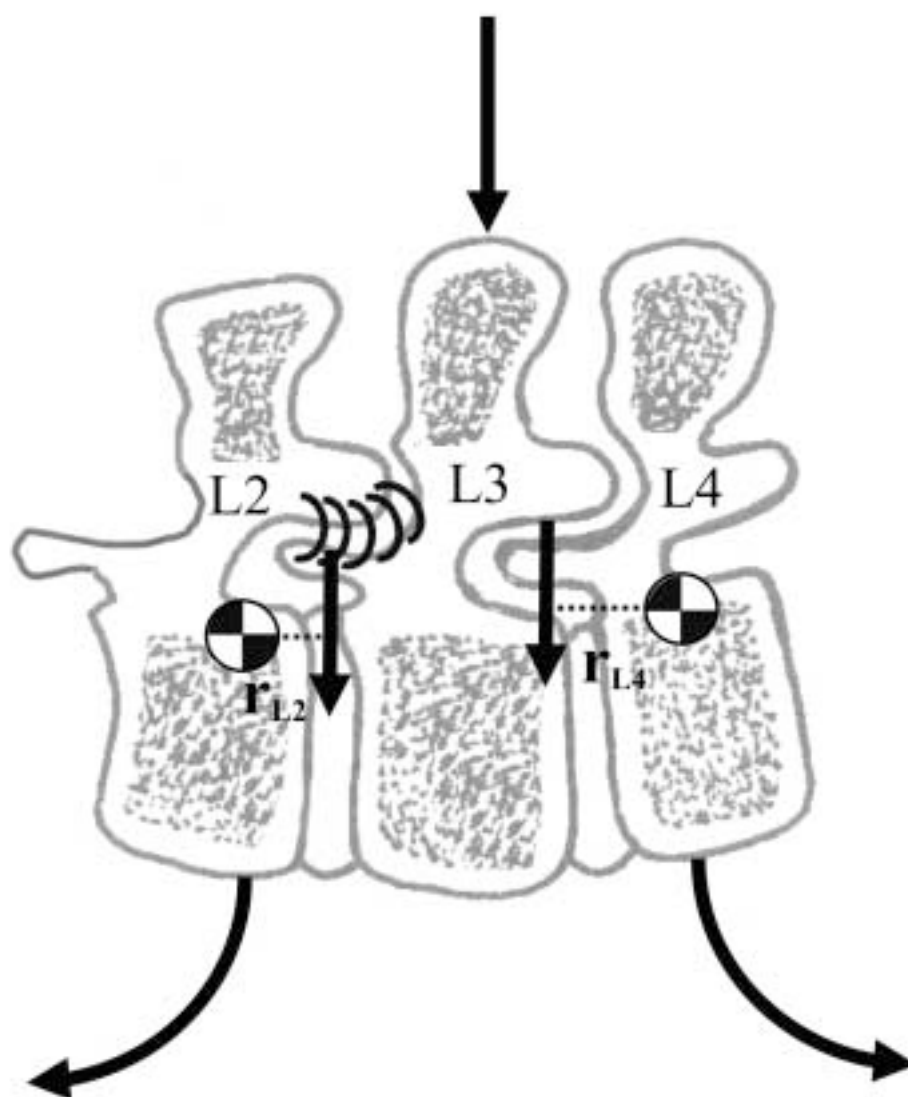


FIGURE 4. Artist's conception of the proposed mechanisms of intervertebral motion resulting from posterior-to-anterior (PA) force on spinous process of L3, representing a midsagittal view of 3 consecutive lumbar vertebrae. The large arrow at the spinous process of L3 indicates location of applied force. The arrow between zygapophyseal articulations of L3 and L4 indicates approximation and circular symbol between zygapophyseal joint of L3 and L2 indicates capsular tightening. The arrow between L3 and L2 depicts transfer of force from L3 to L2. The circular markers are the location of vertebral center of mass. r_{L4} indicates the lever arm of the PA force transferring the bending moment to L4. r_{L2} indicates the lever arm of the PA force transferring the bending moment to L2. The curved arrows indicate the direction of rotatory motion of the L2 and L4 vertebrae.

the capsule becomes taut. Force applied to the L4 and L5 spinous processes resulted in the same pattern of intervertebral motion (eg, larger extension caudally and lesser extension cranially).

Anteriorly directed force on the L1 and L2 spinous processes, located at the cranial end of the lumbar lordotic curvature, resulted in segmental extension at the targeted segment (largest extension) and the other 2 upper segments (L2-L3 and L3-L4 for PA pressure on L1, and L1-L2 and L3-L4 for PA pressure on L2). The remaining caudal segments (L4-L5 and L5-S1) were observed to flex, causing an overall decrease in the lumbar lordosis. The prevailing flexion motion response of the 2 caudal segments was most likely related to the fixed mass of the pelvis,

which served as a counterweight to the PA force application at L1 and L2 (Figure 3D and 3E).

Clinical Relevance

The clinical relevance of this study relates to the interpretation of motion testing and treatment of the lumbar spine. First, because the PA mobilization procedure consistently imparted extension at the tested segment, restriction to motion felt by the examiner would suggest hypomobility in the direction of extension. Also, if improving lumbar extension was a desired treatment effect, then it would appear that PA mobilizations applied at the hypomobile segment could be used to augment this motion.

Secondly, should the PA force reproduce pain at a given level, a common strategy would be to mobilize the segment using oscillatory motions in the pain-free range.¹² Because motion as a consequence of a PA force on 1 spinous process was observed at all lumbar segments, it is plausible that mobilization of a symptomatic segment could be achieved indirectly using PA force at an adjacent segment. The amplitude of motion at the symptomatic segment could be varied as a function of the distance (number of segments) away from the symptomatic level. For example, if a PA force at L5 reproduced or increased pain, it is conceivable that the same grade of mobilization applied to L3 also would cause extension at L5-S1, but to a lesser extent and without direct contact on the spinous process of L5. The pain associated with the manual technique would be diminished or eliminated, and the mobilization would have an effect on movement at the symptomatic level. Although a thorough neurophysiological explanation of this mechanism is beyond the scope of this manuscript, these data may contribute to a kinematic foundation of such a mechanism.

CONCLUSION

The findings suggest that a PA force at 1 spinous process causes motion not only of the target vertebra but also the neighboring vertebrae and that this motion is propagated caudally and cranially. Motion at the target segment was always into extension. Motions at nontargeted segments were, with few individual exceptions, into extension when the targeted vertebrae were L3, L4, and L5. When the targeted vertebrae were L1 and L2, the typical observed motion were towards extension for the 3 most cranial lumbar segments, and towards flexion for the 2 most caudal segments (again with a few exceptions noted for motion taking place at the 3 most caudal segments).

Secondly, we have described a mechanism by which a PA force applied to a lumbar spinous process causes motion at the lumbar spine. This mechanism is based on kinematic data obtained in vivo and can be explained by the lumbar spine's morphology.

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