How to Optimize Pedicle Screw Parameters for the Thoracic Spine? A Biomechanical and Finite Element Method Study

Giovanni F. Solitro, PhD[1], Michelle C. Welborn, MD[3] , Ankit I. Mehta, MD[4] , and Farid Amirouche, PhD[2,5]

Abstract

Study Design: Pedicle screw study.

Objective: The selection of pedicle screw parameters usually involves the surgeon's analysis of preoperative CT imaging along with anatomical landmarks and tactile examination. However, there is minimal consensus on a standardized guideline for selection methods on pedicle screws. We aimed to determine the effects of thoracic screw diameter to pedicle width on pullout strength determined by cortical bone purchase.

Methods: Biomechanical study performed with human cadaveric thoracic vertebrae and experimentally validated three-dimensional finite element model instrumented with pedicle screws of various diameters. We used a variable (SD/PW) ratio to express the screw selection. We hypothesized a positive correlation between the pullout load determined by the bone purchase and the SD/PW. This relationship was first investigated in a validated finite element model considering bone purchase related to the strength of an upper thoracic vertebra. Then, the correlation to the entire spine is evaluated.

Results: The failure load ranged from 371.3 to 1601.0 N, respectively, for 3 and 6 mm screws. The determinant coefficient was increased to $R^2 = .421$ when a linear relationship between pullout load and the SD/PW ratio was used. The peak loads of 1216 and 1288N were found for an SD/PW ratio of .83.

Conclusion: We have found that the screw pullout load is more correlated to SD/PW than other pedicle measures for a maximized SD/PW ratio of .83. This particular value should be considered the upper limit of the indicated SD/PW ratio and a means to determine the optimal screw diameter to enhance pullout strength.

Keywords
pedicle screws, FEA, breaches, thoracic spine, biomechanics, pullout strength

Introduction

For instrumented fixation and correction of the spine, pedicle screw placement has become the predominant modality for cases such as fractures,[1-3] scoliosis,[4-6] degenerative spine, and kyphosis.[7-11] Though complications are rarely associated with pedicle screws, they can occur through misplacement. The various types of complications related to pedicle screw misplacement include: dural lesions,[12-14] neurological deficits,[14-16] bent or broken screws,[13,15] screw loosening,[16] screw-rod disconnections,[16] vertebral fractures,[12,13,15,16] hematomas,[14]

[1] Department of Orthopaedics, Louisiana State University, Chicago, Il, USA
[2] College of Medicine, University of Illinois at Chicago, Chicago, Il, USA
[3] Department of Orthopaedic Surgery, Shriners Hospitals for Children, Portland, OR, USA
[4] Department of Neurosurgery, University of Illinois at Chicago, Chicago, Il, USA
[5] Department of Orthopaedic Surgery, NorthShore University HealthSystem, Evanston, Il, USA

Corresponding Author:
Farid Amirouche, PhD, Department of Orthopaedics, University of Illinois at Chicago, 835 South Wolcott, Chicago, Il 60612, USA.
Email: amirouch@uic.edu

wound infections,[12,14-16] and cerebrospinal fluid leakage.[12,15,16] In the choosing of a pedicle screw, the surgeon must carefully consider the pedicle width and the screw diameter, length, trajectory, and entry point[17-21] to minimize the morbidity and complications of screw placements.[12-14,16] The selection of the screw parameters used involves the surgeon's analysis of the patient's anatomical landmarks and tactile examination[22]; however, preoperative planning with CT and intraoperative imaging techniques such as intraoperative CT and fluoroscopy has been used more recently.[23-26] In addition, it has been noted that larger screw diameters increased the pullout strength.[27,28] Yet, there is minimal consensus on standardized guidelines for selecting screws and methods of assessment on the placement of the screws.[29-31]

In the past, the suggested diameter that can be inserted without causing a breaching during thoracic spinal surgeries was approximately under 80% of the pedicle width in adult or mature spines.[10,12,28,32] Similarly, Liau et al[33] indicated that the optimal pedicle width compared to screw diameter should allow .5 mm cortical margin on both medial and lateral sides. It should also be noted that most surgeons use only a few screw diameter dimensions for the entire thoracic spine.[34-36] Considering the variability in pedicle dimensions among spine levels and gender,[37] limitations on the applicability of these criteria are shown for segments and populations for which commercial screws are too small.[21] Additionally, in scoliotic patients, up to one-third of the mid-thoracic region is not appropriate for safe instrumentation due to pedicle width being smaller than the screw diameter.[32]

This study aims to further assist surgeon preoperative planning providing information on the screw strength in addition to the morphometric visualization used in current planning approaches. The approach proposed in this study could shift screw selection from the paradigm that biggest as possible is better to a screw that is dimensioned to have enough strength to avoid failure for pullout. Most preoperative planning is performed on axial CT slices with the pedicle width reference the screw diameter.[38,39] Therefore, we used the screw diameter and pedicle width (SD/PW) ratio to express the screw selection. Furthermore, we hypothesized that a positive correlation exists between the pullout load and the SD/PW if we consider the bone purchase as an indicator for the pullout strength.

This relationship has been first investigated in a validated finite element model of an upper thoracic vertebra. Then, the transposition of this correlation to the whole spine has been evaluated through pullout experiments on instrumented cadaveric vertebrae. We expect our findings to decrease preoperative planning time by providing a guideline for selecting screw diameter sizes relative to the pedicle dimensions, considering an important factor of bone purchase overlooked in the past as it is not usually available to surgeons. Estimation during planning of the pull-out load has the potential to reduce risk of loosening since it has been previously associated to pull-out strength.[40,41]

Materials and Methods

Informed consent was not required as the study was deemed exempt from the requirement as it was on a cadaveric specimen. The application of all data in this study was approved by the ethics committee of the UIC Office for the Protection of Research Subjects who determined that this study does not meet the definition of human subject research and is limited to cadaver specimens.

Computer Model of the Cadaveric Vertebra

The screw was virtually implanted in a T3 vertebra selected from one of the cadaveric vertebras tested. This vertebra was chosen because previous studies have shown that T3 vertebra tolerated a wide range of screw dimensions for insertion. This selection varied from an SD/PW ratio of .55[42] to 1.16 used by Chan et al[34] When implanted with a screw in diameter of 5 mm and length of 35 mm through the anatomic approach, the cadaveric vertebra exhibited a failure load of 872.10 N (Figure 1). Following a CT scanning using a Bright Speed (GE Healthcare Technologies, Waukesha, WI, USA) scanner (slice thickness of .625 mm, pixel size of .312 mm), the vertebra was reconstructed in the Mimics Suite (Materialise, Leuven, Belgium) as shown in Figure 1A. The screw axis was evaluated through the cylinder best fitting the reconstructed hole and mirrored to the sagittal plane (see Figure1B) in the portion not damaged by the experiment. The material was assigned as elastic perfectly plastic with properties based on the Hounsfield values using the equations proposed by Giambini et al[43] A layer surrounding the screw was modeled to include a failure for shear at a value of .1. This value was found best to replicate the experimental value of the pullout load. The shear failure stress was considered because it has been previously associated with the static strength of threaded connections.[44] The contact between the screw and the bone was modeled as surface-to-surface contact with a coefficient of friction of .2[29,45, 46].

The four SD/PW ratios (see Figure 2) have been recreated by varying the screw diameter in values of 3, 4, 5, and 6 mm, scaling the screw about its longitudinal axis. With the exemption of the chips and the surrounding layer, the vertebra meshed with tetrahedral elements (C3D4), having sizes varying from 0.2 mm to 1 mm in correspondence with the external shell. To insure standard element size distribution across the implanted screw diameters, the vertebra was remeshed for each inserted screw. The screw pullout was performed applying a displacement of 1.32 mm, equivalent to half of the pitch, along the screw axis.[47] By imposing symmetrical conditions on the sagittal plane (zero transverse displacement and zero rotations) and constraining all the degree of freedom in the endplates, the articular surface of the superior facet and the edges of the inferior articular facet, the conditions simulated the restraining action of the capsular ligaments. The pullout force peaks measured in the four simulations were correlated to the values of SD/PW imposed using a linear regression model.
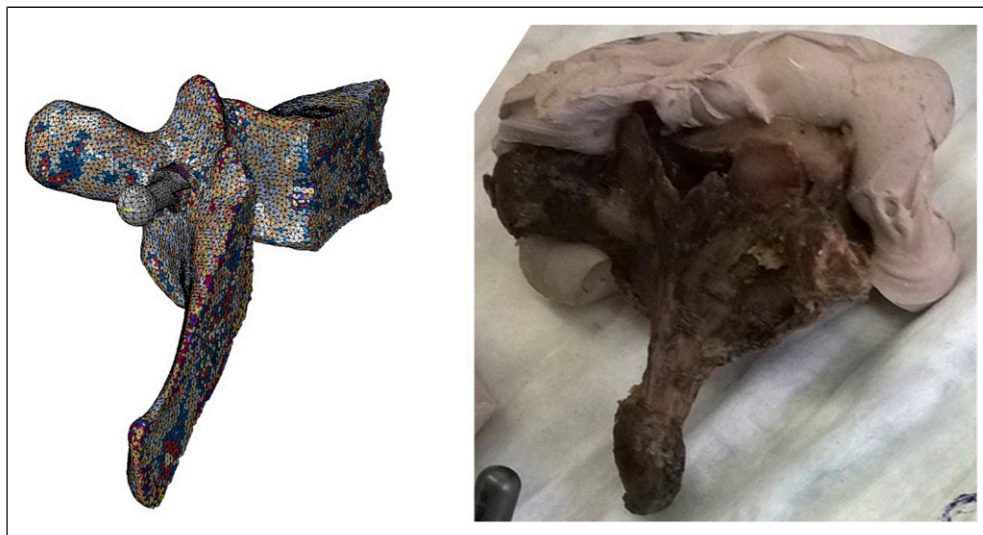
Figure 1. Computer model created to simulate the pullout mechanism experimentally performed in the cadaveric vertebra on the right.

Cadaveric Specimens Testing

Cadaveric experiments were performed on two fresh frozen thoracic spines (T1-T10) with a similar bone mineral density (P=.122) with an average value of .906±.156 g/mm2. The harvested vertebrae were instrumented, avoiding pedicle breaches, with 30, 35, and 40 mm Depuy Expedium polyaxial screws in diameters ranging from 5 to 7 mm (DePuy Synthes, Warsaw, IN) and potted in polyester resin (Bondo Corp, Atlanta, GA). The absence of pedicle breaches was ensured by visual inspection before mechanical testing. Along the screw axis[48] a displacement at a rate of 5 mm/min was applied to the rod locked onto the screws with an Instron electromechanical system (Instron Model 5569, Instron Corp, Canton, MA) using a protocol[47] that accounts for the specifics of the ASTM *F5*43 (see Figure 3). The data was recorded at a frequency of 100 Hz and 5N increments. Following a CT scan using BrightSpeed (GE Healthcare Technologies, Waukesha, WI, USA) scanner (slice thickness of .625 mm, pixel size of .312 mm), the vertebrae were segmented in the Mimics Suite (Materialise, Leuven, Belgium), and the pedicle dimensions were measured in their smaller section. In each section of the identified cortical shell, we measured the sagittal width, the outer width, the inner transverse widths, and the screw hole to determine the screw diameter. The cortical thickness was evaluated as half the difference between outer and inner transverse widths. Relationships between failure loads and characteristic dimensions of the pedicles were evaluated through linear regression.

Results

Computer Model

The four screw diameters simulated resulted in SD/PW ratios varying from .50 to 1.00. All the screw dimensions had cortical bone purchase in the posterior cortex of the posterior elements. Screws in diameter of 5 and 6 mm had cortical purchase in the medial and lateral cortex of the pedicle.

The failure load ranged from 371.3 to 1601.0 N, respectively, for 3 and 6 mm screws. In the vertebra implanted with the 5 mm screw, the failure load was 866.2 N. This vertebra aimed to model the behavior of the cadaveric specimen (see Table 1).

As shown in Figure 4, the screw with a diameter of 6 mm resulted in a stress pattern with values of 11.66 MPa that involved the vertebral body. It resulted in a deformation that extended throughout the entire vertebra (see Figure 33). A peak of 28.9 MPa was measured for the 6 mm screws, while, the 3 mm screw, the stress at the lateral cortex of the pedicle was negligible; however, we observed values of 15 MPa at the posterior cortex in contact with the thread. The 6 mm screw induced complete damage of the pedicle characterized by the avulsion of medial and lateral walls.

The linear correlation between pullout load and the ratio of screw diameter over pedicle width had a coefficient of determination R2=.914 (see Figure 5).

Experimental Results

For both spines, we found that the failure load ranged from 346N to 1288N with an average of 825.4±336.1 N. The pedicle transverse width varied with 5.98 mm and 8.10, respectively, for T3 and T8 of the first spine, while the other specimen ranged from 6.91 mm in T4 to 8.86 mm in T9. The sagittal pedicle width in the first spine varied from 12.26 mm in T1 to 18.15 mm in T6. In the second spine, the variation in sagittal width was narrowed and ranged from 14.28 mm in T3 to 15.22 mm in T9. A linear correlation between the dimensions of the pedicle and the experimentally evaluated pullout load has not been found (see Figure 6). In contrast, a
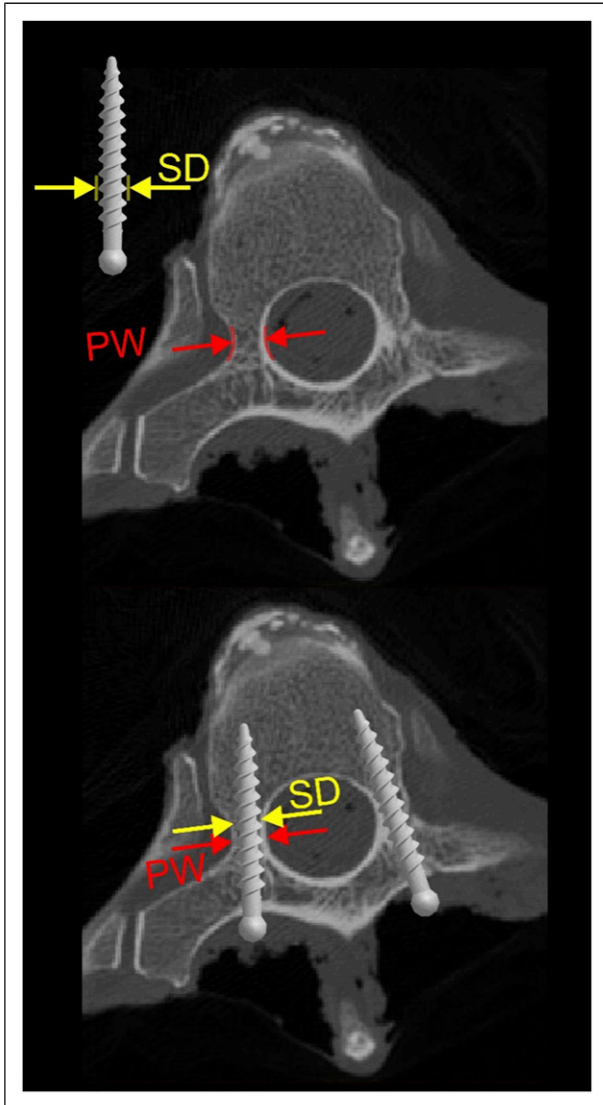
Figure 2. Axial CT slice used to illustrate the pedicle width (PW) and screw diameter (SD) used for SD/PW ratio.

low determination coefficient has been found for the inner pedicle transverse width (R2=.163).

Even though the pedicle transverse and sagittal widths were not significantly different between the two spines (respectively P=.635 and .697), differences were found in terms of cortical thickness (P=.010). The first spine had a cortical thickness ranging from 1.09 mm in T7 to1.87 mm in T1, while the maximal thickness found in the second spine did not exceed 1.26 mm in T7. Considering the values from both spines, we found a weak linear relationship between the pullout load and cortical thickness with a coefficient of determination R2=.299. The coefficient of determination was increased to the value of R2=.421 when a linear relationship between pullout load and the ratio between screw diameter (SD) and pedicle width (PW) was considered. Outliers were identified in the peak loads of 1216 and 1288N found for an SD/PW ratio of .83 (Figure 7).
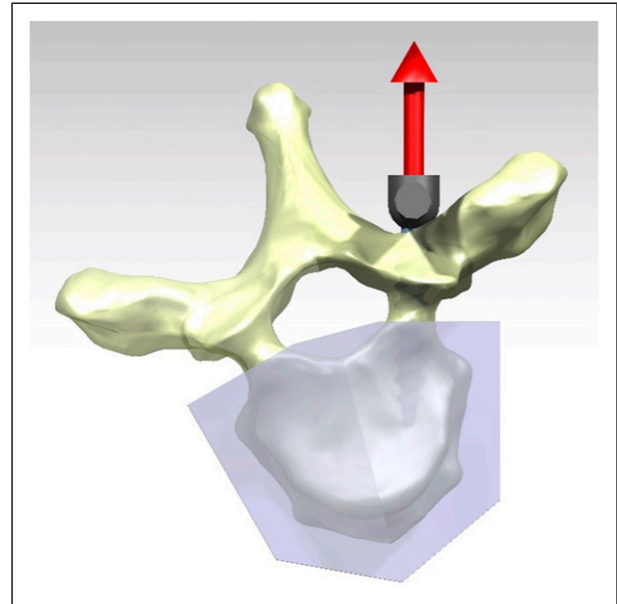

Figure 3. Experimental setup adopted for the testing of a cadaveric vertebra.

Table 1: Values calculated for pullout load in relation to the volume of bone purchase.

screw diameter [mm]	3	4	5	6
pedicle width [mm]	5.98			
SD/PW ratio	0.50	0.67	0.84	1.00
max force [N]	371.3	596.6	866.2	1601.0

Discussion

A commonly accepted criterion for pedicle screw selection has yet to be proposed.[49] There are research studies where primary screw selection have been suggested,[10,12,28,32] but in light of our findings, additional testing supported by clinical evidence is needed. Spinal fixation requires an optimization of the pedicle screw paradigm in spine surgery. As spinal navigation and robotics become more standardized, precision and accuracy of placement of pedicle screws become evident, resulting in decreased mechanical breaches. Despite the fact that most of the pedicle breaches are asymptomatic,[50] the correlation between pullout strength and bone purchase has the potential to further improve clinical outcomes.

This study aimed to provide additional information to the surgeon in performing the screw selection to pedicle dimension to maximize biomechanical performances while avoiding pedicle breaches. We evaluated the pullout strength through computer modeling and the cadaveric testing of thoracic vertebrae. First, we simulated one T3 vertebral level and assessed the pullout strength using four different screw diameters. The failure load was highly correlated to the SD/PW ratio (R2=.914) for this particular level. Still, for SD/PW values
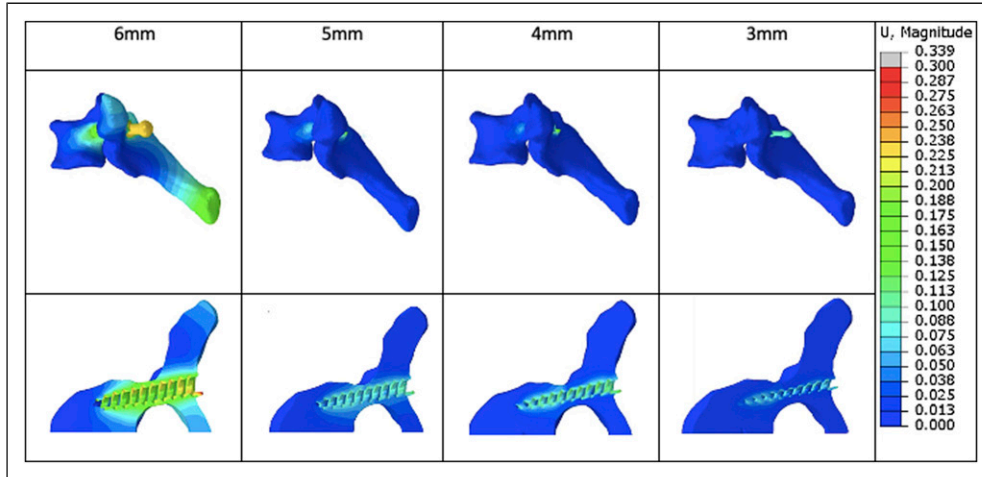
Figure 4. Resulting vertebral deformation at peak loads measured for the four screw diameter considered.
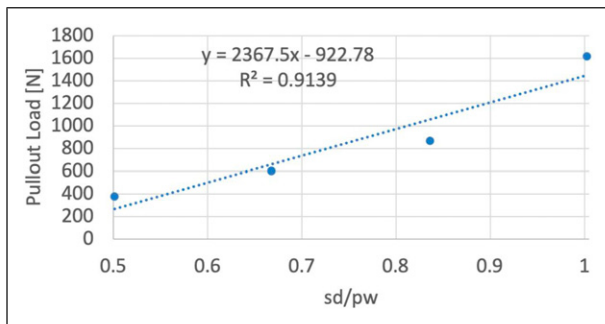

Figure 5. Pullout strength relation to SD/PW ratio.

greater than .80, there were avulsions of the medial and lateral pedicle regions. Clinically these avulsions could compromise neural structures or reduce the ultimate strength of fixation.

The limitations of the computer model proposed can be within the scope of the vertebral level we used. It only accounted for the T3 vertebral level. However, the extension of the results obtained for this particular vertebra to other spinal levels can be justified by its geometrical dimensions and by the resultant failure load. Measurements can be extrapolated to define different spine segments, but we believe this could be overcome by simply performing CT scans on all the vertebrae to be tested. The dimensions of the cadaveric vertebra tested had measures of 5.98, and 13.71 mm for width and height which are within the ranges of width (5.05±1.47 to 5.69±.80) and height 12.25±1.05 (range 8.69-15.85) reported in other morphometric studies for similar vertebral levels.[18,27,33,51] A previous study has shown that T3 vertebrae have values of transverse width (5.6±1.4 mm) and sagittal widths (12.4±1.3) similar to the other upper thoracic vertebrae (T3-T7).[52] Regarding the failure load, the value of 596.57 N that we have found for the SD/PW ratio of .67 closely resembled the value of 596.0 N for an SD/PW approximating .55 found by Heller et al[42] for T3.
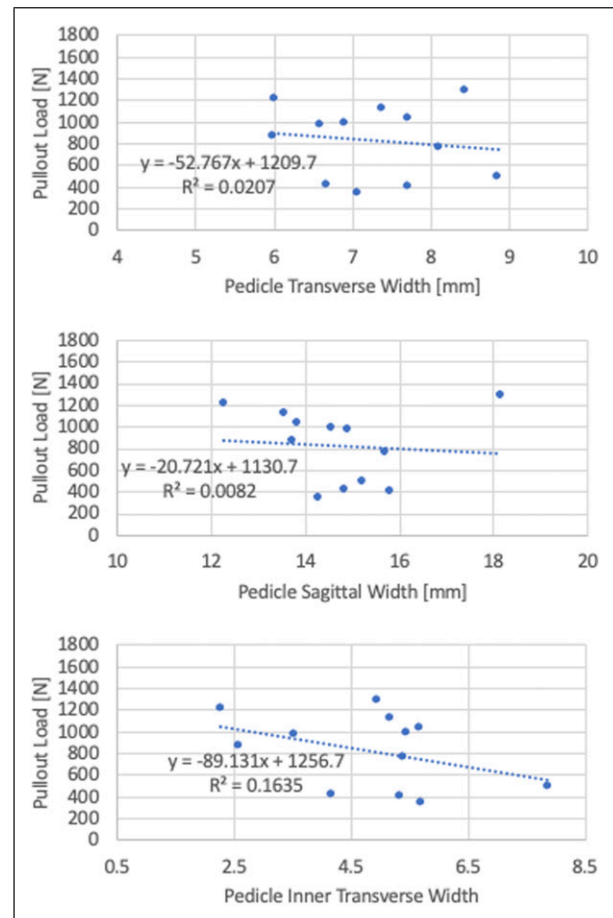

Figure 6. Pullout force relation to pedicle dimensions.

Further studies with various screw designs are also needed since different screw designs lead to different biomechanical strengths.[53] Furthermore, the ratio between the width and the length of the screw requires consideration due to the risk of perforating and injuring anterior vascular
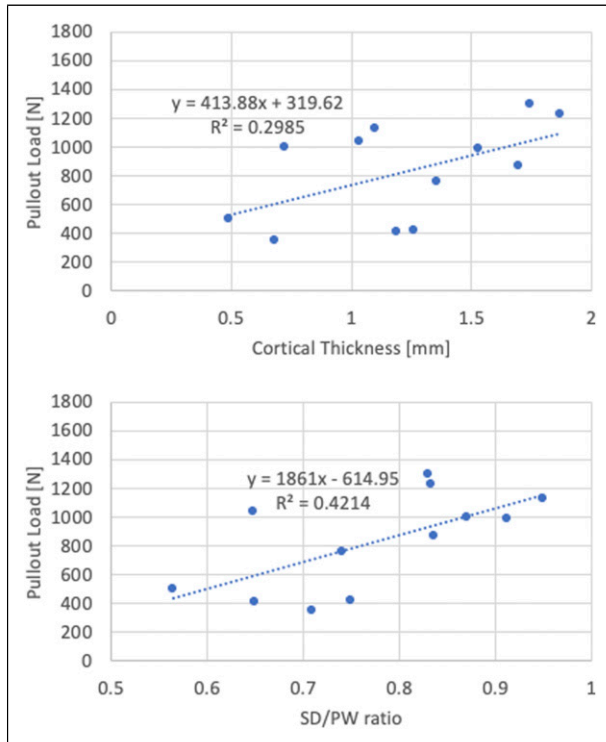
Figure 7. Pullout force in relation to cortical bone thickness and SD-PW ratio.

structures[54] and the impact of screw length on the pullout strength.[45]

When we investigated pullout strength in the entire thoracic groups by performing experiments on the cadaveric vertebra, we found that the pullout was not correlated to the sagittal width, cortical bone thickness, or inner strength pedicle width. Still, it was moderately associated with the SD/PW ratio. Further examination of our experimental values obtained for all the spine segments, the lower correlation coefficient found for the relationship between pullout load and SD/PW ratio indicates a need for further studies. Therefore, our correlation is evaluated individually for each segment. However, the cadaveric experiments revealed that, among the thoracic levels, the highest pullout loads were observed for SD/PW of .83. Therefore, the moderate correlation should be considered due to the variability of vertebral morphology and bone quality among spine segments. Even though we only used vertebrae from two cadaveric specimens, we obtained pullout values in the range of 346N to 1288N with an average of 825.4±336.1 N that is comparable in terms of variability with values obtained in previous studies for the thoracic spine. Hongo et al[36] implanted 5.5 mm screws into thoracic levels T4-T9 with an SD/PW ranging from .78 to 1.15 with an average pullout strength of 672±412N. Another study evaluated the vertebral ranges of T4-T12 with varying screw diameters from 4.8-7.2. The pullout strength for the upper thoracic spine (T4-T8) was 531.7±213.8 N (224-1072N) with an SD/PW range of .52-1.67 and 807.9 ± 207N with an SD/PW range of .50-1.50 for the lower thoracic level (T9-T12).[48]

Liljenqvist et al also note lateral screw penetration due to small pedicle width in certain vertebral levels.

Our findings allow a preoperative planning targeted to the maximization of the pullout load that has the potential to reduce loosening while minimizing screw diameter. Since CT measurements generally do preoperative planning for screw placements[55] and the surgeon's decision,[22] defining a standard to guide the surgeon's screw selection validates evidence-based medicine better than manual planning. This study is limited on quantifying the characteristics of the screw-bone interface through only the pullout strength while it must be recognized that other elements such as bone density and screw orientation play crucial role in determining the effective stability of the constructs.[47]

In conclusion, for the T3 vertebra, we found a high correlation of SD/PW ratio with pullout strength. However, an SD/PW value above .84 failed from pedicle avulsion. In the cadaveric experiment, we found that the pullout load is more correlated to SD/PW than other pedicle measures and is maximized for a value of .83 without failure for pedicle avulsion. Therefore, this particular value should be considered the upper limit of the indicated SD/PW ratio at the time of surgery. Additional clinical testing is needed to identify the effective benefits of a planning tool that includes pull-out strength estimation and to validate that SD/PW approaching a value of .83 maximizes the pullout load without the potential failure for posterior arch avulsion.

Declaration of Conflicting Interests

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ORCID iDs

Michelle C. Welborn, MD https://orcid.org/0000-0002-9422-6849
Ankit I. Mehta, MD https://orcid.org/0000-0001-6931-6095
Farid Amirouche, PhD https://orcid.org/0000-0002-3002-4199

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