Pedicle screw insertion angle and pullout strength: comparison of 2 proposed strategies

Laboratory investigation

Serkan İnceoğlu, Ph.D., William H. Montgomery Jr., M.D., M.P.H., Selvon St. Clair, M.D., and Robert F. McLain, M.D.

Spine Research Laboratory Cleveland Clinic and Department of Orthopedic Surgery, Center for Spine Health, Neurological Institute, Cleveland Clinic, Cleveland, Ohio

Object. Minimally invasive pedicle screws inserted vertically (that is, dorsoventrally) through the pedicle, as opposed to the more common coaxial technique, offer potential advantages by minimizing soft-tissue stripping during screw placement. The screws are designed for insertion through a medial starting point with vertical trajectory through the pedicle and into the vertebral body. As such, no lateral dissection beyond the insertion point is necessary. However, the effects of this insertion technique on the screw biomechanical performance over a short- and long-term are unknown. The authors investigated the pullout strength and stiffness of these screws, with or without fatigue cycling, compared with comparably sized, traditional screws placed by coaxial technique.

Methods. Twenty-one lumbar vertebrae (L-3, L-4, and L-5) were tested. Each pedicle of each vertebra was instrumented with either a traditional, coaxial pedicle screw (Group A), placed through a standard starting point, or a vertically oriented, alternative-design screw (Group B), with a medial starting point and vertical trajectory.

The specimens were divided into 2 groups for testing. One group was tested for direct pullout (10 specimens) while the other was subject to pullout after tangential (toggle) cyclic loading (11 specimens). The screws were cycled in displacement control (± 5 mm producing ~ 4-Nm moment) at a rate of 3 Hz for 5000 cycles. Pullout tests were performed at a rate of 1 mm/minute.

Results. Two-way ANOVA showed that Group B screws with a medial starting point (2541 ± 1090 N for cycled vs 2135 ± 1323 N for noncycled) had significantly higher pullout loads than Group A screws with a standard entry point (1585 ± 766 N for cycled vs 1417 ± 812 N noncycled) (p = 0.001). There was no significant effect of cycling or screw insertion type on pullout stiffness. Tangential stiffness of the Group B screws was significantly less than that of the Group A screws (p = 0.001). The stiffness of both screws in the toe region was significantly affected by cycling (p = 0.001).

Conclusions. The use of Group B screws inserted through a medial starting point showed greater pullout load than a Group A screw inserted through a standard starting point. The greater pullout strength in Group B screws may be due to screw thread design and increased cortical bone purchase at the medial starting point. Nevertheless, anatomical considerations of the medial starting point, that is, pedicle or lateral vertebral body cortex breach, may limit its application. The medial starting point of the Group B screw was frequently in the facet at the L-3 and L-4 pedicle entry points, which may have clinical importance. (DOI: 10.3171/2010.11.SPINE09886)

Key Words • pedicle screw • insertion technique • pullout test • cycling test

Although pedicle screw fixation is a common and reliable method of treatment for a variety of spinal disorders, the invasive nature of traditional placement and potential for fixation failure through screw pullout have been disadvantages of the technique.

In keeping with the emphasis on minimally invasive techniques in spine surgery that have evolved over the past decade, less invasive pedicle screw instrumentation systems have been developed. Traditional techniques of pedicle screw insertion used a more lateral angle with a

Abbreviations used in this paper: BMD = bone mineral density; VB = vertebral body.
Pedicle screw insertion angle and pullout strength

lar bone, which is denser near the cortical wall,\(^7\) or the dense bone of the cortex itself. Therefore, this technique faces the potential disadvantage of under-utilizing the biomechanical capacity of the pedicle complex.

Recently, more minimally invasive pedicle screw systems have been developed, including an alternative percutaneous technique wherein screws are placed through a more medial starting point by following a more vertical trajectory. The screws are placed through a starting point at the junction of the superior articular process and pars. Because of the medial starting point, the trajectory of the screw is directly anterior through the pedicle and into the VB. In theory, this trajectory allows the screw to engage the denser regions of the trabecular bone and partially into the cortical wall of the pedicle and VB. A brief evaluation of the relative value of this new trajectory over the more traditional placement has been recently made available in a subgroup of a series of experiments.\(^4\) These authors showed that direct pullout strength of this new placement may not be superior over that of traditional placement. However, the effect of fatigue and the screw geometry on the efficacy of the technique are still unknown.

We hypothesized that, for fixation in the lower lumbar spine, screws inserted with a more vertical trajectory, through the medialized starting point would provide pullout strength comparable to traditional screws with a coaxial trajectory with or without fatigue exposure.

**Methods**

**Specimen Preparation**

Seven cadaveric adult human spines were obtained and scanned for bone density measurements. After cleaning the musculature and soft tissues, all spines were separated into single levels. Only the lower lumbar vertebrae (L-3, L-4, and L-5) were used for this study as these are the most commonly instrumented vertebrae. Pedicles were instrumented with either a standard pedicle screw (Group A) inserted posterolaterally along a coaxial trajectory (Xia, Stryker Spine) or a screw designed for minimally invasive posterior placement (Group B) (Techtonix, Stryker Spine). Pedicles were instrumented in a paired testing array. The left and right sides were equally used for each screw insertion technique. Care was taken to avoid any bias in insertion with respect to the left or right pedicle. All screws were placed by the same surgeon, using a paired testing design that allowed individual screws to be directly compared with a paired contralateral “control.”

**Instrumentation**

**Coaxial Trajectory (Group A).** The optimal entry point was determined using the technique described by Weinstein et al.\(^{15}\) An awl was used to breach the cortex, and a pedicle probe with a straight, blunt tip was used to extend the trajectory into the VB coaxial with the pedicle axis. The coaxial orientation of the intended pilot hole was confirmed by direct inspection of the pedicle in all planes. The blunt “gear-shift” sound was then passed manually through the pedicle into the VB, sounding the body to a depth of 45 mm. The straight probe was rotated \(360^\circ\) to create a uniform 2.8-mm pilot hole. The hole was tapped using a 6.5-mm diameter tap, to a depth of 45 mm. Screws with a size of \(6.5 \times 45\) mm were inserted until the final thread was engaged in the cortex of the lateral facet surface.

**Vertical Trajectory (Group B).** After determining the optimal entry point for screw insertion based on the surgical technique for the Techtonix system, the laminar cortex was breached using an awl according to the technique guide. The hole was tapped through the pedicle and into the beginning of the VB, without prior use of a pedicle probe. A Techtonix screw measuring \(6.0 \times 45\) mm was inserted until the last thread engaged the laminar cortex (Fig. 1).

All specimens were reexamined to ensure that the cortex of the pedicle was not breached either medially or

**Fig. 1.** A: Lateral photograph demonstrating the ideal starting point of the Group B screw (upper inset). The Group B (Techtonix) screw (lower right inset) has a smaller ratio of inner to outer diameter and a narrower thread pitch compared with a Group A (Xia) screw (lower left inset). \(B\) and \(C\): Illustrations of the screw entry points and trajectories. Standard pedicle screw with coaxial trajectory (Group A) inserted in the right pedicle (that is, the pedicle that appears on the left side of the drawings) is illustrated. On the left pedicle (that is, the pedicle that appears on the right side of the drawings), the screw hole with the medial starting point and vertical trajectory (Group B) is being prepared at the junction of the inferior aspect of the superior articular process and pars in this L-5 vertebra.
laterally and that the anterior vertebral cortex was not penetrated. All specimens were embedded in metal alloy material (CerroBend, Cerro Metal Products Co.) up to the base of the pedicles and into the vertebral canal, keeping the screw insertion region clean of embedding material. Fun Dough (RoseArt Industries, Inc.) was used to plug all vascular channels to prevent metal infiltration into the bone.

**Biomechanical Testing**

The specimens were divided into 2 groups for biomechanical testing. The first group (10 specimens) was tested for direct pullout strength, and the second group (11 specimens) was tested in pullout after a tangential (toggle) cyclic loading in a craniocaudal direction. The vertebral specimens were mounted in a custom testing jig and oriented properly for toggle or axial pullout loading. For pullout tests, specimens were aligned so that the pedicles were in line with the loading axis of the cross-head. Testing was stopped when the load went beyond the point of failure, which was defined as the highest load that the bone-screw interface could resist. The highest load value was recorded as pullout load. Stiffness was defined as the slope of the most linear part of the load-displacement curve before the yield point.

For cyclic load testing, specimens were oriented to keep the pedicle parallel to the ground, and thus perpendicular to the load application axis. A custom-designed adapter with a hinge joint was used to allow the screw to toggle. The toggle test was performed by sagittally cycling the screw in displacement control (± 5 mm, producing ~ 4-Nm moment) at a rate of 3 Hz for 5000 cycles using an Instron 8874 testing machine (Instron Corp.) as originally described by Lotz et al. After completion of cyclic loading, the screws were pulled out at a rate of 1 mm/minute.

In cyclic loading, the stiffness was calculated at the early phase of the curve, that is, the toe region, and late phase of the curve, that is, the elastic region (Fig. 2). A change in the toe region indicated the laxity at the fixation, while the stiffness from elastic zone was the indicator of the integrity of the supporting trabecular structure.

**Statistical Analysis**

Load-displacement data were recorded to determine the pullout load and stiffness. Normality tests were run on the pooled data to test the normality of the distribution. A 2-way ANOVA test was used to assess the effect of cycling and screw (insertion) type on pullout load and stiffness. Tangential stiffness from elastic and toe regions of loading curve were also assessed using a 2-way ANOVA test with factors of cycle and screw (insertion) type. Power analyses were also performed to ensure the reliability of the differences obtained. Paired t-tests were performed with stiffness and pullout load between the insertion techniques. The statistical significance level was defined as 95%.

**Results**

**Bone Mineral Density**

Group A and Group B specimens were divided into 2 groups for pullout tests with and without prior cycling. Statistical analysis showed that the mean BMD value of the vertebrae in the cycled (1.064 ± 0.213 g/cm²) and non-cycled (0.951 ± 0.251 g/cm²) groups was not different (p > 0.05).

**Biomechanical Assessment**

Two-way ANOVA analysis showed that insertion technique (screw type) had a significant effect on the pullout load (p = 0.001), while cycling did not affect it (p = 0.485). There was no interaction between the insertion technique and testing type, that is, prior cycling (p = 0.534). The means ± 5Ds of direct pullout loads of Group A and Group B screws were 1417 ± 812 N and 2135 ± 1323 N, respectively (Fig. 3). After cycling, the pullout loads of Group A and Group B screws were calculated as 1585 ± 766 N and
Pedicle screw insertion angle and pullout strength

2541 ± 1090 N, respectively. Since there was no interaction between the cycling and screw factors, pullout loads for both test types were pooled and illustrated for both screws. The power of this comparison was calculated as 99%.

Pullout stiffness was shown not to have been influenced by testing type (p = 0.540) or by screw type (p = 0.333). There was no interaction between these factors (p = 0.524). In direct pullout, the stiffness of the bone-screw interface in the standard trajectory of the Group A screw and that in the medial trajectory of the Group B screw was 4020 ± 1867 N/mm and 4157 ± 1737 N/mm, respectively. The postcycling pullout stiffness was 3408 ± 1286 N/mm for Group A and 4061 ± 1419 N/mm for Group B. Data pooled from both testing types are illustrated in Fig. 4 for a convenient comparison. The power of this analysis was 17%, and the sample size necessary to obtain 70% power was 122.

Tangential stiffness in the elastic region of the loading curves did not show significant changes through cycling when comparing initial and last cycles, as shown by 2-way ANOVA (p = 0.363); however, the stiffness was found to be influenced by the screw type, that is, insertion technique (p = 0.001). No interaction between the screw type and cycle (initial and last) was found (p = 0.629). One specimen was not included in the analysis since some data from a Group A screw cycling test were lost. The tangential stiffness at the initial and last cycles was 7.27 ± 1.83 N/mm and 7.43 ± 1.42 N/mm for the Group A screw, and 4.65 ± 1.38 N/mm and 5.18 ± 1.02 N/mm for the Group B screw, respectively. Pooled stiffness for Group A and Group B screws were 7.34 ± 1.59 N/mm and 4.91 ± 1.21 N/mm, respectively (Fig. 5). The power of this comparison was 99%. When comparing the initial and last cycles, the power was found to be 17%; however, the sample size necessary for 70% power was 112.

Tangential stiffness in the toe region of loading curves showed significant changes through cycling when comparing initial and last cycles, as shown by 2-way ANOVA (p = 0.001); however, it was not influenced by the screw type, that is, insertion technique (p = 0.372). No interac-

No significant correlation between BMD and pullout strength or BMD and pullout stiffness of Group B screw was noted (p > 0.05). On the other hand, Group A screws showed significant correlations between pullout load and BMD in cycled (r = 0.62, p = 0.04) and noncycled (r = 0.64, p = 0.04) groups, but not for pullout stiffness (p > 0.05).
The medial starting point of the Group B screw was in the facet of the juxtaposed articulation above the construct most notably in the more cephalad lumbar vertebrae (Fig. 7). If the starting point were moved caudally, as advocated by the proponents of the Techtonix System in these situations, the hard bone of the pars interarticularis is encountered. This bone was very difficult to penetrate with the awl.

Because the width of the posterior elements narrows in the more cephalad lumbar vertebrae, so does the lateral border of the pars. If the starting point of the Group B screw is moved inferiorly, out of the facet, it must also be moved more medially to avoid the lateral edge of the pars. Moving this starting point more medially necessitated a more lateral trajectory, increasing the likelihood of the lateral body breach.

Lateral VB breach was encountered in 5 of 21 vertebrae instrumented with a Group B screw and in none of the Group A screw insertions. Almost half of the lateral body breaches were in the L-5 vertebrae (3 of 7 vertebrae).

**Discussion**

**Biomechanical Testing**

Three principal parameters are responsible for performing pedicle screw fixation: screw mechanical properties, bone properties, and surgical technique. The Group B screws, inserted through a medial starting point and delivered along a vertical posterior-to-anterior trajectory, demonstrated superior pullout strength compared with the Group A screw inserted via the standard insertion point and medialized trajectory. The superior pullout strength of the Group B screw may be due to either the medial entry point of the screw, the trajectory, the different quality of the bone engaged, or the screw design itself. Because the medial starting point is either in or around the cortical bone of the pars, it could be inferred that this may be the determinant of the increased pullout load. It may also be hypothesized that vertical screws take better advantage of the vertebral/pedicle complex, obtaining a 3-point fit between the anterior trajectory of the screw, medially oriented pedicle, and curvature of the VB wall. It is possible that the one screw (Techtonix) is superior in design to the other. However, there is evidence that the screw itself is not the determining factor in differential pullout strength.

The Group B screw maintains a relatively greater minor diameter for the measured major diameter, resulting in a smaller thread area compared with more common pedicle screw designs. The design is more typical of a cortical thread design, and the screw is delivered through denser, more cortical-type bone.

Crawford et al. compared Techtonix screws inserted through a standard lateral starting point, as described by Weinstein et al., with those inserted through a medial starting point described in the Techtonix surgical technique. They found no difference in pullout strength between the 2 insertion techniques. These data combined with our findings suggest that neither the structure of the screw alone nor the resulting bone-screw interface could be responsible for the increased peak pullout load and stiffness seen in the Group B screw.

The stiffness of the bone-screw interface in the elastic region did not seem to change after cycling. This suggested that compacted trabecular bone around the screw during cycling was still able to withstand the compressive loading along the screw shaft. However, the mechanical degradation in the supporting bone occurring due to the fatigue could be quantified with the changes in the toe region behavior. When the toe region of the load-displacement curve was examined, the stiffness of the bone-screw interface significantly diminished toward the end of the cycling; however, it tended to be better preserved in the Group B specimens.

The difference in the effects of cycling on the pullout behaviors of the Group B and Group A screws is best explained by the difference in the insertion trajectories. Since each Group B screw was inserted more medially than the Group A screw, it may have gained bone purchase around the dense region of pedicular trabecular bone along the medial pedicle wall. The Group B screw is similar to a cortical screw, with a narrow pitch and smaller ratio of inner to outer diameter. The buttress design threads of the Group B screw might, thus, have engaged the medial cortical bone of the pedicle, which was shown to have a thick and well-organized structure. Moreover, the Group B screw penetrated into, and occasionally through, the anterior vertebral cortex, which increases the resistance to pullout failure in both static and cyclic loading by providing the screw with an additional support point at the distal tip. Even when the Group B screw did not penetrate the anterior vertebral cortex, it may have benefited from the increased density of the juxta-cortical trabecular bone, engaging more strongly reinforced segments of the cancellous VB. Engaged obliquely as the screw approached the anterolateral segment of the cortical rim, these trabeculae would be loaded in shear, and would provide increased resistance to pullout and fatigue failure.

In the current study, a displacement control protocol was preferred during cyclic testing over load control. While small loads may be well withstood by resilient materials, even small loads—exerted over many cycles—will

*Fig. 7.* Photograph showing the standard lower (L-3) lumbar pedicle screw with standard starting point (left) versus the Group B screw with the medial starting point (right). In the L-3 vertebrae, the Group B screw starting point was frequently in the facet.
Pedicle screw insertion angle and pullout strength

result in material destruction, deformation, or implant failure. The concern in this study is that a small deformation on each cycle will be magnified over time irrespective of the displacement, so long as the measured load is not exceeded, and in trabecular bone this can result in cavitation of the specimen if there is no displacement control. We decided to use the displacement control for the following 2 reasons: 1) it has been the commonly preferred technique in screw fatigue studies carried out in the past, and 2) we wanted to control and limit the amount of deflection experienced by the screw to prevent shear stresses during cycling. The tangential loading is achieved via a hinged-joint adapter in screw fatigue studies, and large vertical displacements can impart significant axial forces to the screw, which can destroy the bone threads and contribute to premature pullout of the screw.

The vertical trajectory intended for the Techtonix screw was demonstrated to be at least comparable in strength and fatigue resistance to the traditional pedicle screw placement. This approach is, however, associated with the potential for medial pedicle wall violation if the starting point is not correctly selected, or lateral VB penetration with potential for vessel or nerve injury. Depending on the level instrumented, there is a clear potential for facet impingement increasing the risk for junctional disease.

Anatomical Considerations

The Techtonix system is designed with the more vertical posterior/anterior trajectory in mind. Initially indicated for single or double level, thoracic or lumbar fusions, its less invasive medial starting point and anterior trajectory is best when used to augment an anterior or posterior lumbar interbody fusion as the fusion bed would not otherwise need to span the intertransverse space. The less invasive technique is primarily advantageous in the lower lumbar spine where the traditional pedicle screw starting point and insertion requires a more lateral starting and more medial trajectory, necessitating increased lateral exposure. The cephalad lumbar vertebrae and all thoracic vertebrae have more vertically oriented pedicles, bringing the traditional pedicle screw starting point and Techtonix starting point and trajectory into a similar path.

The relationship of the Group B starting point to the facet and pars in the more cephalad lumbar vertebrae may be a limitation of this approach. A directly anterior trajectory down the pedicle often starts the screw in the margin of the facet at L-4 levels and at all L-3 levels. If the starting point is moved inferiorly, the hard bone of the pars is encountered and more difficult to enter. Furthermore, with the decreasing width of the interpars distance at the upper lumbar levels the starting point is forced medially so as not to violate the lateral pars. If the direct anterior trajectory is used, then the canal may be breached. If a more lateral starting point is used with the vertical trajectory, then the VB may be breached. The starting point could be moved laterally to a more standard pedicle screw entry site; however, this would defeat the less invasive nature of the system’s intention.

Most lateral VB breaches were seen at the L-5 level. Of the 7 L-5 vertebrae used in this study, considerable variation in the shape of the VB was noted. When compared with bodies of L-4 and L-3 specimens, which are more circular in shape, the L-5 bodies were oval. This decreased the anterior/posterior dimension at the level of the pedicle leading to increased lateral body violation by the screw when a more vertical posterior to anterior trajectory is used.

Limitations of This Study

This study was intended to compare different screw trajectories as they are recommended for specific spinal instrumentation systems. Hence, a traditional pedicle screw, intended for a coaxial trajectory, was selected for the Group A tests. The Techtonix screw, intended for the more vertical trajectory, was selected as the Group B test screw. The sizes of screws were not identical, but the difference in outer diameter (the Xia screw was larger) was accepted to obtain a minor diameter that was similar to that of the Techtonix screw. Hence, the 6.5-mm Xia screw was selected for comparison with the 6.0-mm Techtonix screw. The success of this individual screw, designed for and placed in the vertical trajectory, does not suggest that other screws, designed for transpedicular placement, would fare as well. Our biomechanical results may not be generalized to other screw configurations without further testing.

Axial pullout failure is only one aspect of screw strength or failure behavior important to pedicle screw fixation. Zdeblick et al. performed pullout testing in cadaver vertebrae using a custom-designed fixture that shifted the axial load away from the axis of the screw to produce a “wiggle out” effect, which was believed to be more representative of physiological loading. They found a correlation between number of cycles to failure and insertion torque among screws placed in the traditional, coaxial trajectory. “Toggle out” testing and pullout testing after cyclic loading address some of the aspects of cyclic loosening and failure over time, but mechanical failure in clinical constructs rarely involves pure pullout. Run out experiments should also be performed to test the fatigue resistance of the new screws in Group B, which was out of the scope of this study. Paired pedicle screws placed in a traditional lateral-medial trajectory tend to offer additional pullout resistance due to their quadrilateral configuration within the vertebral column. We have not tested construct pairs in this experiment, but it may be that, when cross-linked, the paired Group B screws would offer less resistance to pullout than the more traditional Group A configuration. Since the Group B configuration was intended to be applied in combination with anterior column support, this might not be a serious clinical problem, but used as the top screws in a posterior fusion, this might be a concern. Further investigation is warranted.

Conclusions

The Group B screw with medial insertion point and vertical trajectory showed superior pullout load when compared with the Group A screw with a standard lateral insertion and coaxial trajectory, both before and after fatigue cycling. The pullout stiffness of the Group B screw was also significantly superior following cycling, even though no difference was found prior to cycling. The integrity
of the bone-screw interface tended to be less affected by cycling in Group B. This difference appears to be related to the design of the screw, insertion point, and trajectory. While the biomechanical properties of the Group B screw appear to be superior to the Group A screw placement, anatomical compromise of the superior facet articulation may limit its clinical use in the upper lumbar spine.

Disclosures

This work was supported by a research grant from Stryker Spine. The authors report no other conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: McLain, Inceoglu, Montgomery. Acquisition of data: Inceoglu, St. Clair. Analysis and interpretation of data: McLain, Inceoglu, St. Clair. Drafting the article: McLain, Inceoglu, Montgomery. Critically revising the article: all authors. Reviewed final version of the manuscript and approved it for submission: all authors. Statistical analysis: Inceoglu. Administrative/technical/material support: Montgomery. Study supervision: McLain, Montgomery.

References


Manuscript submitted November 11, 2009. Accepted November 29, 2010. Please include this information when citing this paper: published online February 25, 2011; DOI: 10.3171/2010.11.SPINE09886.

Address correspondence to: Robert F. McLain, M.D., Department of Orthopaedic Surgery, Desk A41, Center for Spine Health, Cleveland Clinic, 9500 Euclid Avenue, Cleveland, Ohio 44195. email: mclainr@ccf.org.