Human lumbar facet joint capsule strains: II. Alteration of strains subsequent to anterior interbody fixation

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Abstract

Background Context: In cases of low back pain (LBP) associated with biomechanical lumbar instability, anterior interbody fixation can be used as a surgical treatment, but its affect on facet joint capsule strains is unknown. *Purpose:* To determine the affect of a single-level antero-lateral interbody fixation, the changes in lumbar facet joint capsule strains at the level of and adjacent to the fixation were evaluated. *Study Design/Setting:* Human cadaveric lumbar spine specimens were tested under displacement-control before and after the addition of a single anterior thoraco-lumbar plate (ATLP) on the L4-5 motion body. *Methods:* Ligamentous lumbar spine specimens (n = 7) were potted and actuated before and after fixation of the L4-5 motion segment with an ATLP in motions of extension, flexion, left and right bending. Joint moments were calculated from the applied load and respective moment arms. Intervertebral angulation was measured using biaxial inclinometers mounted onto adjacent vertebrae. Plane strains of the capsules were measured by optically tracking the displacements of small, infrared reflective markers glued to capsule surfaces. Statistical differences ($p < 0.05$) in moment, intervertebral angle and capsular strain were assessed using ANOVA and Comparison of Linear Regression Lines. *Results:* Fixation resulted in an increase in moment at the three vertebral levels for all motions. There was also an increase in intervertebral angle at L3-4 and L5-S1, and a decrease in intervertebral angle at L4-5 for all motions. Plane strains in the L3-4 and L5-S1 facet capsules increased as a result of the fixation. L4-5 facet capsules experienced decreased and increased strains ipsilateral and contralateral, respectively, to the instrumentation. *Conclusion:* Restriction of a vertebral motion segment using a single ATLP increased adjacent capsular strains, which if supra-threshold for capsule nociceptors, could play a role in LBP. *Keywords*: plane strain, lumbar spine, facet joint capsule, low back pain, failed back syndrome, anterior lumbar fusion

Introduction

Low back pain (LBP) affects 80% of people at some point in their lifetime, with an expected recurrence rate of 85% [1]. While most cases of LBP are self-limiting [1], surgical intervention can be required with an estimated 70,000 lumbar fusion operations each year in the U.S. alone [2,3,4]. Usually these operations are successful [5,6,7], however there appear to be biomechanical consequences due to the altered loading. Specifically, fusion of a lumbar motion segment (two vertebrae, their intervening disc, facet joints, and associated ligaments) can produce increased displacements in the motion segments above and below the fusion level [8]. If the fusions were performed anteriorly, then the increased displacements are greater compared to other fusion types [3]. Fused motion segments are also associated with increased incidence of osteoarthritis (or degenerative joint disease) in these same levels [4,9]. The biomechanical effects on the facet joint capsules above and below fused motion segments are unknown.

Lumbar facet joint capsules are innervated with mechanically sensitive neurons [10,11] and stimulation of capsule nociceptors can be a source of low back pain [12,13,14]. Lumbar facet joint capsules are loaded throughout physiological ranges of motion of the lumbar spine [15], and hence increased vertebral displacements associated with lumbar fusions could be a cause of some cases of failed back syndrome [16,17]. Some forms of idiopathic LBP, which are amenable to conservative treatment due to restricted motion segments, may also be due to increased strains in facet joint capsules [18].

The current study sought to test both of these concepts by measuring plane strains in lumbar facet joint capsules before and after restricting a lumbar motion segment. It was hypothesized that restriction of intervertebral motion at the L4-5 motion segment of a human cadaveric ligamentous lumbar spine specimen, using an anterior thoraco-lumbar plate, would result in increased tensile plane strains in the L3-4 and L5-S1 facet joint capsules during physiological motions of flexion, extension, and lateral bending.

Materials and Methods

Specimen acquisition, preparation, and the testing apparatus have been described in detail in a companion paper [15]. Briefly, unembalmed, intact, human lumbar spine specimens (T12-sacrum; n=7; *mean age:* 50 years +/- 12.96 SD; *range:* 38-64; *sex:* 6 males, 1 female) were dissected free of soft tissues preserving the facet joint capsules and longitudinal ligaments. To facilitate optical measurements of capsule displacements by two CCD cameras, the spinous processes were removed. A specimen was oriented vertically (L3-4 vertebral endplates horizontal) and the sacrum potted. The T12 vertebra was coupled to a linear actuator that, by changing its position relative to the spine, could produce motions of flexion, extension, left or right bending. Joint moments at each vertebral level were determined from the load applied at the T12 vertebra and respective moment arms. Intervertebral angles for the respective joint levels were calculated as the difference in rotation of adjacent vertebral bodies and were measured using two biaxial inclinometers mounted to the anterior aspects of the respective vertebrae (Fig. 1). All analog data (actuator position, load, and 2 angle measurements per inclinometer) were sampled at 1000 Hz and streamed to disk.

To measure capsule strains, small markers (typically nine, arrayed as 3 x 3 matrix) were glued to the facet capsules. Their three-dimensional (3D) centroids were acquired using a commercially available kinematic system (two cameras, model 50, Qualisys, Inc.) at 50 Hz and streamed to disk. Capsule plane strains were calculated post-hoc for each quadrilateral element (typically four per capsule) using a finite element approach that accounted for the rotation of the plane [15].

Experimental Protocol

The experimental protocol was very similar to that previously described in detail [15]. Briefly, specimens were actuated under displacement control at the T12 level in simulated physiological motions of flexion (negative rotation about the X-axis), extension (positive rotation about the X-axis), right bending (RB - negative rotation about the Z-axis) and left bending (LB - positive rotation about the Z-axis) with respect to the neutral position of the spine. Each motion was tested in four trials of increasing displacements of 10, 20, 30, and 40 mm relative to the T12 level. A trial consisted of 10 cyclic displacements of equal amplitude at a speed of 10 mm/sec, with an inter-trial interval of three minutes.

After measurement of facet capsule strains at each of the three vertebral levels (i.e., L5-S1, L4-L5, & L3-4), the L4-5 joint level was fixed using a single Synthes® Anterior Thoraco-Lumbar Plate (ATLP). The plate was applied onto the left anterolateral aspects of the respective vertebrae using two interbody screws per vertebra (Fig. 2). Once the ATLP was in place, the testing protocol was repeated in its entirety.

Data Analysis

The contribution of each motion segment to the total range of motion of the lumbar spine is different in flexion than extension [8,15]. For this reason, flexion and extension were analyzed as separate motions, instead of one continuous movement through the neutral position, as were left bending and right bending. The stiffness of each motion segment was calculated as the slope of the most linear portion of the moment - IVA relationship for each respective motion [3].

Principal strains (E1 and E2, defined based on their directions relative to the X- and Y-axes, respectively) of the facet capsules were calculated from the plane strains for each quadrilateral element (typically four per capsule) on each capsule. In general (84% and 80% of the un-plated and plated elements, respectively), the magnitude of one of the principal strains was positive (tensile) and the other negative (compressive). To facilitate systematic comparison, the positive strain was placed into a group referred to as $\hat{E}_1$ and the negative principal strain was placed into a group referred to as $\hat{E}_2$; in cases where both strains were either positive or negative, the most positive strain was placed in $\hat{E}_1$, keeping its sign if negative [15].

Statistical differences ($p < 0.05$) in the relationships between displacement and strains, IVA and moment, before and after spinal fixation, were assessed by comparison of linear regression lines (CLRL) [19]. At each tested displacement, differences in IVA and moment resulting from spinal fixation were compared using ANOVA (Sigma Stat, v2.03). Due to low statistical power, which resulted from the relatively high variability in strain patterns and relatively small sample size [15], ANOVA and other related approaches were inappropriate to evaluate strain differences. Changes in stiffness of the vertebral levels were compared using ANOVA (Sigma Stat, v2.03).

Results

Motion Segment Biomechanics

Following fixation at the L4-5 vertebral level, mean joint moments increased relative to the un-fixed state at all vertebral levels for all motions (Fig. 3), though not all increases were significant. On average, the greatest increase in mean moment occurred at L4-5 during extension and flexion, while L5-S1 exhibited the greatest increase during bending (with the exceptions of 20 and 30 mm of flexion and 30 mm in left and right bending, respectively; percent increase range from 5.58% - 64.76%). Increases in mean moment following fixation were typically greatest at 20 and 30 mm of displacement for all motions (ANOVA, $p < 0.05$ in 9 of 12 and 7 of 12 vertebral level/motion combinations, respectively). The relationship between moment and displacement was highly correlated at all vertebral levels during all motions in both the un-plated and plated specimens (R^2 range from 0.918 - 0.9899). For all vertebral levels, this relationship was only statistically different between the un-plated and plated states during bending (CLRL, $p<0.05$, see Fig. 3).

Spinal fixation at the L4-5 level resulted in increases in mean IVA at L3-4 and L5-S1, and decreases in mean IVA at L4-5 during all motions (Fig. 4). Similar to the moment results, the greatest percent change in IVA typically occurred at L4-5 during extension and flexion (with the exception of 40 mm extension and 10 and 40 mm flexion) and at L5-S1 during bending (with the exception of 10 mm left bending). At the level of L4-5, IVA was significantly reduced at every displacement during flexion and from 20 – 40 mm in extension (ANOVA, $p<0.05$). The relationship between IVA and displacement was also significantly different for these motions

(CLRL, $p<0.05$). Fixation did not result in a significant reduction in IVA at L4-5 at any displacement during bending, nor was the relationship between IVA and displacement significantly altered. Significant differences at L5-S1 were observed from 20 – 40 mm during extension, 30 – 40 mm during flexion, and at 20 and 30 mm during bending (ANOVA, $p<0.05$). The relationship between IVA and displacement was significantly altered at L5-S1 after fixation during all motions (CLRL, $p<0.05$). Compared to the changes at L4-5 and L5-S1, the changes at L3-4 were smaller, and were only significant at 10 mm of flexion (ANOVA, $p<0.05$).

The mean stiffness of the specimens for each motion varied according to vertebral level, as did the change in stiffness subsequent to fixation (Fig. 5 and Table 1). Specifically, the mean stiffness, as a result of plating at L4-5, increased at L3-4 and L4-5 during all motions, but decreased at L5-S1 (with the exception of flexion). Changes in stiffness were only significant at the level of L4-5 during motions of flexion and right bending ($p = 0.009$ and $p = 0.0002$, respectively), motions that induced a tensile load (relative to the 'Y-axis' of the spine, see Fig. 1) in the facet joints ipsilateral to the ATLP.

Strains

Before and after fixation, the mean principal strains ($\hat{E}_1$ and $\hat{E}_2$) were highly correlated with all spine motions (flexion, extension, and bending) at each of the three motion segments (Figs. 6-7). The mean Pearson correlations, combining all motions (before and after fixation, respectively), were as follows: $\hat{E}_1$ – 0.9074 +/- 0.19 SD, & 0.9281 +/- 0.15 SD; $\hat{E}_2$ – 0.8569 +/- 0.23 SD, & 0.86711 +/- 0.19 SD. $\hat{E}_1$ increased with increasing displacement and was largest at L5-S1, decreasing in magnitude as the vertebra increased in a cephalic direction. $\hat{E}_2$ capsular strains became more negative with increasing displacement and were largest at L4-5 and L5-S1, which had strains of similar magnitudes, while the strains were smaller at L3-4.

In the left and right L3-4 facet capsules, fixation of the motion segment below resulted in mixed patterns of strains, dependent on the spine motion. During flexion and extension, there were no significant differences in the principal strains ($\hat{E}_1$ and $\hat{E}_2$) following fixation (Fig. 6). Lateral bending produced mirror symmetry in the magnitudes of the mean principal strains ($\hat{E}_1$ and $\hat{E}_2$) on the right and left facet capsules in both the un-plated and plated states. The relationship between $\hat{E}_1$ and displacement was significantly increased following fixation, but only for the capsule experiencing tension (i.e. the right facet capsule during left bending and the left facet capsule during right bending) (Fig 7). $\hat{E}_2$ remained unchanged during bending after fixation.

In the L4-5 facet capsules, spinal fixation resulted in significant alterations in principal strains, which appeared to be influenced by the side on which the ATLP was located (Fig. 6 – 7). Ipsilateral to the instrumentation (i.e., the left side), all motions resulted in decreased mean principal strains ($\hat{E}_1$ and $\hat{E}_2$), though significance was only observed in motions producing tension of the capsule (flexion and right bending) ($\hat{E}_1$ – flexion and right bending; $\hat{E}_2$ – right bending; CLRL, $p<0.05$). Contralateral to instrumentation (i.e., the right side), all motions with the exception of flexion resulted in significant increases in the relationship between $\hat{E}_1$ and displacement, but $\hat{E}_2$ strains remained unchanged.

The L5-S1 capsules experienced an increase in mean principal strain as a result of fixation at L4-5, but the increases were not uniform from the left to the right side (Figs. 6-7). On the left capsule, tensile motions (flexion and right bending) produced significant changes in the relationship between $\hat{E}_1$ capsular strains and displacement (CLRL, $p<0.05$), while $\hat{E}_2$ strains remained unchanged. Mean principal strains ($\hat{E}_1$ and $\hat{E}_2$) on the left capsule remained unchanged during extension and left bending. On the right capsule, the relationships between $\hat{E}_1$ capsular strains and displacement were significantly greater during extension and left bending (CLRL, $p<0.05$), but were unchanged during flexion and right bending. $\hat{E}_2$ strains on the right capsule remained unchanged during all motions.

Discussion

This is the first report of the effects of vertebral motion segment fixation on facet capsule strains. Fusion of two vertebrae has been shown to result in the transfer of the motion that had previously occurred at the operated level to the adjacent segments [8,3,17,9,20], and to L5-S1 in particular [8]. Fixation at L4-5 using a single ATLP reduced, but did not eliminate, motion at the level of fixation. Therefore, this acute fixation model may also simulate some biomechanical effects associated with restricted vertebral motion segments as seen in other idiopathic forms of LBP that are amenable to conservative treatments (e.g., high velocity low amplitude spinal manipulations). The effect of this motion reduction was observed in the decrease in L4-5 mean capsular strains ipsilateral to instrumentation and the increase in L4-5 mean capsular strains contralateral to instrumentation. The motion reduction at L4-5 also elicited an effect on the adjacent motion bodies, distal and proximal. Both L3-4 and L5-S1 experienced an increase in moment, IVA and capsular strain following fixation at the L4-5 motion body, supporting the concept that a transfer of motion to adjacent segments following fixation could play a role in failed back syndrome.

The transfer of motion to the adjacent segments altered the relationship between strain and displacement in the adjacent facet capsules. Significant differences in the relationship between strain and displacement were found at a vertebral level during motions that had corresponding significant differences in the relationship between IVA and displacement, moment and displacement, or both. Fixation had a greater effect on these relationships at L5-S1, compared to L3-4. This was demonstrated not only by the frequency of statistical significance in the changes in moment and IVA, but also by the significantly increased capsular strains at L5-S1, which has not previously been shown in the literature. Assuming that in-vivo instrumentation ultimately leads to a greater degree of fixation, if not outright fusion, of the motion bodies, it could be extrapolated that the increased capsular strain observed in the adjacent segments would be further increased for fused motion segments.

Fixation using the ATLP did not result in statistical differences in the strains produced on the facet capsules ipsilateral to instrumentation during compressive motions (extension and left bending), corresponding to the mathematical model of Lee and Lagranga [17]. Their model predicted that under a compressive load, an anterior fusion of the lumbar spine would cause a slight increase in shear stress and compressive stress on the disc of the adjacent segment, while exhibiting less of an effect on the facet joints themselves. It is possible that the acute effect of a single ATLP prior to bony fusion is insufficient to decrease the motion of the facet joints, and therefore surrounding capsules, due to the facet – lamina geometry. During extension, the superior facet process can impinge onto the lamina of the vertebra below, restricting further extension of that motion segment [21,22,23]. This is unlike flexion, in which the facet joints are principally constrained by soft tissues and could be better restrained by the ATLP. Our results directly support this, as flexion and the lateral bending resulting in tensile load application on a facet joint more often resulted in significant changes in vertebral body motion (IVA) and capsular strains compared to extension and the compressive bending motion (i.e., left bending on left capsules, right bending on right capsules). This is further supported by the intervertebral stiffness calculations, which showed significant increases only at the level of the ATLP (L4-5) during flexion and right lateral bending, motions resulting in tensile loads in the facet joints ipsilateral to the ATLP.

The degree of fixation achieved acutely with a single ATLP could be comparable to the loss of normal intervertebral motion seen in types of non-surgical LBP syndromes. If so, the alterations in developed moment, IVA and capsular strain measured in the current study could be indicative of lumbar biomechanics and strain in patients suffering from restricted vertebral body motion pathologies, such as lumbar spine stenosis. In these patients, who employ more conservative treatments such as exercise, physical therapy or spinal manipulation, regaining normal intervertebral motion of the restricted body reduces LBP [24,25], suggesting that changes in lumbar biomechanics and capsular strain consequent to a restriction contributed to the LBP.

The increased principal strains on the adjacent facet joint capsules, due to the ATLP, directly implies increased stress as well. This could potentially lead to structural changes in the capsule, similar to those observed in other soft tissues due to increased loading conditions. Adjacent disc degeneration resulting from hyper-mobility of juxta-fused segments has been shown in numerous studies [8,17,9,20,26,27]. Following anterior fixation of the lumbar spine, the posterior longitudinal ligament demonstrated a decrease in stiffness and elastic modulus and exhibited a breakdown of collagen fibrils [28]. Given the structural similarity of the capsule (e.g., similar collagen makeup), it is reasonable to infer that increased loading could result in a similar breakdown of collagen fibrils, decreasing its stiffness and increasing strains along the axis of the collagen fibers (i.e., E1 principal strains during extension and flexion and E2 principal strains during bending). Increased strain heightens the potential for an increase in supra-threshold stimuli to mechanically sensitive neurons.

When interpreting the results of this study, there are methodological factors to consider. First, the effect the surrounding soft tissues on capsular strain was not measured. The multifidi muscles have some insertions in the facet capsule and are most active during extension [29], which could cause capsular strain independent of the strain resulting from the motion itself. Therefore, the use of cadaveric specimen in the current study would tend to lead to more conservative strain measurements along the axis of muscle contraction (i.e., E1) than would be measured during extension in-vivo. The interspinous ligaments, which primarily tend to resist flexion, were removed along with the spinous processes to facilitate viewing of a capsule by two cameras. Removal of these ligaments could lead to smaller measured joint moments than occur in-vivo. The strain measurements would not be affected as the experiments were performed under displacement control. Second, variability in the strain data, probably resulting from the varying demographics of the specimens and relatively small sample size, lowered the power of paired statistical tests making them inappropriate for use. Changes in strain after fixation with the ATLP could not be tested for significance at each displacement, and some significant differences were likely missed. However, the statistics comparing the increasing or decreasing trends of strain, resulting from fixation, as a function of displacement were not underpowered, and showed significant differences, despite the variability and sample size. Increasing the sample size, and thereby, increasing statistical power of the strain data, would most likely only serve to show more statistical significance than demonstrated in this study. Third, the experimental protocol described earlier required that each of the specimens were subject to several freeze-thaw cycles and exposures to the air for the capsule being tested, which could have altered the material properties of the capsules. Any drying of the capsules that may have occurred would have tended to reduce pliancy of the tissue, and hence, could have reduced strain magnitudes along the axis of the collagen fibrils. This effect would again have made the current study's measurements a conservative approximation of in-vivo capsular strains.

In conclusion, the data from the current study indicate that acute decrease in intervertebral motion results in increased capsule strains of the adjacent motion segments during physiological spine motions. The implications of the increased strains on spine function, proprioception, and low back pain need further investigation.

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Figure Legends

Figure 1. The schematic of the experimental setup. **a)** Two CCD cameras were used for optically tracking the markers glued to the facet joint capsule surface for subsequent strain calculations. **b)** A human cadaveric lumbar spine specimen was fixed to the testing surface, with coordinate axes as shown. **c)** A force transducer was used to measure the applied load. The loading apparatus consisted of **d)** a displacement controlled linear actuator with **e)** an optical position encoder for the determination of actuator position. **f)** Biaxial inclinometers were attached to the facet joint capsule's respective anterior vertebral bodies for measurement of intervertebral angle.

Figure 2. X-ray of a lumbar spine specimen after an anterior lumbar fixation plate was screwed into the L4-5 vertebrae. Note the insertion of two screws per vertebrae.

Figure 3. Joint moments measured during extension, flexion, and left and right lateral bending at L3-4, L4-5, L5-S1 in normal lumbar spines and lumbar spines with anterior interbody fixation (plated) at L4-5. Error bars are standard deviations. * - indicates statistical significance ($p<0.05$, ANOVA) between the normal and plated spines at that displacement. ** – indicates statistical significance in regression lines between the plated and normal spines from 0 – 40 mm of displacement for that motion.

Figure 4. Intervertebral angle (IVA) measured during extension, flexion, and left and right lateral bending at L3-4, L4-5, L5-S1 in normal lumbar spines and lumbar spines with anterior interbody fixation (plated) at L4-5. Error bars are standard deviations. * - indicates statistical significance ($p<0.05$, ANOVA) between the normal and plated spines at that displacement. ** – indicates

statistical significance in regression lines between the plated and normal spines from 0 – 40 mm of displacement for that motion.

Figure 5. Fixation of the L4-5 vertebral motion segment, using an anterior thoraco-lumbar plate (ATLP) increased the joint stiffness (defined as the most linear portion of the Moment-Intervertebral Angle relationship). Regression lines used to calculate stiffness in the representative specimen data (at L4-5) are shown. Mean stiffness at L4-5 of all specimens was significantly increased after the addition of the plate during flexion ($p = 0.009$) and right lateral bending ($p = 0.0002$).

Figure 6. Average $\hat{E}_1$ and $\hat{E}_2$ Principal Strains on the right and left side facet joint capsules of the lumbar spine during motions of extension and flexion before (normal) and after (plated) fixation at L4-5. Regression lines of data shown. ** – indicates statistical significance of the regression lines from 0 - 40 mm during that motion.

Figure 7. Average $\hat{E}_1$ and $\hat{E}_2$ Principal Strains on the right and left side facet joint capsules of the lumbar spine during motions of left lateral bending and right lateral bending before (normal) and after (plated) fixation at L4-5. Regression lines of data shown. ** – indicates statistical significance of the regression lines from 0 - 40 mm during that motion.

Stiffness (Nm/deg)	Extension	Flexion	LLB	RLB
L3-4 Normal	1.07±1.13	1.24±1.04	1.19±0.74	0.74±0.34
L3-4 Plated	1.28±0.41	1.85±1.47	1.26±0.64	0.98±0.52
L4-5 Normal	2.03±1.06	0.82±0.53	1.75±1.22	0.99±0.32
L4-5 Plated	3.29±2.02	2.15±1.39*	1.94±0.59	1.94±0.59*
L5-S1 Normal	1.54±0.64	1.29±0.87	2.85±1.36	2.05±0.67
L5-S1 Plated	0.95±0.53	1.42±1.26	1.76±0.71	1.86±0.96

[1] LLB- left lateral bending

[2] RLB – right lateral bending

Table 1. Mean stiffness of the lumbar spine vertebra, defined as the most linear portion of the Moment-Intervertebral Angle relationship, before (normal) and after (plated) the addition of a single anterior fixation plate at L4-5. * - indicates statistical difference ($p < 0.05$) between the normal and plated states for that vertebrae during that motion. L4-5 Flexion: p = 0.009; L4-5 RLB: p = 0.002.

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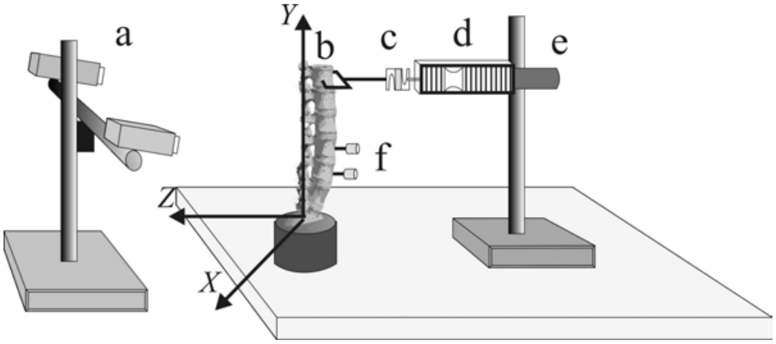

Figure 1. The schematic of the experimental setup. **a)** Two CCD cameras were used for optically tracking the markers glued to the facet joint capsule surface for subsequent strain calculations. **b)** A human cadaveric lumbar spine specimen was fixed to the testing surface, with coordinate axes as shown. **c)** A force transducer was used to measure the applied load. The loading apparatus consisted of **d)** a displacement controlled linear actuator with **e)** an optical position encoder for the determination of actuator position. **f)** Biaxial inclinometers were attached to the facet joint capsule's respective anterior vertebral bodies for measurement of intervertebral angle.

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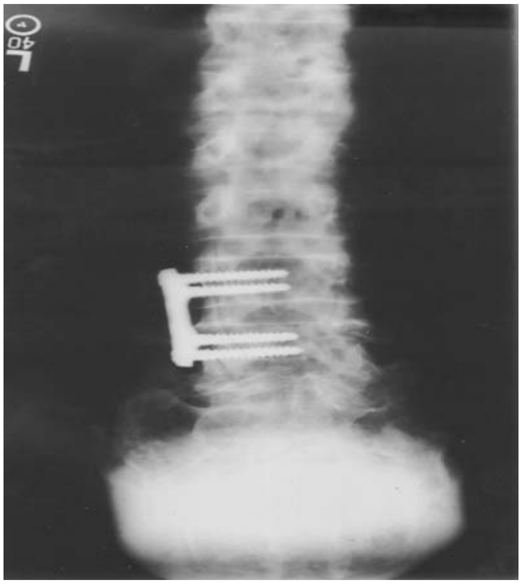

Figure 2. X-ray of a lumbar spine specimen after an anterior lumbar fixation plate was screwed into the L4-5 vertebrae. Note the insertion of two screws per vertebrae.

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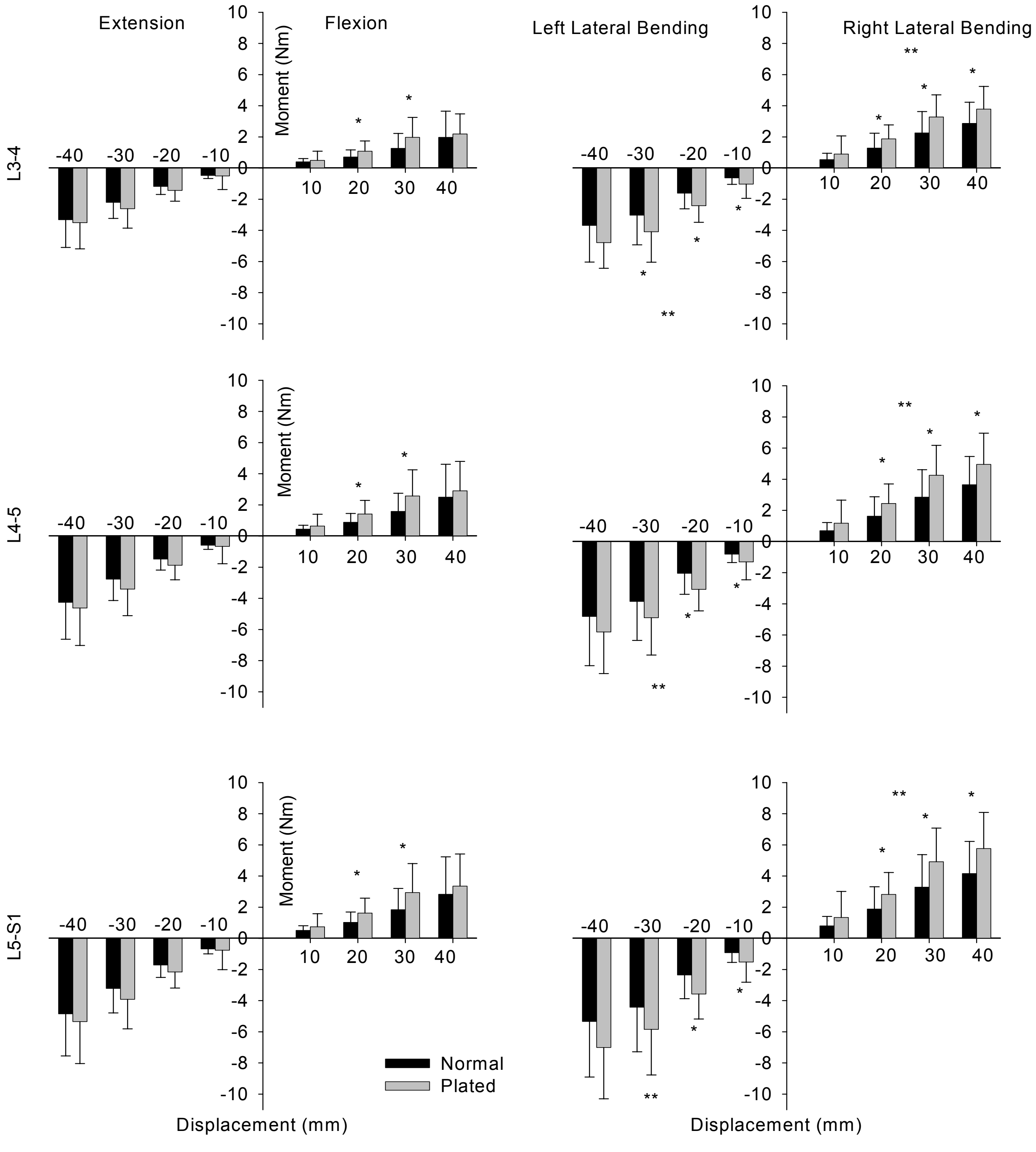

Figure 3. Joint moments measured during extension, flexion, and left and right lateral bending at L3-4, L4-5, L5-S1 in normal lumbar spines and lumbar spines with anterior interbody fixation (plated) at L4-5. Error bars are standard deviations. * - indicates statistical significance ($p<0.05$, ANOVA) between the normal and plated spines at that displacement. ** – indicates statistical significance in regression lines between the plated and normal spines from 0 – 40 mm of displacement for that motion.

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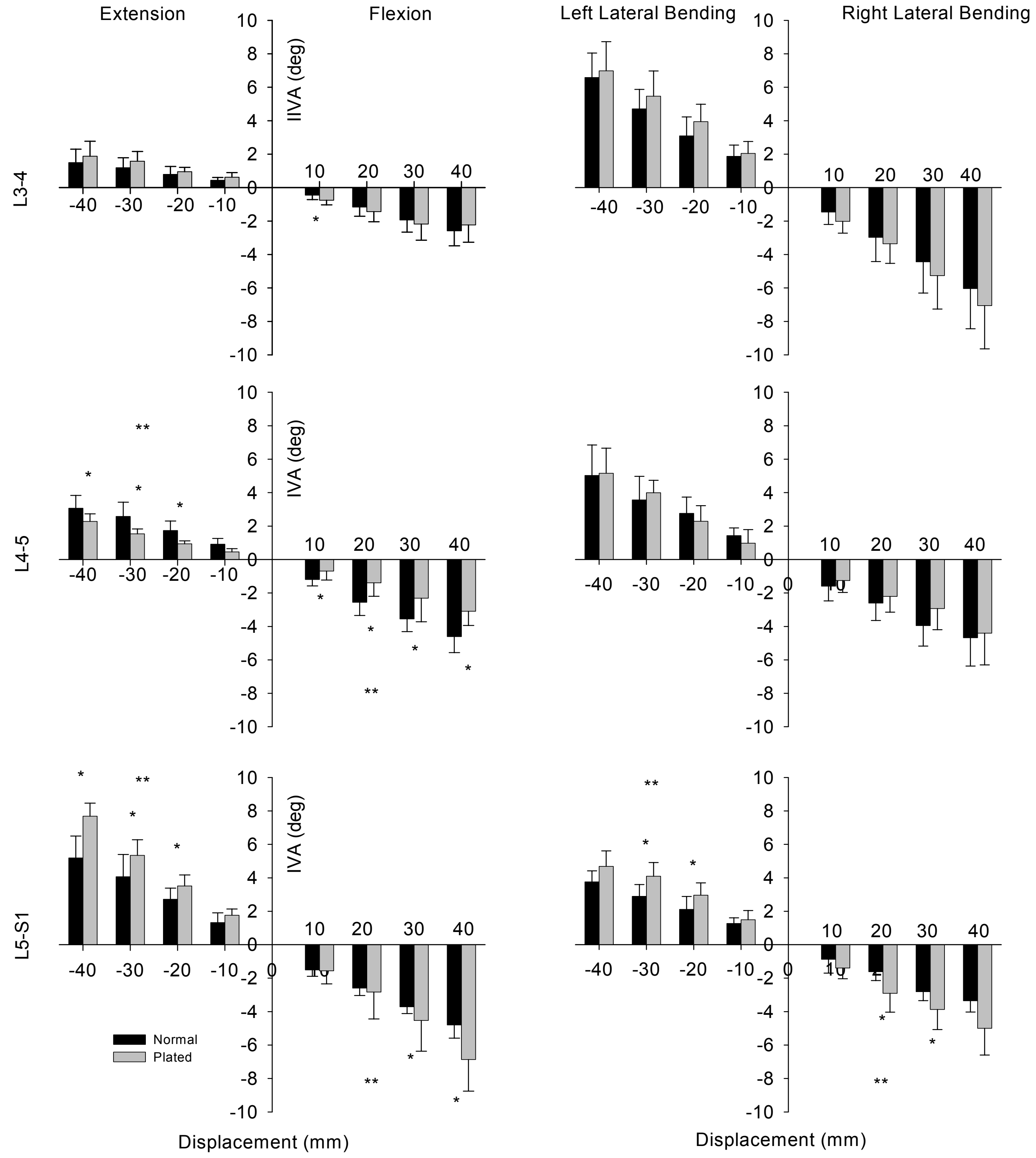

Figure 4. Intervertebral angle (IVA) measured during extension, flexion, and left and right lateral bending at L3-4, L4-5, L5-S1 in normal lumbar spines and lumbar spines with anterior interbody fixation (plated) at L4-5. Error bars are standard deviations. * - indicates statistical significance ($p<0.05$, ANOVA) between the normal and plated spines at that displacement. ** – indicates statistical significance in regression lines between the plated and normal spines from 0 – 40 mm of displacement for that motion.

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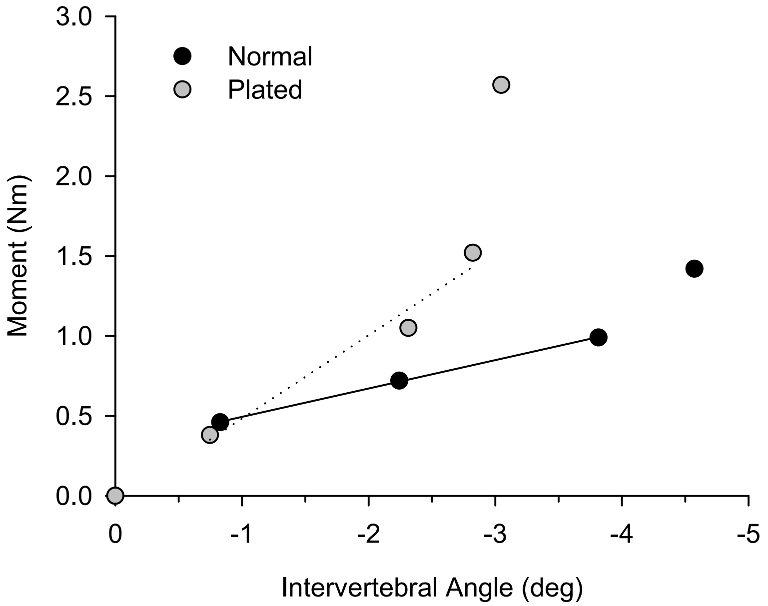

Figure 5. Fixation of the L4-5 vertebral motion segment, using an anterior thoraco-lumbar plate (ATLP) increased the joint stiffness (defined as the most linear portion of the Moment-Intervertebral Angle relationship). Regression lines used to calculate stiffness in the representative specimen data (at L4-5) are shown. Mean stiffness at L4-5 of all specimens was significantly increased after the addition of the plate during flexion (p = 0.009) and right lateral bending (p = 0.0002).

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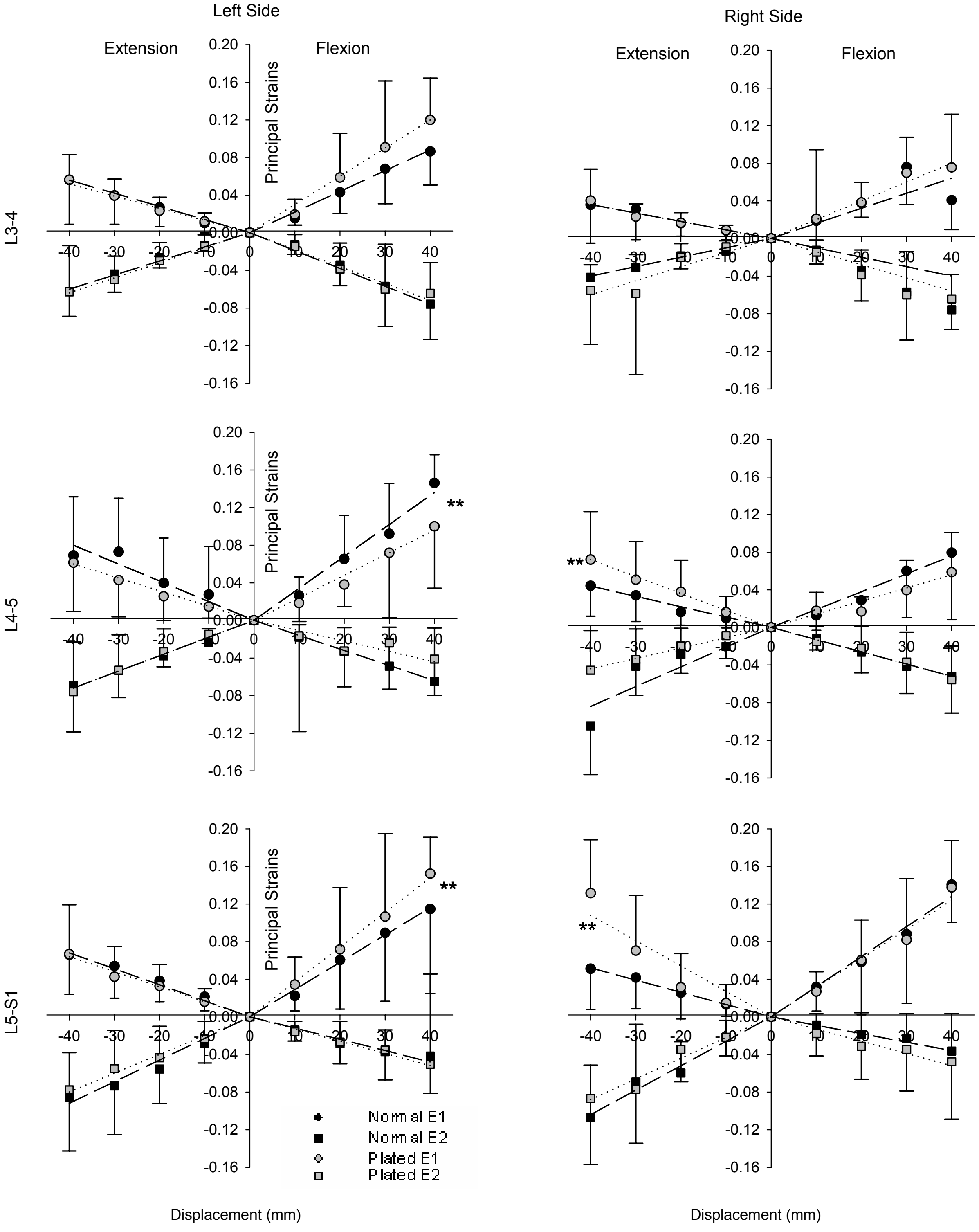

Figure 6. Average $\hat{E}_1$ and $\hat{E}_2$ Principal Strains on the right and left side facet joint capsules of the lumbar spine during motions of extension and flexion before (normal) and after (plated) fixation at L4-5. Regression lines of data shown. ** – indicates statistical significance of the regression lines from 0 - 40 mm during that motion.

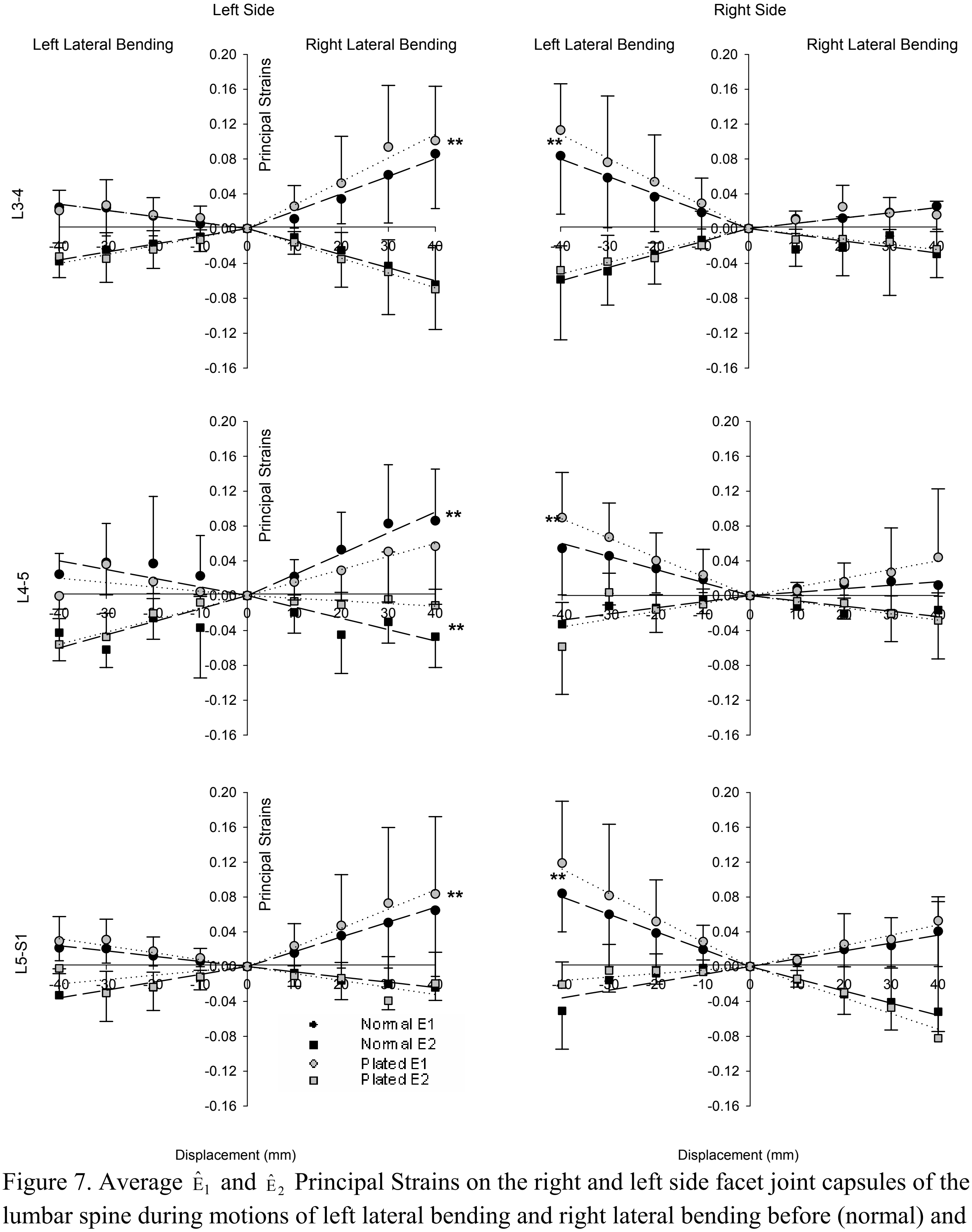

Figure 7. Average $\hat{E}_1$ and $\hat{E}_2$ Principal Strains on the right and left side facet joint capsules of the lumbar spine during motions of left lateral bending and right lateral bending before (normal) and after (plated) fixation at L4-5. Regression lines of data shown. ** – indicates statistical significance of the regression lines from 0 - 40 mm during that motion.