Spine

SPINE Volume 37, Number 16, pp E942–E948
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BIOMECHANICS

Pullout Analysis of a Lumbar Plate With Varying Screw Orientations

Experimental and Computational Analyses

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Study Design. Experimental and finite element analysis of anterior lumbar interbody fixation (ALIF) plate pullout.

Objective. The objective of this study was to determine the effect of screw angle and orientation on ALIF plate pullout strength.

Summary of Background Data. It has been thought that angling the screws in an ALIF plate leads to better fixation strength; however, a few studies are published on this question, which produced conflicting results.

Methods. Using custom guides, screws were configured in 9 different orientations to affix ALIF plates to polyurethane foam blocks. Pullout tests were performed at a rate of 1 mm/min. In addition, finite element analyses were performed on a 2-dimensional screw-block model to gain insight into the internal stress during pullout.

Results. The pullout load was the greatest, with screws positioned 12° outward sagittaly and 6° inward coronally (936 ± 72 N). This orientation was statistically greater than the orientation with the lowest pullout load (812 ± 45 N, $P < 0.05$); however, no group was statistically different than placing the screws straight in (868 ± 86 N, $P > 0.05$). Finite elements analysis showed some gain in pullout strength at 12° followed by some loss at greater angles. As the screw insertion angle increased, stress levels elevated within the block even in the regions away from the screw.

Conclusion. Significant difference was found between certain screw-angle configurations; however, when compared with simply placing the screws straight in, the difference was never more than 8%. This implies that there is greater freedom in the angle and placement of screws than previously thought. Our results show that there is little change in fixation strength when placing the screw in a different direction.

Key words: lumbar fusion, screw angle, anterior plate, pullout test. **Spine 2012;37:E942–E948**

Anterior vertebral plating is a commonly used technique to immobilize the spine in the presence of anterior column instability. After being successfully practiced in the cervical spine for a long time, the anterior plates have recently become popular in supporting the lumbar spine in anterior interbody fusion surgeries.

The stability of the fusion segment relies on the fixation strength of the screws. Although healthy vertebral trabecular bone provides a reliable environment for fixation in the lumbar spine for pedicle screws, anterior plate screws have limited ability to take advantage of the vertebral trabecular core due to their limitations in size. Moreover, the density of bone in the vertebral body is not as high as that in the pedicle.[1] This makes plate screws more prone to losing the bony engagement, especially in the elderly patient population.

In order to increase the pullout strength of anterior lumbar plates, screws are inserted oblique to the plate rather than perpendicular. Specific screw angulations vary between manufacturers and surgeons. Although this screw orientation has been intuitively thought to increase the screw-holding power, there is no evidence that plates with angled screws have increased pullout strength compared with those with screws placed straight into the vertebral body.

In the literature, studies investigating the influence of screw angle on pullout strength show conflicting results. Certain studies have indicated that placing screws at a 10° angle would produce a higher pullout load.[2,3] Other studies indicate that placing screws straight in yields the highest pullout load.[4,5]

In this study, plate pullout performance with various screw orientations was investigated using a uniform foam model. Finite element analysis (FEA) was also employed to help understand mechanisms of screw-block interaction that may explain differences in experimentally observed behaviors by analyzing the stress distribution at the screw-foam interface

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Acknowledgment date: April 4, 2011. First revision date: November 10, 2011. Second revision date: January 18, 2012. Acceptance date: March 3, 2012.

The device(s)/drug(s) is/are FDA approved or approved by corresponding national agency for this indication.

No funds were received in support of this work.

No benefits in any form have been or will be received from a commercial party related directly or indirectly to the subject of this manuscript.

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DOI: 10.1097/BRS.0b013e318254155a

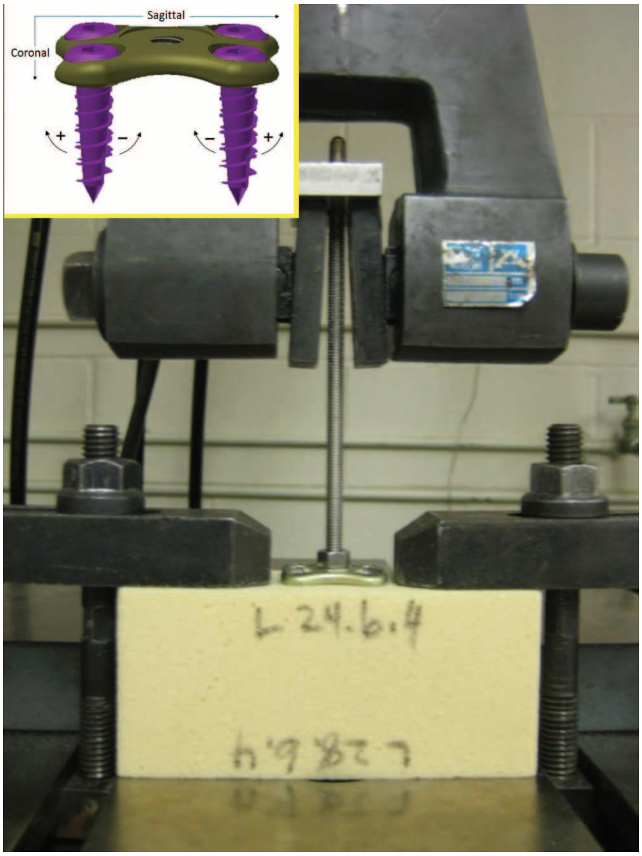

Figure 1. Experimental setup. Plate inserted in foam block was pulled out *via* a threaded rod attached to the load cell. Sagittal and coronal planes represented the long and short edges of the plate, respectively. (+) and (−) denoted screw angles away from and toward the center of the plate for both planes, respectively.

TABLE 1. Screw Orientation and Pullout Load for Each Experimental Group and Statistical Significance Among the Groups

Groups	Sagittal Angle (°)	Coronal Angle (°)	Pullout Load (N)*	Significance ($P < 0.05$)
1	0	0	868 ± 86	NS
2	+12	0	843 ± 48	a
3	−12	0	883 ± 75	NS
4	0	+12	812 ± 45	a
5	0	−12	813 ± 52	a
6	+12	+12	833 ± 29	a
7	−12	−12	868 ± 47	NS
8	+12	−6	936 ± 72	b
9	+6	−4	816 ± 66	a

Sagittal and coronal planes represented the long and short edges of the plate, respectively. (+) and (−) denoted screw angles away from and toward the center of the plate for both planes, respectively. “b” was significantly higher than “a.”

**Mean ± standard deviation.*

NS indicates not significant.

and within the foam block. We hypothesized that screw angulations had little effect on the holding power of the plate.

MATERIALS AND METHODS

We tested 9 groups of plate insertion techniques with varying screw orientations for pullout using foam blocks. Also, a 2-dimensional computational model of the screw used in the experiment (without the plate) was generated, and FEA was performed simulating a pullout test to gain insight into the internal stress changes in the block as the screw insertion angle changes.

Testing was performed with polyurethane foam blocks (Sawbones Inc., Vashon, Washington). A total of 45 foam blocks with a size of 130 × 40 × 60 mm were prepared. The size of the blocks was chosen to ensure secure gripping and multiple uses without damaging the block. The density of the foam blocks was 0.16 g/cm^3, which was used in the previous plate pullout studies and showed similar properties as mildly osteoporotic cancellous bone.[6]

Each block was instrumented using a custom insertion guide prepared for each group. After securing the guide on the block, pilot holes were prepared using a drill bit supplied by the manufacturer for use with their self-tapping screws (6.0 × 20 mm; LANX Inc., Broomfield, CO). The plate (LANX Inc.) and 4 screws were fastened to the center of each block. Screw insertion was monitored using a torque-wrench (TS-100; The Triangle Tool Group, Inc., Orangeburg, SC). Pretest trials showed that the screws could be safely fastened up to 0.56 N·m. To ensure consistency, a single investigator placed all screws. Each block was used to test 2 plates, yielding 10 plates for each group.

All blocks were randomly divided into 9 groups. Each group of blocks was instrumented with different screw orientations (Table 1). Angles were selected on the basis of the maximum angle allowed by the plate in both the sagittal and coronal planes and both converging (“−,” to the center of the plate) and diverging (“+,” away from the center of the plate) directions (Figure 1). The maximum angle permitted in all directions by the plate was found to be 12°.

Group 1 was the control group in which screws were placed straight in perpendicular to the plate. Groups 2 through 5 had screws placed at 12° in each direction (sagittal and coronal) away from the perpendicular. Groups 6 and 7 had screws placed all diverging away from the plate and converging toward the center, respectively. Group 8 had screws placed 12° out sagittal and 6° in coronal as is common practice in the cervical region.[7] Group 9 had screws placed at the angle that was recommended by the manufacturer 6° out sagittal and 4° in coronal.

Biomechanical testing was performed using the Instron 8521 testing machine. Each plate was attached to the load cell *via* threaded rod that fitted to the threaded hole in the center of the plate (Figure 1). The plate was not allowed to

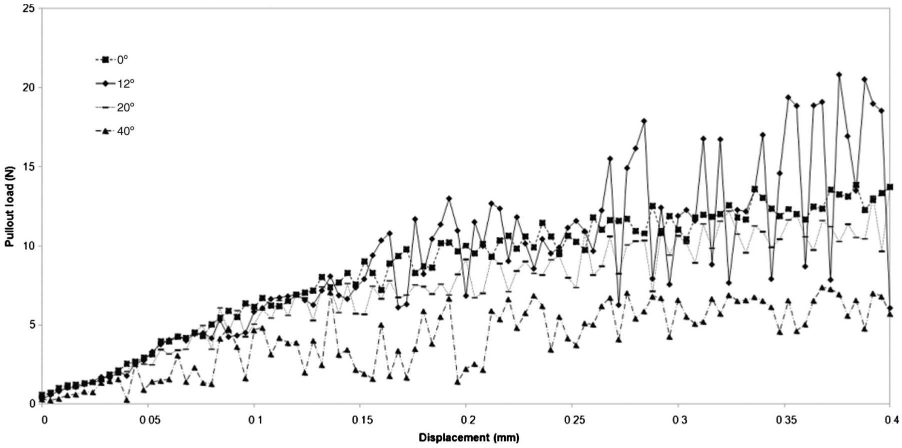

Figure 2. Reaction forces (*i.e.*, pullout loads) during screw pullout obtained with finite element analysis. Pullout loads leveled off toward the end of the given displacement. As the angle of the screw increased, they tended to level off earlier.

rotate during pullout to be able to keep failure mode consistent among the specimens. Plates were pulled out at a rate of 1 mm/min up to failure,[5] which was defined as the consistent drop in load despite increasing displacement. The pullout load was defined as the maximum load encountered in the load-displacement curve before the failure. Ten specimens were tested per group. Statistical comparison of maximum pullout load was done using 1-way analysis of variance and Tukey tests for multiple comparisons at the confidence level of 95%.

Finite Element Modeling

A 2-dimensional model of a block and screw was developed. The screw was modeled as a rigid wire with a similar geometry to that of the axial cross section of the experimental screw used in this study. The block was modeled as deformable and given the elastic-plastic material properties (density = 0.16 g/cm^3; Young modulus = 58 MPa, Possion ratio = 0.2; Yield stress = 1.5 MPa). The values were obtained from the manufacturer's documentation and the literature.[8] The screw was modeled as inserted into the block at 0°, 12°, 20°, and 40°. The screw was allowed to rotate during pullout as dictated by the plate design.

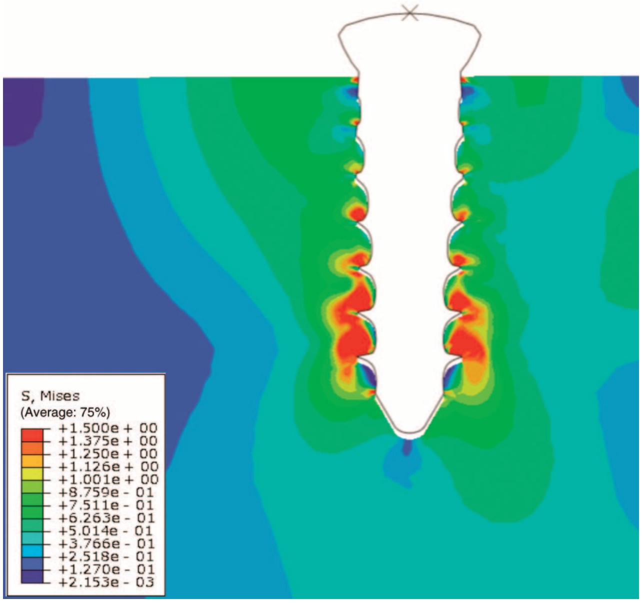

Figure 3. Stresses around the screw (0°) during vertical pullout (MPa).

A minimal frictional contact was defined between the screw and block with a friction coefficient of 0.01. The block was held at the bottom edge. The top edge was allowed to expand in the loading direction but restricted in the transverse direction. The screw was given the vertical displacement of 0.4 mm to simulate a pullout experiment.[9] Previous studies on screw pullout used 0.01 mm of displacement.[10] However, plate pullout might occur at larger displacement than that seen in a single screw pullout, especially when plate screws are triangulated. Hence, in our analysis, a larger displacement was deemed to be more realistic. The block was meshed using quadrilateral plain stress elements. Simulation was run by FEA software (ABAQUS/Explicit; Dassault Systémes, Providence, RI), using adaptive mesh technique to overcome excessive deformations. Screw pullout load for each screw simulation was calculated by averaging the reaction force data obtained within the last 5% of full pullout.

RESULTS

Group 1, with screws placed straight in, had a pullout load of 867.56 ± 86.24 N (Table 1). None of the other groups were statistically different from group 1 ($P > 0.05$). Group 8 with screws placed at a sagittal angle of 12° and a coronal angle of −6° had the highest value with an average pullout load of 936.39 ± 72.28 N. This value was statistically higher than groups 2, 4, 5, 6, and 9 ($P < 0.05$) but not group 1 ($P > 0.05$). Group 4 with a screw angle of 0° sagittal and 12° coronal had the lowest average pullout load (811.56 ± 45.36 N) and was statistically lower than the highest group (group 8) but not statistically different from the straight in (group 1) approach.

Finite Element Analysis

The pullout loads (reaction forces) obtained for the 0°, 12°, 20°, and 40° screw orientations were 13.2, 15.7, 11.5, and 6.1 N, respectively (Figure 2). Pullout loads leveled off toward

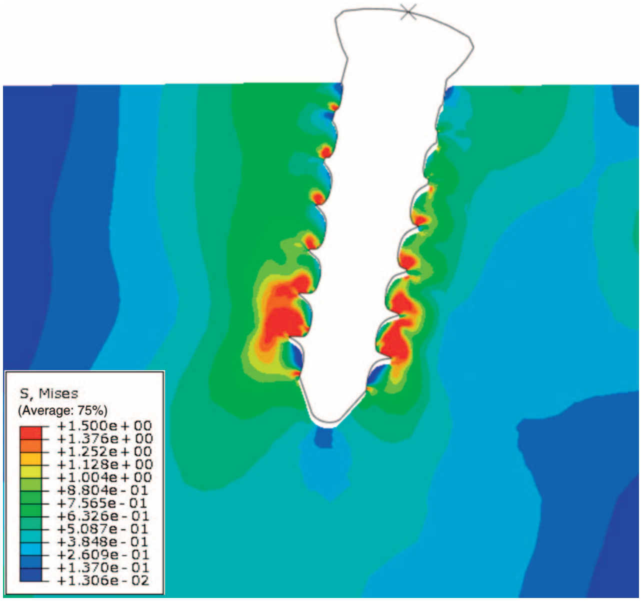

Figure 4. Stresses around the screw (12°) during vertical pullout (MPa).

the end of the given displacement. As the angle of the screw increased, they tended to level off earlier.

The stress distribution within the block showed changes as the screw angle increased. The pullout resistance of the screw inserted at 0° mostly relied on the threads and stresses were localized around the thread roots, especially around the tip of the screw. As the screw insertion angle increased, stress levels elevated within the block even in the regions away from the screw (Figures 3–6).

Stress at an element, chosen in front of the first screw thread in all models, showed a quick increase in lower insertion degrees and rapidly reached the highest value, that is, yield stress (Figure 7). As the screw angle increased, the stress at the thread developed slowly and reached the highest value at the end of the pullout period. The displacement of the top surface of the block, close to the screw insertion point, also showed differences among the models. For greater insertion angles, larger displacements were measured at the block surface in the vertical direction, where boundary conditions were set free (Figure 8). The screw rotated 0.3°, 0.5°, and 0.7° during pullout simulation in 12°, 20°, and 40° models, respectively.

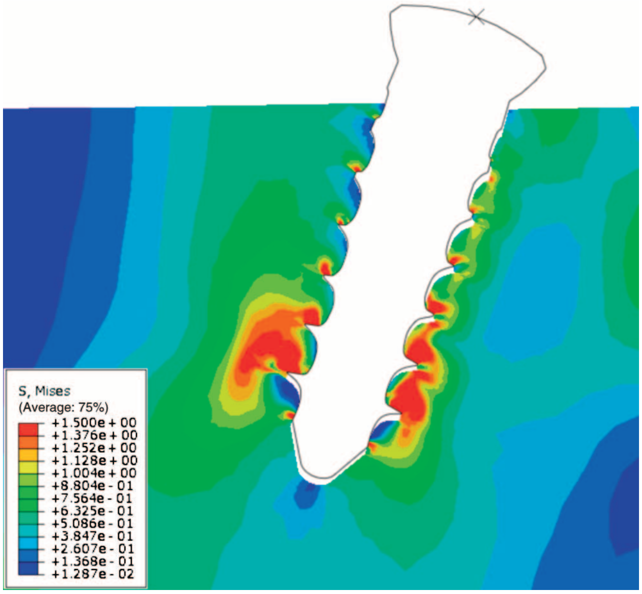

Figure 5. Stresses around the screw (20°) during vertical pullout (MPa).

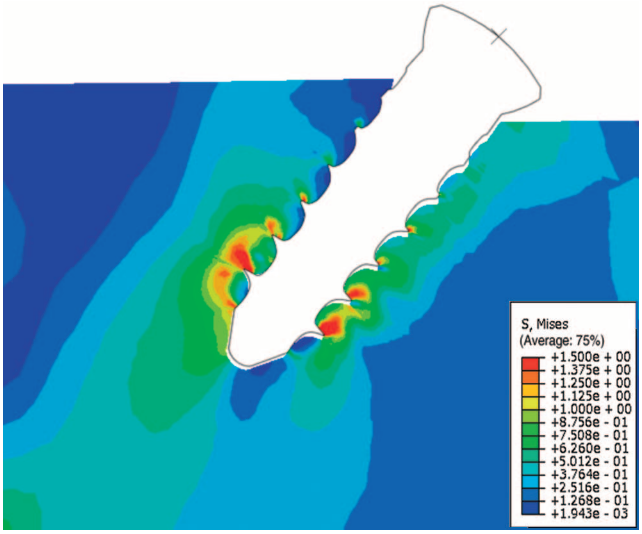

Figure 6. Stresses around the screw (40°) during vertical pullout (MPa).

DISCUSSION

Our results showed that screw orientation has some influence on the pullout strength of anterior plates; however, no specific orientation proved to be significantly stronger than simply placing the screws straight in. With respect to angle, some important differences were noted. Angling the screws in the coronal plane produced the lowest pullout values, and these values were statistically different from placing the screws at 12° sagittal by −6° coronal. It should be noted that the difference between the straight approach and all the different orientations was never more than an 8% variation. This result was consistent with the literature that indicated an 8% decrease[4,5] and a 7% increase.[2] Our finite element analyses results also supported our experimental results. It was shown that at the 12° insertion, the screw gained a slight increase in pullout resistance; however, in higher insertion angles, pullout load reduced as has been previously shown experimentally.[2]

The FEA showed that the screw pullout resistance relied on the structural stiffness of the block as the screws were inserted at a larger angle. The rotation of the screw during pullout allowed the load sharing between the threads and the rest of the block; however, it did not add significantly to the vertical component of the reaction forces, which is recorded as the pullout load in the experimental setup.

The block surface was restricted in the horizontal direction, perpendicular to the screw insertion plane, to simulate the integrity of the block as seen in the 3-dimensional case. However, it was allowed to expand in the vertical direction,

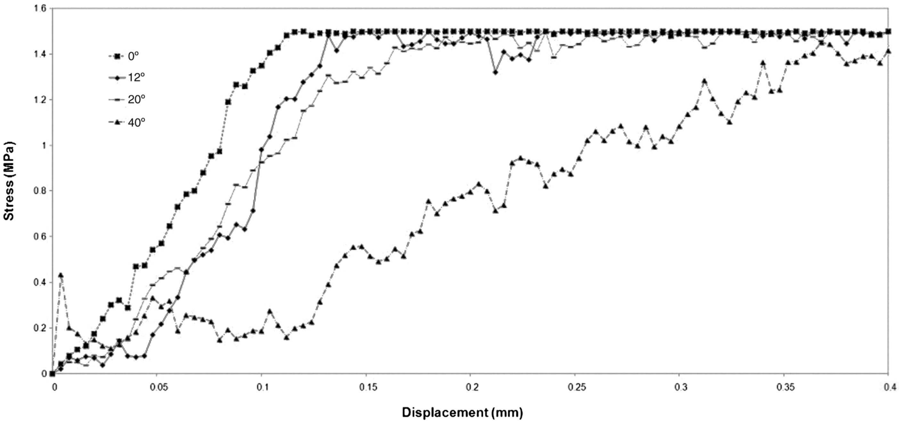

Figure 7. Change in stress at an element in front of the first screw thread as the screw was pulled out. Note that stress developed at the foam thread at a slower rate for larger screw insertion angles.

which simulated boundary conditions imposed by the experimental setup, and this remarkably inhibited the resistance of foam against the screw advancement. This became a major disadvantage in the 40°-insertion model, where the pullout load was the lowest and the surface expansion was the largest. This observation showed that screw angulation changed the load-sharing (*i.e.*, stress distribution) characteristics of the foam block. When the screw was vertically inserted, load sharing was localized around the threads. As the insertion angle increased, stress around the threads decreased and was absorbed by larger areas of the block supporting the foam-screw interface. This, however, did not translate into a larger pullout resistance because of the vertical expansion of the block as the screw was pulled out. It might be possible that a strong lamination at the top surface of the block (*similar to cortical shell of the vertebra*) would allow the compression of the material on top of the screw shaft and thus yield increased pullout resistance for large screw insertion angles.

Both in our experimental groups and previous studies, statistically significant differences have been seen among pullout loads at certain screw angles. However, these differences in the fixation strength were about 7% to 8%. In a clinical setting, if the movement of high-risk structures is required to orient the screws in a particular direction, such a small gain in the fixation strength may be negligible compared with the additional risk to the patient. Surgeons should aim the screw to an area with higher bone mineral density because it plays a more important role in fixation strength than angle.[11–13]

Previous studies using anterior plates have compared the straight in approach with that of one specific orientation.[4,5] Here, we compared plate pullout strength with screws placed straight in with screws placed 12° in each direction. Twelve-degree screw placement was chosen because it was determined to be the maximum angle the plate would permit in all directions. The plating systems are designed with either a variable angle screw or a fixed angle screw that locks into place. The fixed-angle version of the current device was not used in this experiment, but the angles from that system was simulated in this experiment with 6° out sagittal and 4° inward coronal orientation. We also tested the book value of 12° out and 6° in.[7] To isolate the effect of screw orientation from anatomical geometry and density variations, a synthetic model composed of polyurethane foam was used. The benefit of using polyurethane foam is that it limits inter- and intrasample variability while also simulating the biomechanical properties of cancellous bone.[2,4–6]

Anterior lumbar interbody fusion is a procedure used to help lower back pain due to disc degeneration, correct spinal defects, and stabilize the spinal column. Historically, anterior

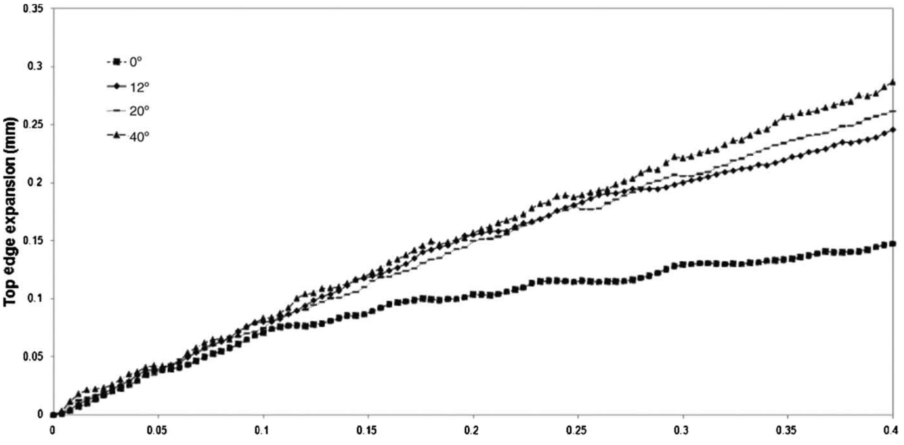

Figure 8. Displacement at the top surface of the block around the screw insertion point as screw was pulled out. Note that larger displacement occurred for larger screw insertion angles.

fusion in the cervical region has been a common practice; however, only in recent years has technology allowed for anterior fusion of the lumbar region to become popular. As a result, many of the techniques and practices for fusing the lumbar region have their basis in research performed in the cervical region, using cervical plates and screws. For cervical procedures, surgeons are taught to orient their screws toward the center of the vertebra, with screws positioned 12° away from the fusion plate in the cephalad and caudal directions and 6° in toward the midline.[7] This avoids risk to many high-risk neurological structures lying on the lateral sides of the cervical vertebra.[4] It is also thought that additional fixation strength is gained by placing the screws toward the center of the vertebra, with little evidence.[7]

In the lumbar region, placing the screws of the anterior lumbar interbody fusion plate toward the center of the vertebra becomes more challenging because of the great vessels covering the anterior surface lumbar vertebra. To place the screws in this direction, the great vessels must be moved aside, increasing the chance of vascular damage or a thrombus being formed because of arteriosclerosis in elderly patients.[14] Older patients may also be experiencing osteoporosis, and angling the screws toward the center of the vertebra will place the screw in the weakest part of the bone.[15,16] Our results showed that screws inserted in various different angles would have similar pullout strength when the size is kept the same. This finding helps surgeons prioritize the patient's safety and surgical convenience without compromise to the strength of the construct.

When placing an anterior plate, there are many factors that influence stability, such as screw length,[17,18] screw angle,[2,4,5] surrounding anatomy,[7,14] or bone density.[11–13,18] Screws are placed in an anterior plate angled "up and in" toward the center of the vertebra, because it allows for the use of longer screws and requires the screw to pull through more bones preventing back out of the screw and plate system.[4,5,7] The assumption that angling the screws increases fixation strength has even guided implant design, with many manufacturers supplying plates that allow only a specific screw angle and orientation. Recent research has suggested that placing the screws straight in provides stronger pullout resistance than an angled approach even when the screw is shorter.[4,5] Single screw pullout studies have shown that there may be an optimal angle at which a screw may be inserted that would provide the greatest pullout resistance[2]; however, these studies do not take into account the orientation of the screw with respect to the plate, nor the effect of plate and screw interaction which has been shown to have a significant effect on pullout strength.[5]

The current experiment and results are limited with the foam material and should be carefully applied to vertebra. Although foam blocks eliminate inter- and intraspecimen variability and thus provide a well-controlled testing environment for comparative analyses and the isolation of particular parameter(s) from others, these results cannot replace those from cadaveric investigations because of the significant differences in material and structural properties between the vertebral bone and the foam block. Our model has the density similar to the central vertebra; however, it did not have any feature to simulate the cortical shell. For constructs where some screws engage multiple cortices or are inserted in or close to the end plates, results might differ from those of the current study.

Our FEA deviated from the experimental setup in a way that it was based on a 2-dimensional model and investigated only 1 screw. In addition, the material definition was not exactly simulating the foam mechanical properties. Therefore, our results from FEA are not expected to match exactly those of the experiment. Nevertheless, the FEA analysis was aimed to test the change in stress distribution within a block for various insertion angles in order to measure the differences and gain insight into the findings of the experimental results. Our model also does not address the question of whether the screws have an effect on each other in converging orientation. Better material definition and a more realistic 3-dimensional model can be considered as a future study.

In conclusion, significant difference was found between certain screw-angle configurations; however, when compared with simply placing the screws straight in, the difference was never more than 8%. This implies that there is greater freedom in the angle and placement of screws than previously thought. Our results show that there is little change in fixation strength when placing the screw in a different direction.

➢ Key Points

- ☐ There were minor differences in the pullout strength between different screw angles.
- ☐ The additional fixation strength gained by placing screws at an angle is not significantly different than placing the screws straight in.
- ☐ Stresses at the foam threads were more localized around the screw for smaller screw insertion angles.
- ☐ In larger insertion angles, maximum stress at the foam thread was reached at larger displacements of the screw. In addition, larger displacements were found at the top surface of the block as the insertion angle increased.

Acknowledgments

The authors thank Lanx, Inc. for providing necessary plates and screws, Elisabeth Clarke, Kathleen Elias, and Mary Kolb for all of their administrative help, and Jeffrey Chen and Warrie Layon for their help in performing the pullout tests.

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