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A Follower Load Increases the Load-Carrying Capacity of the Lumbar Spine in Compression

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Study Design. An experimental approach was used to test human cadaveric spine specimens.

Objective. To assess the response of the whole lumbar spine to a compressive follower load whose path approximates the tangent to the curve of the lumbar spine.

Summary of Background Data. Compression on the lumbar spine is 1000 N for standing and walking and is higher during lifting. *Ex vivo* experiments show it buckles at 80–100 N. Differences between maximum *ex vivo* and *in vivo* loads have not been satisfactorily explained.

Methods. A new experimental technique was developed for applying a compressive follower load of physiologic magnitudes up to 1200 N. The experimental technique applied loads that minimized the internal shear forces and bending moments, made the resultant internal force compressive, and caused the load path to approximate the tangent to the curve of the lumbar spine.

Results. A compressive vertical load applied in the neutral lordotic and forward-flexed postures caused large changes in lumbar lordosis at small load magnitudes. The specimen approached its extension or flexion limits at a vertical load of 100 N. In sharp contrast, the lumbar spine supported a load of up to 1200 N without damage or instability when the load path was tangent to the spinal curve.

Conclusions. Until this study, an experimental technique for applying compressive loads of *in vivo* magnitudes to the whole lumbar spine was unavailable. The load-carrying capacity of the lumbar spine sharply increased under a compressive follower load, as long as the load path remained within a small range around the centers of rotation of the lumbar segments. The follower load path provides an explanation of how the whole lumbar spine can be lordotic and yet resist large compressive loads. This study may have implications for determining the role of trunk muscles in stabilizing the lumbar spine. [Key words: follower load, load carrying capacity, lumbar spine, muscles, stability] **Spine 1999;24:1003–1009**

In intradiscal pressure studies and electromyographic measurements of trunk muscles, in conjunction with mathematical models, investigators have estimated the compressive load on the lumbar spine to reach 1000 N during standing and walking.[14] The compressive load on the lumbar spine is substantially higher in many lifting activities and is estimated to reach several thousand Newtons.[13,16]

There have been a number of studies performed on single motion segments of the lumbar spine. In most cases the motion segments have been subjected to compressive preloads of physiologic magnitudes. For example, Janevic et al[10] showed that a compressive preload significantly increases the bending and shear stiffness of individual human lumbar functional spinal units. However, in studies of the whole lumbar spine, physiologic compressive loads have not been applied.

Results of *ex vivo* experiments by Lucas and Bresler[12] and by Crisco[5] on the ligamentous thoracolumbar spine and the ligamentous lumbar spine, respectively, showed that the spines buckled at load levels far below those seen *in vivo*. In those experiments compressive vertical load was applied at the superior end of the specimen. The Euler stability[17] of the ligamentous spine, characterized by a critical load (maximum load-carrying capacity), was determined by those experiments. When the load exceeded the critical value, the spine, constrained to move only in the frontal plane, became unstable and buckled.

In the sagittal plane, when a compressive load is applied to a whole lumbar spine specimen along a vertical path (Figure 1A), bending moments are induced because of the inherent curvature of the lumbar spine, and the specimen undergoes large changes in its curvature at relatively small load levels. Once the end of the range of motion of the specimen is reached, further loading of the specimen in compression can cause damage to the soft tissue or bony structures.[7] This has been a limiting factor in *ex vivo* testing of long specimens of the lumbar spine under compressive loads of physiologic magnitude.

For the whole lumbar spine to sustain, without damage, the large compressive loads seen *in vivo* during standing and walking, the internal shear forces and bending moments in the spine must be small. Therefore, the resultant internal compressive load must be tangent to the curve of the lumbar spine passing through the centers of rotation of the lumbar segments (Figure 1B). The resultant internal compressive load described earlier is called a "follower load" in this article. Because the follower load remains tangent to the spinal curve, in principle, each spinal segment would be loaded in nearly pure compression. Individual lumbar functional spine

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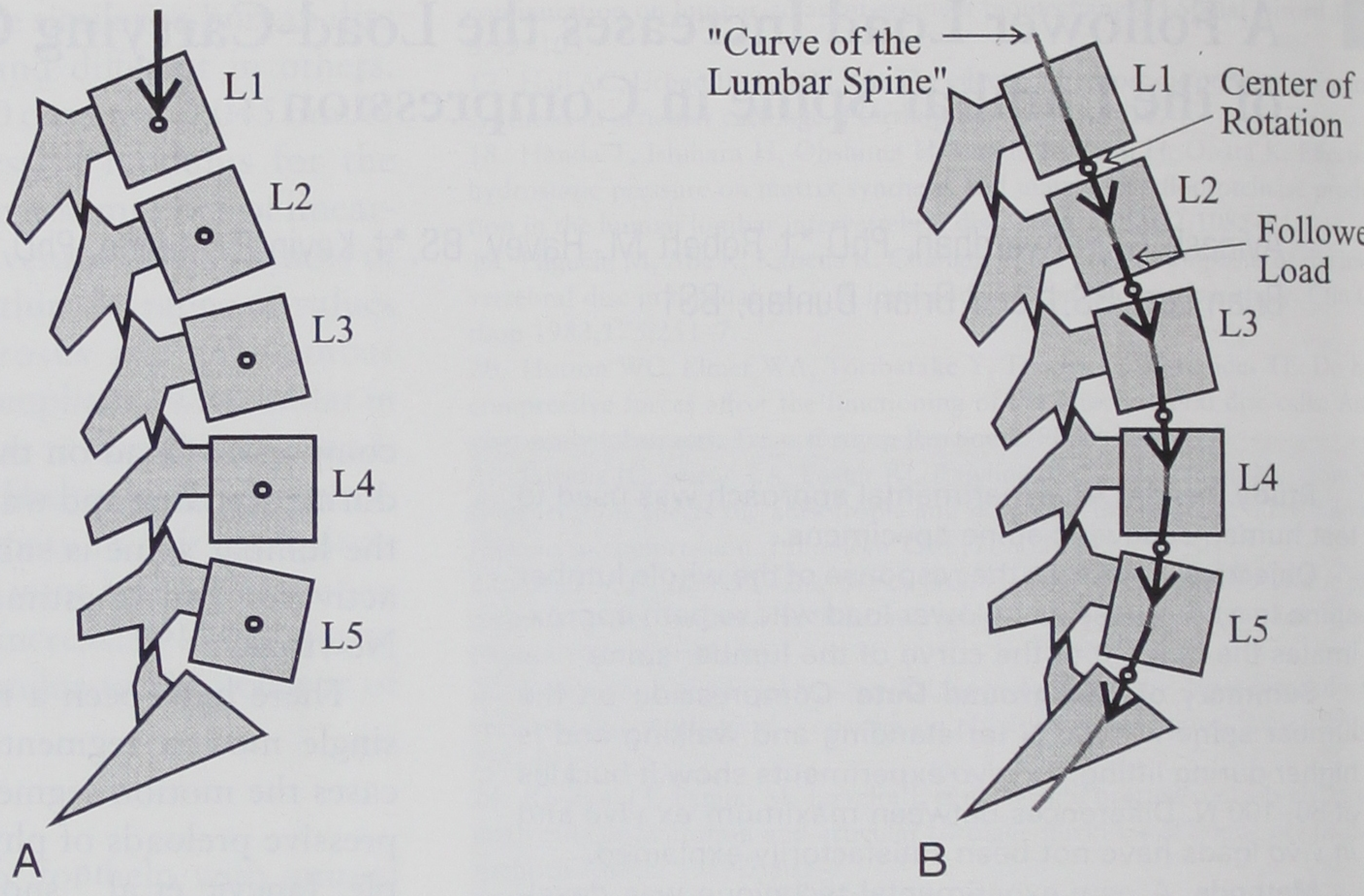

Figure 1. Depiction of compressive vertical load path (**A**) and compressive follower load path (**B**). Under the compressive follower load, the resultant internal load on the spine remains tangent to the spinal curve, passing through the center of rotation of each segment. This allows the whole lumbar spine to be lordotic and yet support large compressive loads.

units are estimated to withstand 3000–5000 N in compression without damage.[1,2,8] Therefore, in the postulated loading scheme, it would be feasible for the whole lumbar spine to support the large compressive loads seen *in vivo*.

The purpose of this study was to investigate the load-carrying capacity of the whole lumbar spine under a compressive follower load of physiologic magnitude the path of which approximates (follows) the tangent to the curve of the lumbar spine. The following hypothesis was tested: A follower load significantly increases the load-carrying capacity of the lumbar spine in compression. That is, the lumbar spine can support a much larger compressive load if it is applied along a path that approximates the tangent to the curve of the lumbar spine compared with the vertical load path.

■ Materials and Methods

The hypothesis that a follower load increases the load-carrying capacity of the lumbar spine in compression was tested using five fresh human cadaveric lumbar spine (L1–sacrum) specimens. The protocol for handling cadaveric material followed the guidelines of the Centers for Disease Control and the regulations of the institution where the experiments were performed. The specimens were from three men and two women with an age range of 25 to 43 years. Causes of death were unrelated to spine disease. Anteroposterior and lateral radiographs were obtained for each specimen to rule out obvious spinal disease. The specimens were cleaned of extraneous soft tissue, leaving the discs, facet joints, and ligaments intact. The L1 vertebra and sacrum were anchored in cups using bone cement and pins. All tests on the human cadaveric spine specimens were performed at room temperature. Care was taken to prevent dehydration of the tissue by wrapping the specimens in saline-soaked gauze.

New Technique for Application of Compressive Follower Loads. A new technique was developed for applying a compressive follower load to a multisegmented spine specimen (L1–sacrum) so that its path approximated the tangent of the curve of the lumbar spine. The load was applied bilaterally by cables and dead weights. The loading cables were firmly anchored to the cup holding the L1 vertebral body and passed freely through cable guides attached to the bodies of L2–L5 (Figure 2A). The cable guides consisted of small tubes inserted in swivel rod ends that were attached to the bodies of L2–L5 by plastic U-shaped mounts and pins (Figure 2, B and C). The threaded portion of the rod ends allowed anteroposterior adjustments of the path of the loading cable by up to 10 mm. The cables passed over pulleys attached to the cup holding the sacrum and were connected to a loading system underneath the specimen. The location of the cables was determined by approximating the center of rotation of each segment from a lateral radiograph of the specimen in the neutral lordotic posture. The cable path approximated the tangent to the curve of the lumbar spine (Figure 3). Because the cable guides move with the vertebrae, the cable arrangement assures that the load path approximates the tangent to the spinal curve as the spine is deformed under loading.

Compressive follower loads of up to 1200 N were applied in increments. This large range of loading, which covers a significant portion of the physiologic range, was generated by a mechanical lever system attached to the loading cables under the specimen. The lever amplified the force caused by dead weight by a factor of approximately 10. The tension in the cables was measured by two tension-load cells. The maximum follower load magnitude (1200 N) was limited by the strength of the loading cables used in the apparatus.

The sagittal and lateral angular motions of L1 in relation to the sacrum that were induced by applied loads were measured by two angle sensors attached to the top cup (resolution, 0.1°). The base reaction forces and moments were measured using the six-component load cell placed under the specimen. The load cell data were used to verify that the resultant force acting on the spine was in the direction of the cable.

Test Protocol. Each specimen was mounted in the specimen's neutral lordotic posture, with the L1 vertebra positioned over the sacrum in a way that approximated the normal standing

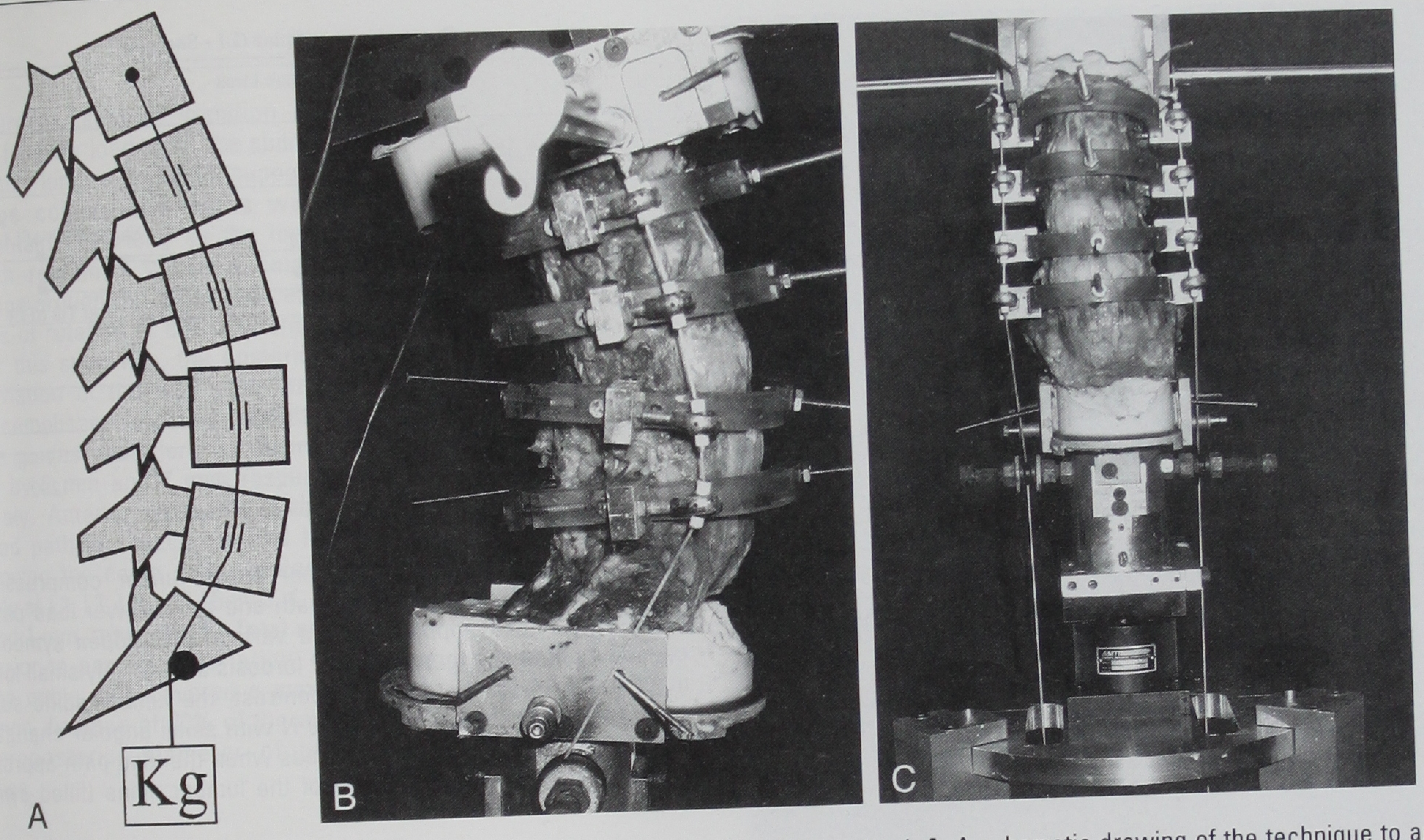

Figure 2. A human cadaveric lumbar spine subjected to a compressive follower load. **A,** A schematic drawing of the technique to apply a compressive follower load. **B,** The loading cables were firmly anchored to the cup holding the L1 vertebral body and passed freely through cable guides attached to the bodies of L2–L5. The cable guides consisted of small tubes inserted in swivel rod ends that were attached to the bodies of L2–L5 by plastic U-shaped mounts and pins. The cables were passed over pulleys attached to the cup holding the sacrum and were connected to a loading system underneath the specimen. **C,** Front view of the specimen shows bilateral cable placement.

posture.[3,9] Baseline measurements of the available range of motion were performed in flexion, extension, and lateral bending by applying incremental loads to the loading arms attached to L1, up to a maximum bending moment of 10 Nm.

The spines were tested under compressive vertical and follower loads in the neutral lordotic posture and in two flexed postures (at 15° and 25° of flexion from neutral). These tests were performed in random order. Both the vertical and follower compressive loads were applied bilaterally to the L1 vertebra. The points of application of both loads were on the same transverse (medial–lateral) axis.

Lumbar Spine Under Compressive Vertical Loads. The load-carrying capacity of the human cadaveric lumbar spines was determined under a compressive load applied in a vertical path. The load was applied using dead weights hung from the loading arms attached to L1. The magnitude of the compressive load was increased to a maximum of 110 N. The sagittal and lateral angular motions of L1 relative to sacrum were measured at each load increment. To test the specimen in a forward-flexed posture, the compressive load was first removed and the specimen positioned in the desired posture, using a flexion moment. The testing of the specimen in the new posture was repeated under compressive vertical loads.

Lumbar Spine Under Compressive Follower Loads. The load-carrying capacity of the human cadaveric lumbar spines was determined under a compressive follower load, which was applied bilaterally, by means of cables passed through cable guides attached to the vertebrae, approximating the tangent to the curve of the lumbar spine, as described. The magnitude of the compressive follower load was increased to a maximum of 1200 N. The sagittal and lateral angular motions of L1 in relation to the sacrum were measured at each load increment. To test the specimen in a forward-flexed posture, the compressive follower load was first removed and the specimen positioned in the desired posture using a flexion moment. The testing of the specimen in the new posture was repeated under compressive follower loads.

The cable path was varied to determine the effect of "imperfections" in the follower load path on the load-carrying capacity of the lumbar spine. Two variations in the follower load path were studied, in which the path was moved anteriorly and posteriorly in relation to the initial path location by moving the cable guides. The total anterior-to-posterior variation of the cable path covered a maximum distance of 20% of the anteroposterior diameter of the disc. However, the amount of variation was not uniform at all levels within a given specimen. Larger deviations were made at the L4 or L5 cable guides, and the remaining guides were moved as needed to maintain a "smooth" path of the cable. Also, the variation at each level was not uniform across all specimens because of the differences in the initial cable positions among different specimens. The locations of the follower load paths were documented using lateral radiographs. For a given location of the follower load path, the magnitude of the load was increased to a maximum of 1200 N. The sagittal and lateral angular motions of L1 in relation to the sacrum were measured at each load increment. These data were acquired for the neutral lordotic and forward-flexed postures.

To assess the repeatability of the results, each test described was performed twice and the results compared. The human

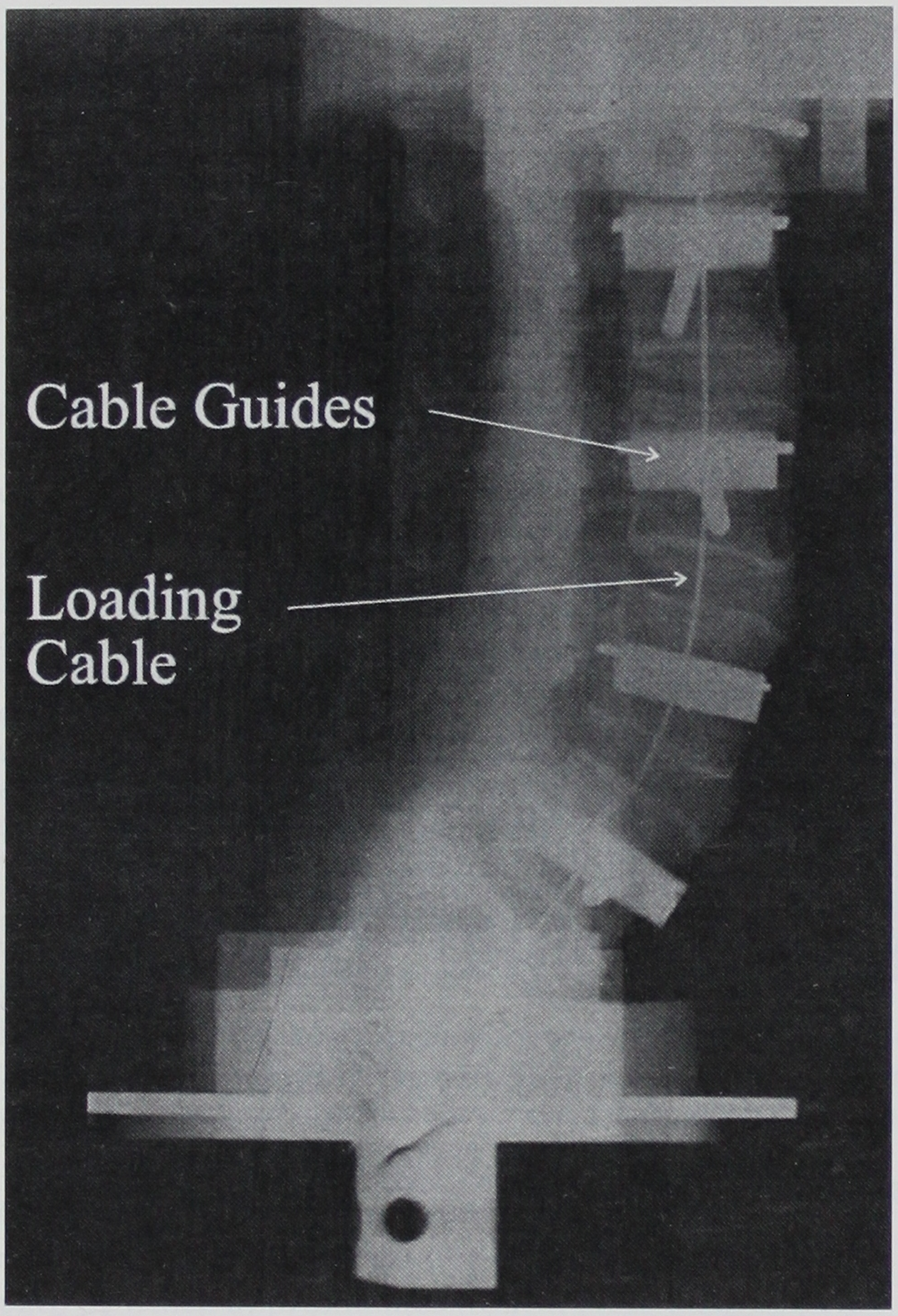

Figure 3. Radiograph showing the path of the loading cable used to apply a compressive follower load to the spine specimen.

cadaveric spine specimens were also examined visually and radiographically for any obvious damage.

■ Results

A compressive load applied to the lumbar spine along a vertical path caused large changes in lumbar lordosis at relatively small load magnitudes. This is demonstrated by the results of one of the five specimens tested (Figures 4 and 5, open symbols). In the neutral lordotic and forward-flexed postures, the lumbar lordosis changed by 10–15° when a vertical load of only 100 N was applied to L1. These results were typical of all five specimens.

In sharp contrast, all lumbar spine specimens supported a compressive load of up to 1200 N with small angular changes in both the sagittal and frontal planes when the load path was tangent to the curve of the lumbar spine (Figure 4, filled symbols). This behavior was observed in all three postures tested. Under a compressive follower load of 1200 N, the lumbar spine did not collapse in flexion or extension. It remained in an upright position away from the limits of motion (Figure 5, filled symbols).

The ability of the lumbar spine to carry large compressive loads was maintained as long as the load path re-

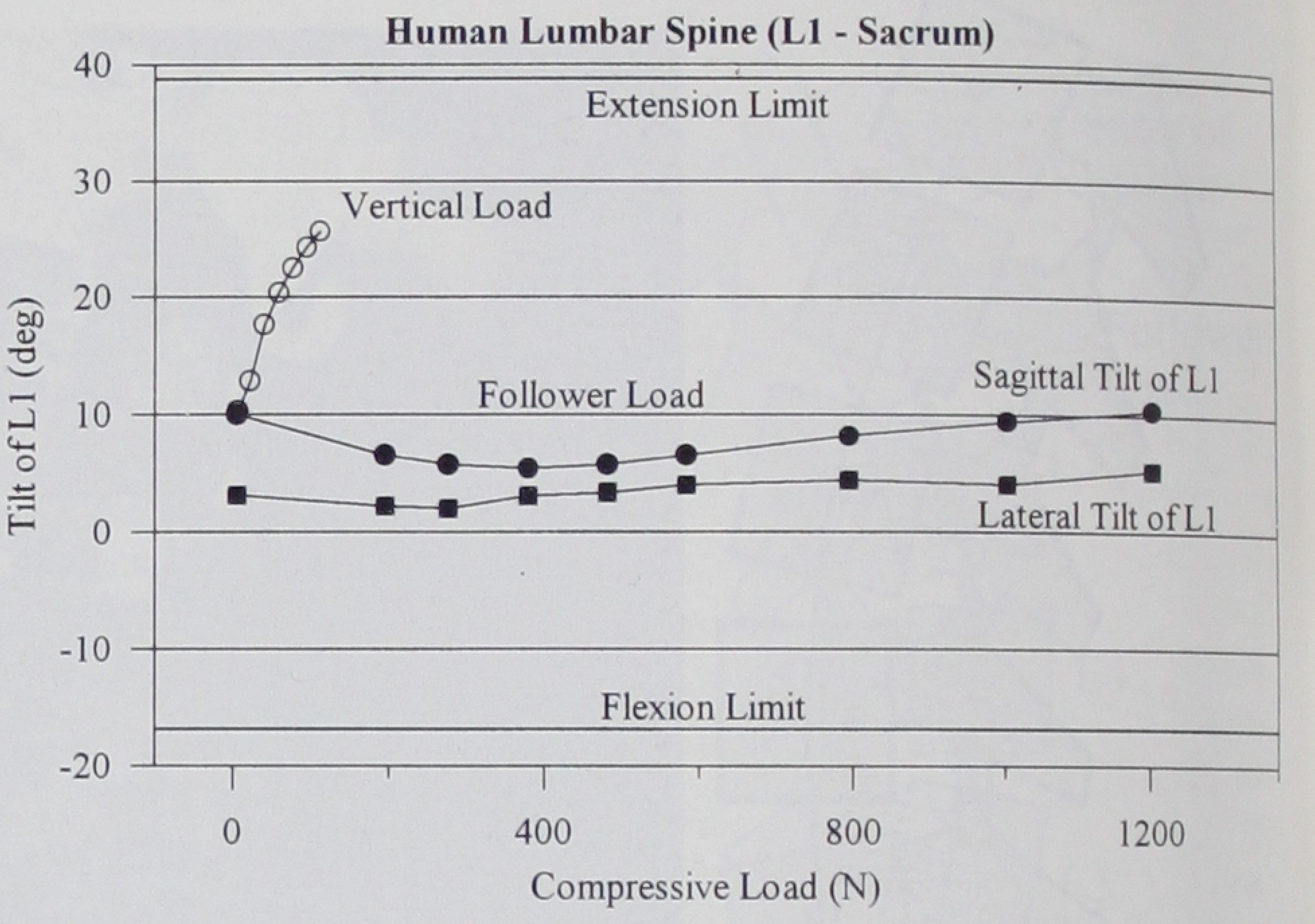

Figure 4. Human cadaveric lumbar spines under compressive loads applied along the vertical path and the follower load path. Compressive load applied along a vertical path (open symbols) caused marked changes in lumbar lordosis at relatively small load magnitudes (~100 N). In sharp contrast, the lumbar spine supported a compressive load of 1200 N with small angular changes in both the sagittal and frontal planes when the load path approximated the tangent to the curve of the lumbar spine (filled symbols).

mained within the small range of variation investigated in the study (Figure 6). When the follower load path was at the extremes of this range of variation in the neutral lordotic posture, the lumbar spine underwent larger angular changes; however, it remained in an upright position away from the limits of motion.

The follower load path that minimized the angular change under load was found to be posture dependent. The load path that caused minimal angular changes of the lumbar spine in the neutral lordotic posture induced somewhat larger changes in the forward-flexed posture (Figure 6).

The results were repeatable in each case tested. The variation in the sagittal tilt and lateral tilt of L1 were within 1° for two runs of each loading case. No obvious

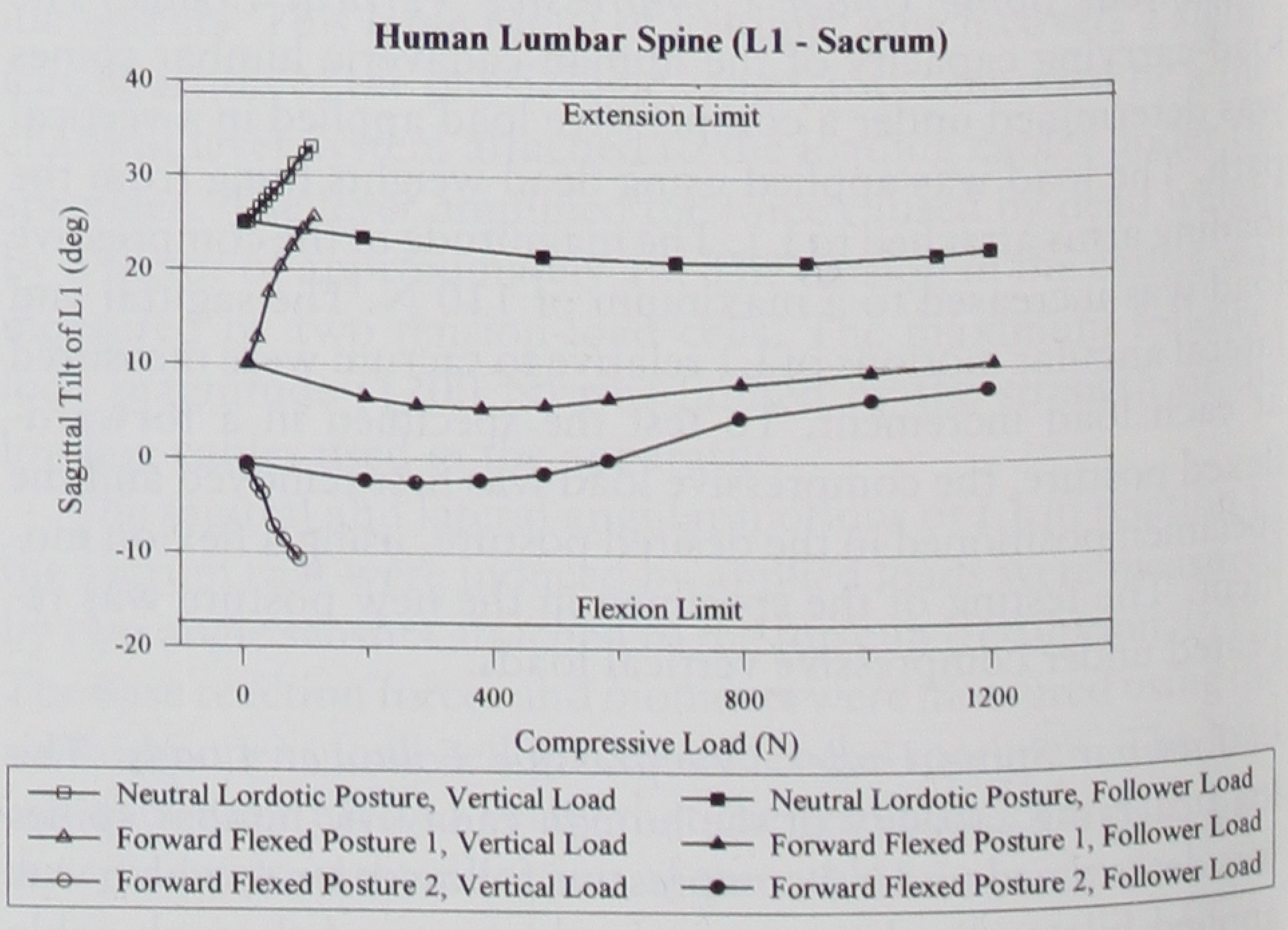

Figure 5. Increased compressive load-carrying capacity under a follower load path in neutral lordotic and forward-flexed postures.

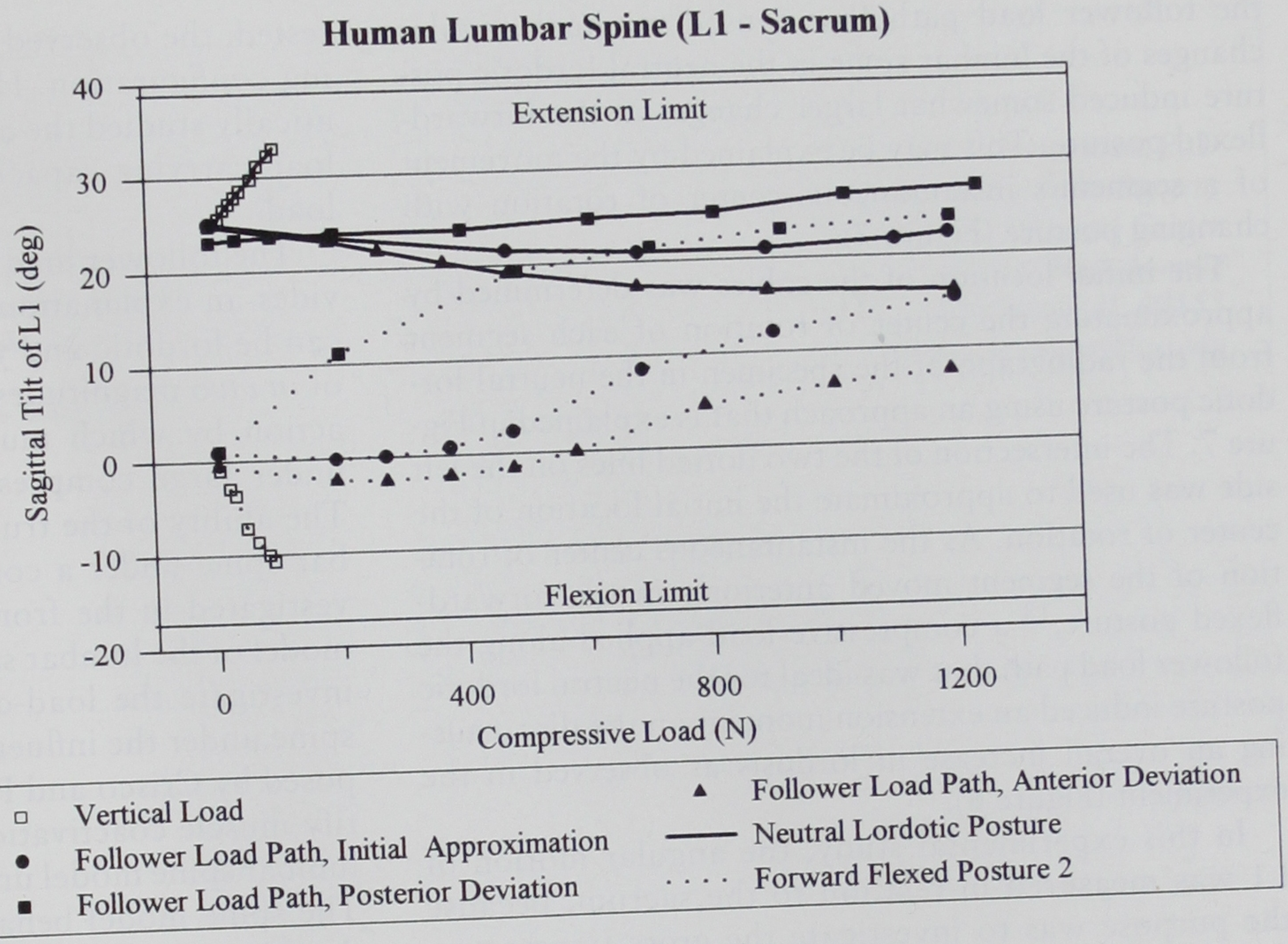

Figure 6. Effect of variation in the follower load path. The ability of the lumbar spine to support large compressive loads was maintained as long as the load path remained within a small range around the estimated centers of rotation of the segments. For this specimen, the posterior deviation of the load path was accomplished by moving the cable guides posteriorly at L4 and L5 by 2 mm and 7 mm, respectively. Anterior deviation of the load path was accomplished by moving the cable guides anteriorly at L2, L3, L4, and L5 by 3, 4, 7, and 1 mm, respectively. Total anterior-to-posterior variation of the cable path covered a maximum distance of 20% of the anteroposterior diameter of the disc.

evidence of damage to the specimens was noted in all specimens tested.

■ Discussion

This is the first report of an *ex vivo* experiment on the load-carrying capacity of the whole lumbar spine, in which the load levels approximate those *in vivo*. The fundamental difference between the current study and others is the way in which the compressive load was applied to the lumbar spine. Rather than vertically, the compressive load was applied along a follower load path—that is, the path that approximated the tangent to the curve of the lumbar spine passing through the centers of rotation of the lumbar segments.

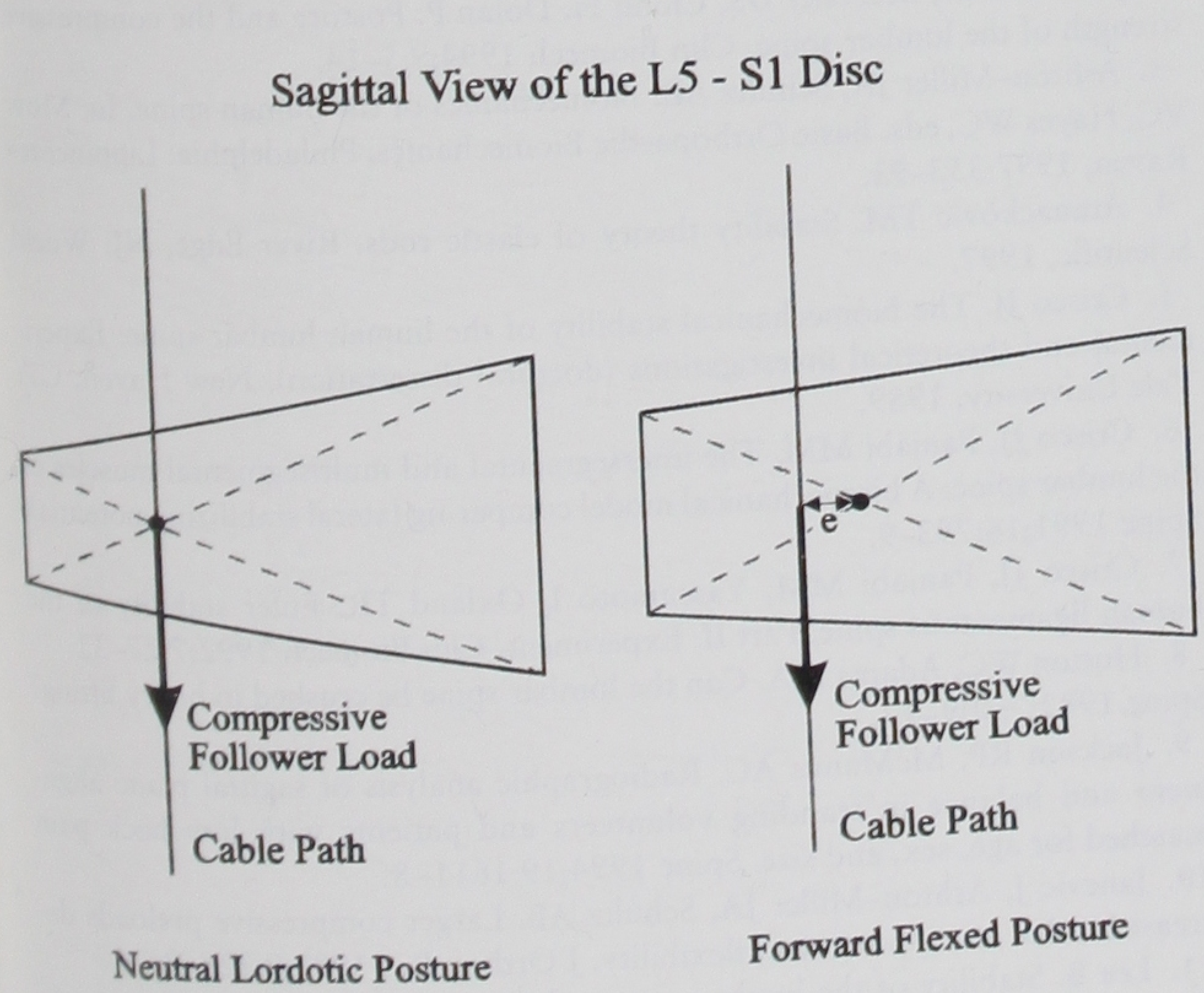

Figure 7. Effect of posture on the follower load path. The follower load path that minimized the angular change under load was posture dependent. As the instantaneous center of rotation of the segment moved anteriorly in the forward-flexed posture, a compressive load applied along the follower load path that was ideal for the neutral lordotic posture induced an extension moment on the segment, causing an overall increase in lordosis.

Lumbar spines, loaded in compression along the follower load path, supported a compressive load of 1200 N. This increase in compressive load-carrying capacity (*i.e.*, an increase in the ability to sustain compressive loads without damage), was observed in the neutral lordotic and forward-flexed postures. This is in sharp contrast to the large angular deformations in the sagittal plane at compressive vertical loads of approximately 100 N shown in the results of the current study and previous studies, such as that by Crisco et al.[7] The results in their study also showed that the lumbar spine becomes unstable in the frontal plane under a vertical load of less than 100 N, far below the physiologic loads estimated *in vivo*.

The increase in the load-carrying capacity of the spine under a compressive follower load, as observed in the current experiments, is consistent with a body of work described in Timoshenko and Gere,[17] Atanackovic,[4] and elsewhere. Using mathematical models, several investigators have predicted that, in many cases, the buckling load of beam columns subjected to compressive follower loads is significantly greater than that of columns under compressive loads applied along a vertical path. Until the current study, experimental demonstration of this phenomena had not been reported in the literature. What had been needed was an experimental technique for applying a follower load.

The load-carrying capacity of the lumbar spine sharply increased under a compressive follower load as long as the load path remained within a small range around the estimated centers of rotation of the lumbar segments. However, the path that minimized the angular change under load was found to be posture dependent;

the follower load path that caused minimal angular changes of the lumbar spine in the neutral lordotic posture induced somewhat larger changes in the forward-flexed posture. This may be explained by the movement of a segment's instantaneous center of rotation with changing posture (Figure 7).

The initial location of the cables was determined by approximating the center of rotation of each segment from the radiograph of the specimen in the neutral lordotic posture using an approach that is explained in Figure 7. The intersection of the two dotted lines on the left side was used to approximate the initial location of the center of rotation. As the instantaneous center of rotation of the segment moved anteriorly in the forward-flexed posture,[18] a compressive load applied along the follower load path that was ideal for the neutral lordotic posture induced an extension moment on the disc, causing an overall increase in lordosis as observed in the experiment (Figure 6).

In this experimental study, the angular motion of L1 was measured in relation to the sacrum, because the purpose was to investigate the gross (macro) response of the spine under compressive loads. All five human cadaveric specimens showed a significant increase in load-carrying capacity under compressive follower loads. The data were not averaged, because the locations of the follower load paths (cable paths) were different among the specimens. Therefore, the results of human cadaveric specimens were presented by graphing the response of a single, representative specimen. In this study, the maximum load-carrying capacity (*i.e.*, the buckling load) was not determined. All of the tested specimens were loaded to 1200 N, and none of them buckled. The experimental apparatus could apply a maximum load of 1200 N. This is the maximum load that the cables could withstand without breaking. Improvements in the experimental apparatus will permit higher load levels.

Every effort was made to minimize friction and binding between the loading cables and their guides. Cables were made of polyethylene fibers, and brass guide tubes were used. The tube ends were flared to prevent binding. The guide tubes were inserted in swivel rod ends to minimize further any binding. During the loading protocol, no binding between the cable and its guides was observed; slight motion of the cable in the tubes was noted during loading increments when spinal segments underwent compression under the follower load. Further, when imperfections were introduced in the load path, substantial changes in lumbar lordosis were observed, as noted in Results, indicating that the cable guides did not impede spinal motion under an applied load.

The increase in the compressive load-carrying capacity under a follower load path, compared with that of a vertical load path was observed in all human cadaveric specimens studied. Thus, within the range of variation in material properties of the specimens tested, the observed response was related to the loading configuration. However, we have not yet systematically studied the effect of material properties on the load-carrying capacity under a compressive follower load.

The follower load path described in this article provides an explanation of how the whole lumbar spine can be lordotic and yet resist large compressive loads of *in vivo* magnitudes. This may show a mechanism of action by which muscles stabilize the lumbar spine under large compressive loads experienced *in vivo*. The ability of the trunk muscles to maintain the lumbar spine under a compressive follower load was investigated in the frontal plane using a mathematical model of the lumbar spine.[11,15] The model was used to investigate the load-carrying capacity of the lumbar spine under the influence of a muscle architecture proposed by Crisco and Panjabi.[6] It was possible to identify muscle coactivation patterns that maintained the lumbar spine model under compressive follower loads. The spine model behaved similarly to the human cadaveric spine; the load-carrying capacity increased under the compressive follower load.

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