Mechanical Behavior of the Human Lumbar and Lumbosacral Spine as Shown by Three-Dimensional Load-Displacement Curves*

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ABSTRACT: The lumbar region is a frequent site of spinal disorders, including low-back pain, and of spinal trauma. Clinical studies have established that abnormal intervertebral motions occur in some patients who have low-back pain. A knowledge of normal spinal movements, with all of the inherent complexities, is needed as a baseline. The present study documents the complete three-dimensional elastic physical properties of each lumbar intervertebral level from the level between the first and second lumbar vertebrae through the level between the fifth lumbar and first sacral vertebrae. Nine whole fresh-frozen human cadaveric lumbar-spine specimens were used. Pure moments of flexion-extension, bilateral axial torque, and bilateral lateral bending were applied, and three-dimensional intervertebral motions were determined with use of stereophotogrammetry. The motions were presented in the form of a set of six load-displacement curves, quantitating intervertebral rotations and translations. The curves were found to be non-linear, and the motions were coupled. The ranges of motion were found to compare favorably with reported values from *in vivo* studies.

CLINICAL RELEVANCE: Knowledge of the physical characteristics of the spine is clinically important whenever loads or displacements, or both, are applied to the spine. It is necessary to understand not only the amounts of spinal motion, but also the motion characteristics of non-linearity and coupling, which are documented in the present study, in order to better understand the clinically important problems, and treatment, of spinal instability in association with low-back pain and after spinal trauma.

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In earlier clinical studies of the lumbar spine, excessive horizontal slippage of a vertebra with respect to the caudal vertebra was considered to be a sign of instability[8,9]. Recent clinical studies, however, have documented that, in older patients who have low-back pain, the intervertebral motions are smaller than in the normal population[4,21]. Other studies have revealed abnormally large relative motions in young athletes who have low-back pain[4]. Abnormal coupled motions[21] and asymmetrical associated moments[19] have also been observed in patients who have low-back pain. Thus, there is evidence to suggest that abnormal motion (less, more, or of a different type than normal) may be an indicator of abnormal mechanics of the spine and, therefore, may be associated with some types of low-back pain. However, to designate a motion as abnormal requires knowledge of the normal motions.

The human spine is a three-dimensional structure that exhibits non-linear viscoelastic mechanical behavior. Therefore, to document the physical properties of the spine, it is necessary to use methods that are compatible with this spinal behavior. *In vivo* studies of the lumbar spine are generally restricted to the sagittal plane motion, measured on lateral radiographs made with the spine in full flexion and extension[4,22,23]. Some three-dimensional *in vivo* studies have used biplanar radiography[13,20,30]. Although such *in vivo* measurements provide important functional information, they have substantial shortcomings. For example, the loads that are applied to the spine are unknown, and the accuracy of the measurement system is generally poor. More accurate *in vivo* measurements of motion have been reported recently, with use of roentgenstereophotogrammetry[7,27], but this is an invasive technique.

In vitro models allow a more controlled environment for the study of the physical properties of the spine. A multitude of *in vitro* studies have been performed on lumbar cadaveric segments in an effort to describe the normal mechanical properties[1,3,6,10,11,17,26,31]. Instruments that are used to study the physical properties of the lumbar spine should measure three-dimensional motions, allow unconstrained physiological spinal movements, take into consideration the viscoelastic nature of the spine, and document the non-linear behavior of the spine. It is also advantageous if the study is done on whole lumbar spines, instead of on a two-vertebrae segment. The present study was designed and conducted with use of these criteria and, therefore, represents a comprehensive assessment of the physical properties of the lumbar spine.

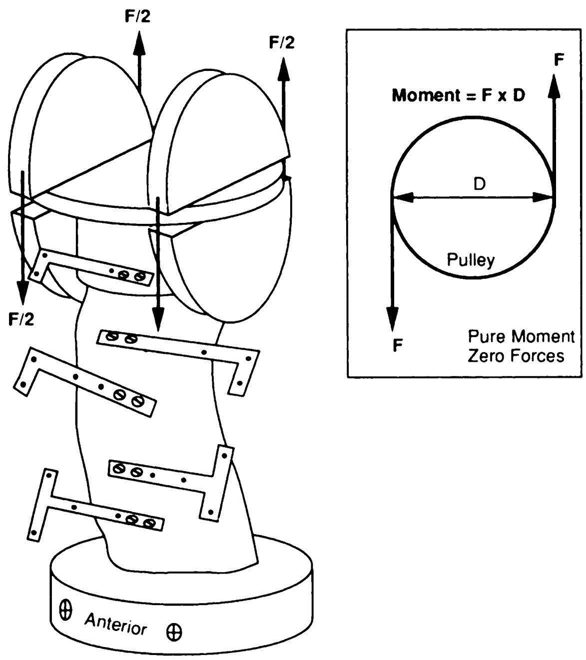

FIG. 1

Illustration of the experimental setup. The two end-vertebrae of the whole lumbar-spine specimen are fixed in epoxy mounts. The bottom mount is fixed to a table while the top mount carries a loading fixture. The design of the loading fixture is such as to apply pure moments to the specimen. The fixture consists of three round pulleys, two vertically oriented and one horizontal. The vertical pulleys are used for the application of flexion, extension, and bilateral bending (by turning of the fixture 90 degrees around the axis of the spine). The horizontal pulley is used for the application of torsional loading. A flexion loading setup is shown. Two forces (F) (divided into halves [F/2]) — parallel, equal, and opposite — are applied to the vertical pulleys. The inset shows the pure moment being generated by these forces, separated by distance D, while the resultant force is zero. To measure vertebral motions with use of stereophotogrammetry, a Plexiglas marker that carries a minimum of three 0.8-millimeter steel balls arranged non-collinearly is rigidly attached to the anterior aspect of each vertebra. The arrangement for the application of pre-load is not shown.

The purpose of the present study was to document the three-dimensional load-displacement behavior of the human cadaveric lumbar and lumbosacral spine at each vertebral level, from the level between the first and second lumbar vertebrae through the level between the fifth lumbar and first sacral vertebrae.

Materials and Methods

The methodology for the present study has been well established both conceptually[15] and experimentally[16-18]. The specific methods are essentially identical to those used recently in a study of the mechanical properties of the thoracolumbar junction[14].

Preparation of the Specimens

Nine fresh-frozen, whole lumbosacral-spine specimens (five were from the first lumbar through the first sacral vertebra and four were from the second lumbar through the first sacral vertebra) were dissected of all non-ligamentous soft tissue. All of the specimens were from men, and the average age at the time of death was fifty-one years (range, thirty-five to sixty-two years). Radiographs of the specimens did not show any abnormal findings besides normal degenerative changes. The sacrum and the most cephalic (the first or the second lumbar) vertebra were mounted in polyester resin casts (Plastic Padding, Gothenburg, Sweden) such that the superior end-plate of the fourth lumbar vertebra was horizontal. Plexiglas markers, each containing at least three non-collinear steel balls (0.8 millimeters in diameter), were rigidly attached to the anterior aspect of each vertebral body and served as points for the stereophotogrammetric motion measurement. Three steel balls are sufficient for the documentation of the three-

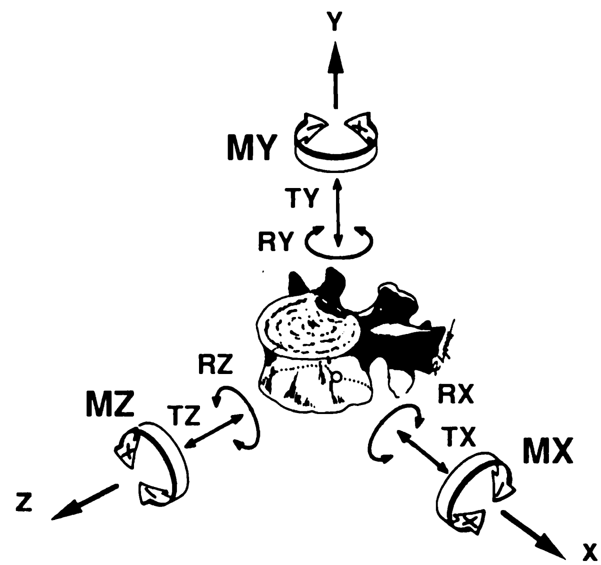

FIG. 2

Illustration of the three-dimensional coordinate system that is necessary to describe the three-dimensional physical properties of the spine. The origin of the coordinate system is located at the inferoposterior corner in the mid-sagittal plane of the vertebral body. The X axis is directed to the left and perpendicular to the sagittal plane. The Y axis is directed superiorly, and the Z axis is directed anteriorly. The broad arrows show the pure moments: +MX = flexion, −MX = extension, +MY = left torque, −MY = right torque, +MZ = right bending, and −MZ = left bending. The thin, circular arrows show the rotations: +RX = flexion, −RX = extension, +RY = left rotation, −RY = right rotation, +RZ = right lateral bending, and −RZ = left lateral bending. The thin, straight arrows show the translations: +TX = left, −TX = right, +TY = superior, −TY = inferior, +TZ = anterior, and −TZ = posterior.

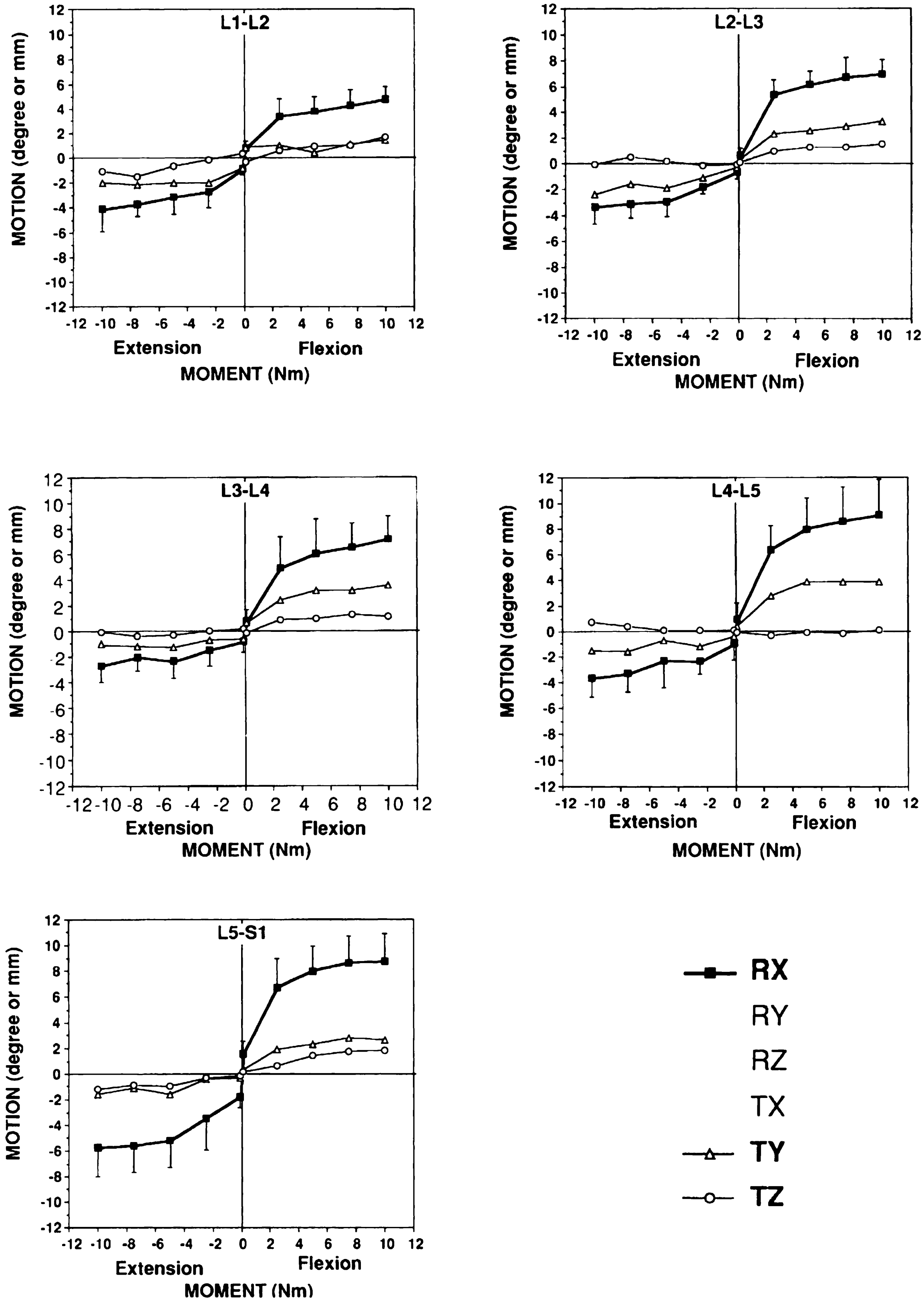

FIG. 3

Load-displacement curves at each of the five levels due to the application of flexion and extension moments. The main motion, defined as the rotation in the direction of the applied moment, is indicated by the heavier line. The standard deviations (I bars) are plotted for the main motion only. Also shown are coupled motions, defined as all rotations and translations other than the main rotation. For clarity, rotations and translations that were not significantly different from zero are not plotted. +RX = flexion, −RX = extension, +RY = left rotation, −RY = right rotation, +RZ = right lateral bending, −RZ = left lateral bending, +TX = left translation, −TX = right translation, +TY = superior translation, −TY = inferior translation, +TZ = anterior translation, and −TZ = posterior translation.

dimensional motion of a vertebra, but additional balls were necessary in the event that some balls were not seen by both cameras during the experiment.

Flexibility Test

In the flexibility test, the most caudal (the first sacral) vertebra was fixed to the test table while the loads were applied to the most cephalic (the first or second lumbar) vertebra. The vertebrae were unconstrained, to allow natural physiological movements of the spine to occur in response to the applied load.

The specimen was placed in a testing machine that was calibrated for stereophotogrammetric measurements. Throughout the experiment, the specimen was enclosed in ordinary polyethylene wrap to prevent dehydration. The specimen was loaded by pure moments, applied to the most cephalic vertebra by equal and opposing forces generated by pneumatic actuators (Fig. 1). For example, four forces of equal magnitude resulted in a flexion moment applied to the cephalic vertebral mount and the specimen. With proper choices of force vectors, pure moments of flexion, extension, bilateral axial torque, and bilateral lateral bending were applied individually in four equal load increments to a maximum value of ten newton-meters. The design of the loading system was such that the moment vector remained pure; in other words, it was unaltered in magnitude and direction with respect to the most cephalic vertebra as the whole lumbar-spine specimen deformed. Throughout the testing, a compressive pre-load of 100 newtons was applied along the longitudinal axis of the specimen. By special design, the pre-load remained along the axis of the specimen, which was formed by a straight line that joined the centers of the vertebral bodies of the most cephalic and the most caudal vertebrae, while the spine deformed under the applied moments. The moments were applied in three load-unload cycles to pre-condition the specimen, with thirty seconds of creep allowed at each load-step to reduce variations caused by viscoelasticity of the spine.

At each load increment of the third load cycle, stereophotographs were made of the specimen with its attached markers. The photographs were digitized and the relative three-dimensional motions of each vertebra were calculated. The motion was expressed in a coordinate system with its origin located at the inferiormost point on the posterior wall of the body of the moving vertebra (Fig. 2). The Y axis was oriented along the posterior wall of the body of the inferior vertebra. The X axis was directed to the left, and the Z axis was oriented anteriorly. The three-dimensional motion of one vertebra with respect to another consists of three body rotations and three translations. The rotation angles were the Euler angles given in X-Y-Z sequence.

Accuracy of the Measurements

A rigid body with four vertebral markers, each containing several steel balls, was used to estimate the precision of the motion measurement system[14]. With the markers fixed in space, the rigid-body Euler angles and translations were calculated from ten stereophotogrammetric images. The precision (the standard deviation of the measurements[2]) was found to be dependent on the plane of rotation as follows: ±0.60 degree for flexion-extension, ±0.33 degree for lateral bending, ±0.17 degree for axial rotation, and ±0.37 degree for average three-dimensional rotation. For translations, the precisions were: ±0.43 millimeter for vertical direction, ±0.35 millimeter for anteroposterior, ±0.22 millimeter for lateral, and ±0.33 millimeter for average translation.

Statistical Analysis

The goal of the statistical analysis was to compare the motions at the different lumbar intervertebral levels under identical loading conditions. Each applied moment produced three rotations and three translations of each vertebra. The vertebral motions of the different levels under each maximum applied moment (flexion, extension, left-right axial torque, and right-left lateral bending) were compared with use of a factorial analysis of variance. The *post hoc* Fisher least-significant-difference test identified which levels were significantly different from one another for each applied moment. All tests were performed at a 95 per cent level of significance.

Results

The three-dimensional behavior of the entire lumbosacral spine is presented in the form of average load-displacement curves for each combination of vertebral level and moment type. For the sake of compactness, the six moments are grouped into three pairs: flexion-extension, left-right axial torques, and left-right lateral bendings. This results in fifteen separate graphs (three moment pairs at five levels), each of which contains six curves representing the six-degrees-of-freedom motion at the intervertebral joint (Figs. 3, 4, and 5).

Flexion-Extension Moment Loading

In flexion moment loading, the main motions (flexion rotation) at the caudal lumbar levels (between the fourth and fifth lumbar vertebrae and between the fifth lumbar and first sacral vertebrae) were significantly greater than the motions of the cephalic vertebral levels (between the first and second and between the second and third lumbar vertebrae) ($p < 0.003$). At all levels, the coupled rotations (such as axial rotation and lateral bending) were small (less than 1 degree). The translations in the sagittal plane were notable. At all levels, the translations were directed cephalad and anteriorly (Fig. 3). At the levels between the second and third, the third and fourth, and the fourth and fifth lumbar vertebrae, the cephalic translation component was always greater than the anterior translation component. At the levels

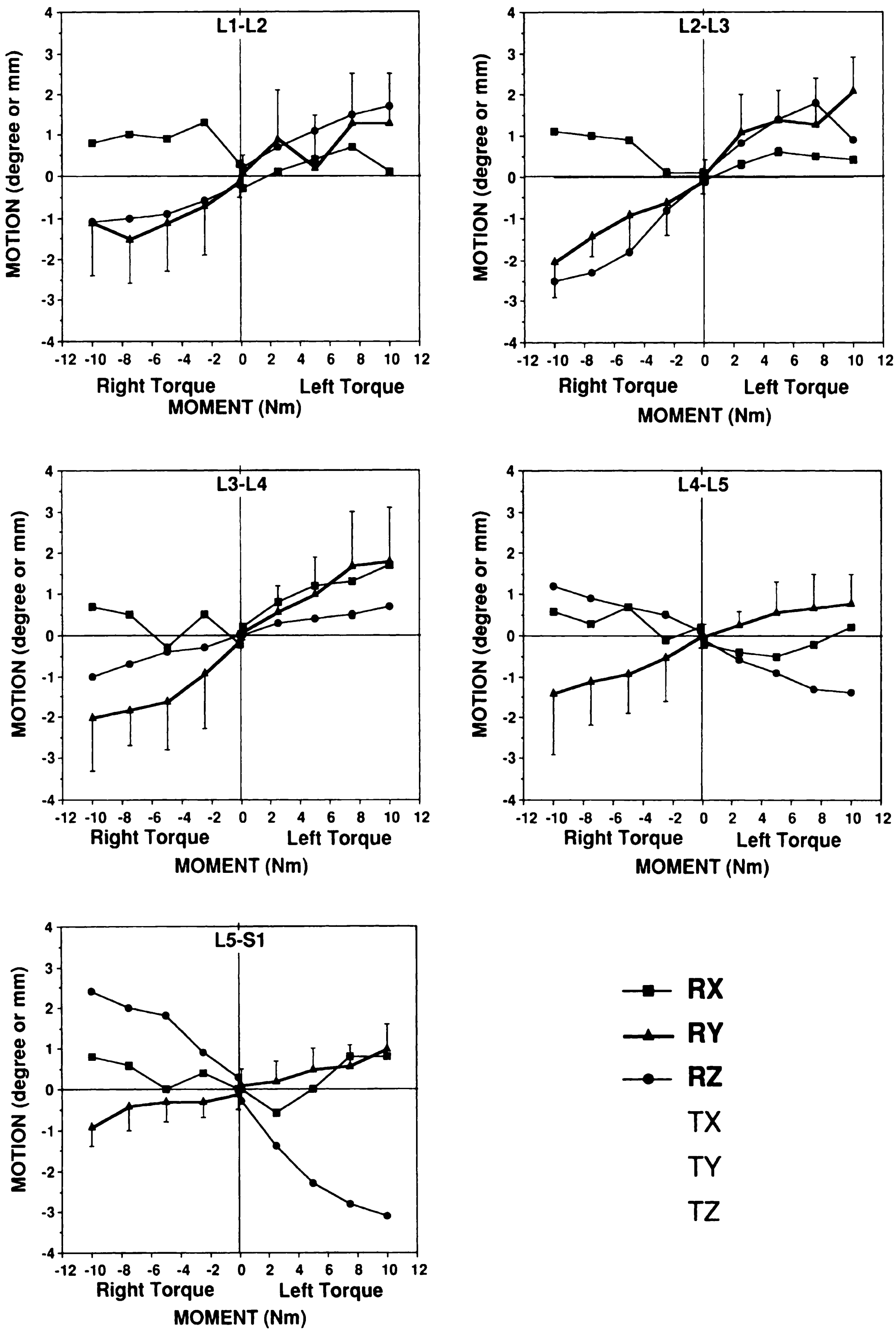

FIG. 4

Load-displacement curves at each of the five levels due to the application of right and left axial torques. The main motion, defined as the rotation in the direction of the applied moment, is indicated by the heavier line. The standard deviations (I bars) are plotted for the main motion only. Also shown are coupled motions, defined as all rotations and translations other than the main rotation. For clarity, rotations and translations that were not significantly different from zero are not plotted. +RX = flexion, -RX = extension, +RY = left rotation, -RY = right rotation, +RZ = right lateral bending, -RZ = left lateral bending, +TX = left translation, -TX = right translation, +TY = superior translation, -TY = inferior translation, +TZ = anterior translation, and -TZ = posterior translation.

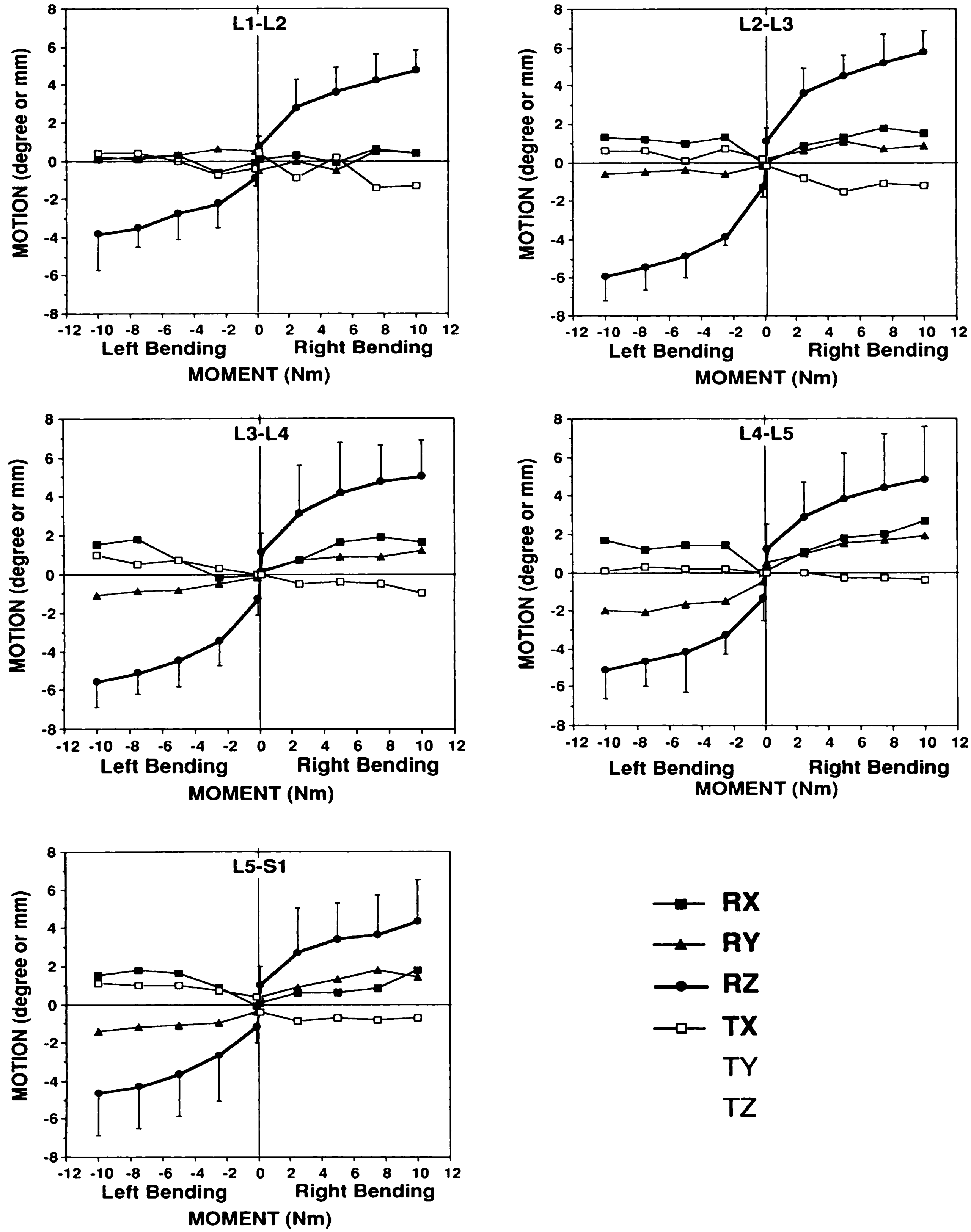

FIG. 5

Load-displacement curves at each of the five levels due to the application of left and right lateral bending moments. The main motion, defined as the rotation in the direction of the applied moment, is indicated by the heavier line. The standard deviations (I bars) are plotted for the main motion only. Also shown are coupled motions, defined as all rotations and translations other than the main rotation. For clarity, rotations and translations that were not significantly different from zero are not plotted. +RX = flexion, −RX = extension, +RY = left rotation, −RY = right rotation, +RZ = right lateral bending, −RZ = left lateral bending, +TX = left translation, −TX = right translation, +TY = superior translation, −TY = inferior translation, +TZ = anterior translation, and −TZ = posterior translation.

between the first and second lumbar vertebrae and the fifth lumbar and first sacral vertebrae, the cephalic and anterior translations were almost equal (approximately 1.5 and 2.0 millimeters, respectively). However, these differences were not significant.

With extension moment loading, the largest main motions (extension rotation) were at the level between the fifth lumbar and first sacral vertebrae, with an average of 5.3 degrees. These motions were significantly greater than the mean extension rotations at the levels between the first and second (4.1 degrees), the second and third (3.3 degrees), the third and fourth (2.6 degrees), and the fourth and fifth lumbar vertebrae (3.6 degrees) ($p < 0.006$). Similar to the response under flexion moment loading, extension moment loading produced coupled rotations of axial rotation and lateral bending that were less than 1 degree at all levels. Translation motions were generally less than those induced under the flexion moment loading. Axial translations were caudad at all levels, with the largest mean value (2.6 millimeters) at the level between the first and second lumbar vertebrae. Anterior-posterior translations were less than 1.1 millimeters at all levels, except at the level between the first and second lumbar vertebrae, where a posterior translation of 1.7 millimeters was observed. The average vertical and anterior-posterior translation for all levels due to the extension moment loading was 1.6 millimeters caudad and 0.8 millimeter posteriorly. The lateral translation was less than one millimeter at all levels. The translations were not significantly different at any of the vertebral levels.

Axial Torsional Loading

With the application of right and left axial torques, the main motions (axial rotation) for all levels averaged 1.4 degrees to each side, with the largest motion approximately 2 degrees to one side at the levels between the second and third and the third and fourth lumbar vertebrae (Fig. 4). The motion at the level between the second and third lumbar vertebrae was significantly greater than that between the fourth and fifth lumbar vertebrae and that between the fifth lumbar and first sacral vertebrae ($p < 0.05$). Coupled flexion rotations, induced by both left and right axial torques, averaged 0.9 degree at all vertebral levels. Coupled lateral bending rotations were present at all levels. At the cephalic levels, the lateral rotation was to the opposite side of the applied torque (in other words, coupled right lateral bending was associated with left axial torque), with the greatest magnitude (1.8 degrees to one side) being at the level between the second and third lumbar vertebrae. At the two most caudal lumbar levels, the coupled lateral rotation was to the same side as the applied axial torque. The coupled lateral rotations at the level between the fourth and fifth lumbar vertebrae were significantly different from the rotations at the levels between the first and second, the second and third, and the third and fourth lumbar vertebrae ($p < 0.0001$). Translational motions under axial torsional loading were small (generally less than one millimeter). Lateral translations were in the same direction as the coupled lateral rotations; in other words, right translation was associated with coupled right lateral rotation. The vertical and anterior-posterior translations were small and inconsistent.

Lateral Bending Moment Loading

With the application of left and right lateral bending moments, the main motion (lateral rotation) was greatest between the second and third lumbar vertebrae, averaging 5 degrees to one side, although it was not substantially different from the motions at the other levels (Fig. 5) ($p > 0.05$). Coupled flexion rotation was only 0.4 degree between the first and second lumbar vertebrae, but it averaged 2 degrees at all levels caudad to the first and second lumbar vertebrae. This motion was flexion for both the right and the left lateral bendings. At the levels between the fourth and fifth lumbar vertebrae and between the fifth lumbar and first sacral vertebrae, maximum axial rotation of 1 to 2 degrees to the opposite side of the applied moment was observed. Coupled axial rotation averaged less than 1 degree at the levels between the first and second, the second and third, and the third and fourth lumbar vertebrae, and it was significantly different from the rotation at the level between the fourth and fifth lumbar vertebrae. Lateral translations were observed to be in the same direction as the applied lateral bending moment (in other words, right lateral bending produced right translation), and they averaged 1.1 millimeters to one side for all levels. Vertical translations were generally small (less than one millimeter) and in a superior direction.

Discussion

The present study documents the complete three-dimensional elastic physical properties, in the form of load-displacement curves, at each of the vertebral levels of the human lumbar and lumbosacral spine. Because of the *in vitro* nature of this study, the effect of the spinal muscles on the motion was not determined. The applied loads were three pairs of pure moments in addition to a compressive pre-load; therefore, the study does not address the effect of various applied forces on intervertebral motion. With these limitations in mind, we think that the present study is the most comprehensive description of the kinetics of the human lumbar spine to date.

Comparison with Previous Studies

In vitro biomechanical studies, such as the present one, are generally more accurate than *in vivo* studies. However, the obvious criticism of an *in vitro* study is that it may deviate from the clinical situation and, therefore, its results may be very different from those

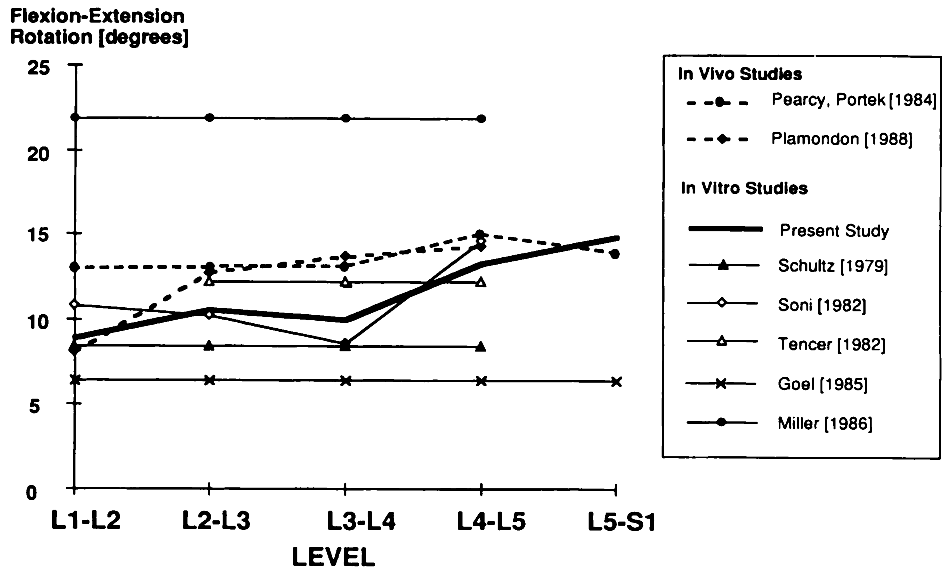

FIG. 6-A

Figs. 6-A, 6-B, and 6-C: Graphs comparing the results of the present study with previous *in vivo* and *in vitro* studies[6,12,13,20,21,24,26,29,31]. For the *in vitro* studies, the maximum applied moments were: present study, ten newton-meters; Schultz et al.[26], 10.6 newton-meters; Soni et al.[29], 6.8 newton-meters; Tencer et al.[31], 11.2 newton-meters; Goel et al.[6], three newton-meters; and Miller et al.[12], seventy newton-meters.
Fig. 6-A: Ranges of motion in flexion-extension.

obtained *in vivo*. Thus, a comparison of the results of both types of studies is warranted.

Many studies have described the motions at various lumbar intervertebral levels. Some were *in vivo*[5,13,19,32], some were *in vitro*[6,10,11,18,26,31,35], and others were mathematical predictions[28,33]. Most of these reports focused on the determination of main motions or stiffness values, or both. Few measured the coupled motions (rotations or translations, or both).

The ranges of motion in flexion-extension, axial rotation (to one side), and lateral bending (to one side), as reported in the present study, were compared with those in previous three-dimensional *in vivo* and *in vitro* studies[6,12,13,20,21,24,26,29,31] (Figs. 6-A, 6-B, and 6-C). For flexion-extension, the ranges of motion in the present study were somewhat less at the cephalic lumbar levels than the *in vivo* motions reported by Pearcy et al.[21] and by Plamondon et al.[24] (Fig. 6-A). A possible reason may be the effect of muscles on the motions between the fifth lumbar and first sacral vertebrae, which obviously are

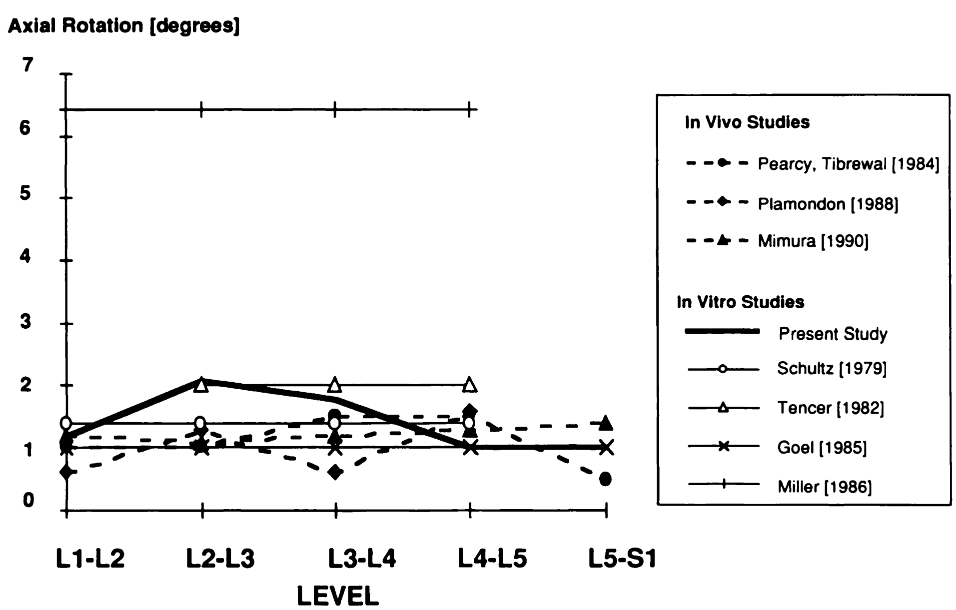

FIG. 6-B

Ranges of motion in axial rotation to one side.

not included in the measurements for the present study. Also, in the *in vivo* measurements, it is conceivable that the errors at the level between the fifth lumbar and first sacral vertebrae are higher because of the poor quality of the image of that level. The values of Goel et al.[6] and of Schultz et al.[26] slightly underestimated the *in vivo* motions. The average displacements reported by Tencer et al.[31] and by Soni et al.[29] were within the *in vivo* ranges. The values reported by Miller et al.[12] were approximately twice those of the *in vivo* motions. This may be because of the application of excessive loads (seventy newton-meters) *in vitro*.

In axial rotation, the motions reported in the present study, as well as those of Tencer et al.[31], Soni et al.[29], Schultz et al.[26], and Goel et al.[6], approximated closely the *in vivo* motions (Fig. 6-B).

In lateral bending, the motion reported by Goel et al.[6] was approximately 50 per cent of the *in vivo* motions (Fig. 6-C). The lateral bending rotations reported by Pearcy and Tibrewal[20] decreased significantly ($p < 0.01$) at the levels between the fourth and fifth lumbar vertebrae and between the fifth lumbar and first sacral vertebrae. These declines were not found in the *in vivo* study by Plamondon et al.[24]. Variation with these reported studies may be due to differences in the methodologies of the studies rather than in the magnitudes of the applied loads. Our reasoning is that, beyond the initially high flexibility, increasing loads are associated with small increases in motion.

Because of the relatively high accuracy of the techniques used for measurement in the present study, several significant differences were observed between intervertebral levels. Most of these differences were small (less than 2 degrees) and, therefore, would be difficult to measure clinically. However, if more accurate clinical measurement techniques are developed[27], those measured differences may be detectable and thus have clinical importance.

Methodological Considerations

Some technical refinements in the present study are noteworthy as they differentiate this study from previous investigations. Such refinements are necessary to study the true three-dimensional physical properties of the human spinal column.

Methods of testing flexibility compared with those for stiffness: In our system for the measurement of flexibility, three different pairs of pure moments were applied to the first or second lumbar vertebra, while the sacrum was fixed rigidly to the test table. The first through fifth lumbar vertebrae were completely unconstrained and able to move freely, because of the mechanical design of the load application apparatus. The resulting motions were measured on stereophotographs with the use of markers attached to each vertebra. This non-contacting motion-measurement-system ensured that the physiological motions of the spine were allowed to take place freely. In contrast, when universal materials testing machines, such as the Instron (Canton, Massachusetts) and MTS (Minneapolis, Minnesota) machines, are used to determine the physical properties of the spine or to study the effect of spine injuries or instrumentation, the stiffness method is often used. In such a method, displacements are given to the most cephalic vertebra, while the loads are measured at either the most cephalic moving or the most caudal fixed vertebra. This method may apply non-physiological displacements to the spine and possibly constrain the spine so that it moves in unnatural modes. Often in such situations, the end conditions are not precisely defined, resulting in load-displacement

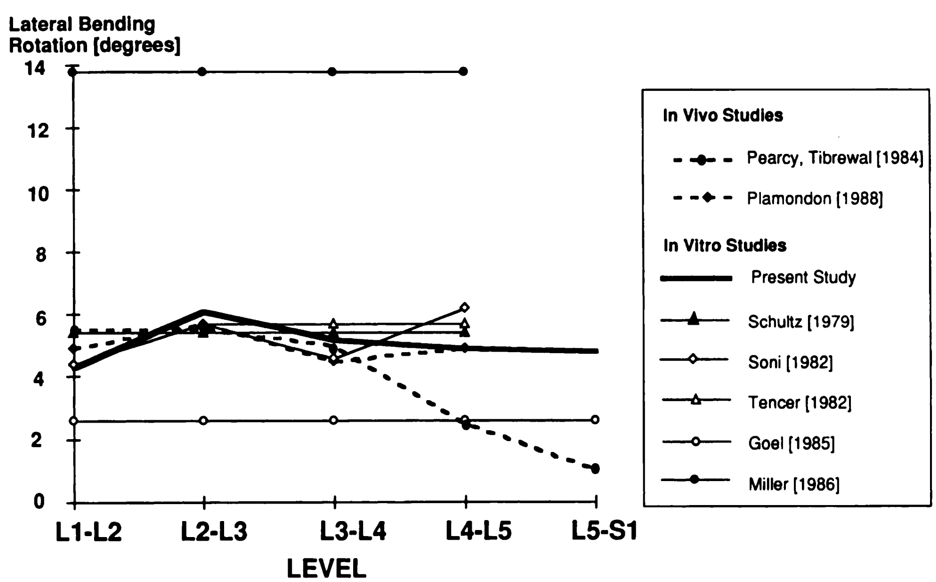

FIG. 6-C

Ranges of motion in lateral bending to one side.

curves with substantial associated uncertainties.

Translatory motions: We defined the coordinate system such that its origin was at the inferoposterior corner of the vertebral body in the mid-sagittal plane. If we had chosen another point, such as the center of the vertebral body, as the origin of the coordinate system, then the translations measured would have been different for the same spinal motion. In many studies of the biomechanical behavior of the lumbar spine, the origin of the coordinate system is not clearly defined and often is never mentioned. This is a serious deficiency. A measurement of vertebral translation must be associated with a specific coordinate-system origin on the vertebra. An example can be described from our measurements. In flexion, the vertebral body translation was found to be directed anteriorly and superiorly. If we had chosen a different point as our origin, such as the anteroinferior corner of the vertebral body, the translation would have been directed anteriorly and inferiorly for the same spinal motion.

Non-linear load-displacement curves: Most studies in the literature on the spine have presented the shape of the load-displacement curves as linear (straight lines)[16,26], while some have found it to be non-linear[18,35]. The reason for this discrepancy lies in the methodology used. Nearly all studies used some type of pre-conditioning to stabilize the physical properties of the viscoelastic spinal specimen. This involves loading and unloading of the spinal specimen several times. If the measuring system is set at zero at the end of the pre-conditioning, then the results are often straight-line load-displacement curves. On the other hand, if the pre-conditioning motion, which exhibits relatively high flexibility, is included, the resulting load-displacement curves are non-linear. We believe that the latter alternative is the proper method because the pre-conditioning motion is part of the range of motion of the spine. The non-linearity of the spinal behavior — that is, high flexibility at low loads and increased stiffness as the loads increase — is a necessary condition for the efficiency of spinal function. It allows the spine to move with minimum muscular effort around the neutral position and, simultaneously, it blocks the motion toward the ends of the range of motion. Such biphasic behavior is common to nearly all joints in the body. Therefore, we believe that the non-linear biphasic behavior of the lumbar spine, as documented here, is an important characteristic of the spine.

Main and coupled motions: The three-dimensionality of physical properties of the spine has two aspects. To determine the physical properties, the loads are applied in several different directions and the motion is measured in the direction of each applied load. These are the main motions. Most of the clinical literature deals with main motions and uses the abnormal ranges of main motions as indicators of spinal instability. The main motions may be normalized with respect to similar motions at adjacent vertebral levels, to decrease variability due to lordosis or kyphosis[34]. The main motions, absolute or normalized, represent the quantity of motion at the spinal level.

The quality of motion is represented by coupled motions. These are all associated motions, rotatory as well as translatory, that are produced in addition to the main motions. The coupled motions may be normalized with respect to the main motion, to compensate for variation in flexibility between subjects. It has been shown in clinical studies that coupled motions may be better indicators of lumbar spinal instability[8,9,30]. In a recent study of patients who had low-back pain, coupled moments (lateral bending moment and axial torques) were produced while the subjects performed flexion motion against resistance[19]. These coupled moments were absent in normal subjects. Therefore, coupled motions and coupled moments may be clinically useful tools for the determination of spinal derangement. Additional clinical studies are needed to validate these findings.

Variation with spinal level: We found marked differences in the load-displacement curves with spinal level. We believe that the variation with level is mainly due to the inherent variations in the physical properties of the spinal units. However, we acknowledge that these differences may include additional effects of the possible variation in the load vector applied to each vertebral level, which may arise from the lordosis of the lumbar spine at neutral posture or from the changes in the lordosis with spinal motion.

Comparison with Clinical Instability

The authors of a previous *in vitro* study proposed thresholds of clinical instability[25]. The upper threshold values are flexion-extension rotations of 15 degrees at the level between the first and second lumbar vertebrae through the level between the third and fourth lumbar vertebrae, 20 degrees at the level between the fourth and fifth lumbar vertebrae, and 25 degrees at the level between the fifth lumbar and first sacral vertebrae and an anterior translation of 4.5 millimeters at all levels. We compared these values with the flexion-extension ranges of motion measured in the present study.

The maximum rotations measured at the five levels (the level between the first and second lumbar vertebrae through the level between the fifth lumbar and first sacral vertebrae) were 11.6, 11.8, 14.5, 16.6, and 14.6 degrees. These values are lower than the corresponding instability thresholds proposed by Posner et al.[25]. Similarly, the maximum anterior translations of the vertebral body in flexion for the same vertebral levels were 3.1, 3.3, 2.0, 1.9, and 3.0 millimeters in the present study. Again, these values are within the previously established limits.

Therefore, it appears that the thresholds of clinical instability that were established by Posner et al.[25] are appropriate.

Findings of the Present Study

Non-linear behavior: The many load-displacement curves presented here clearly show that spinal behavior is highly non-linear. As an example, the flexion behavior at the level between the fourth and fifth lumbar vertebrae shows that the flexibility at low loads is more than three times that at the heaviest loads used in the present study. Therefore, if spinal behavior is to be quantified in the form of flexibility or stiffness values, then it should be defined at more than one load value, and it cannot be averaged and represented by a single value for stiffness or flexibility.

Variation with spinal level: In flexion-extension, there is clearly increasing motion moving inferiorly from the level between the first and second lumbar vertebrae to that between the fifth lumbar and first sacral vertebrae. However, this trend is not found with lateral bending, with which the greatest motions occur at the level between the second and third lumbar vertebrae. Similarly, the largest axial rotations occur at the level between the second and third lumbar vertebrae. From the cephalic to the caudal lumbar vertebral levels, the coupled motions of axial rotation under lateral bending moments and lateral rotation under axial torque change significantly. No significant differences were observed in the translational motions between vertebral levels.

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