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Pull-out strength of the suprapedicle claw construct: a biomechanical study

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Abstract The pull-out of the superior screw is a well recognized problem in anterior instrumentation of the spine for scoliosis. A biomechanical pull-out study of anterior vertebral body screw in cadaveric thoracic spine was therefore designed to investigate and compare the pull-out strength of three different anterior vertebral body fixations using the AO Universal Spine System: simple bicortical screw, bicortical screw with an opposite washer (sometimes called pull-out resistant nut), and a new construct made of a bicortical screw with the addition of a suprapedicular hook on the same vertebra (or claw construct). The T4 to T9 vertebral bodies from six human cadavers (total of 36 specimens) were instrumented with three different instrumentation constructs after measuring the bone mineral density of each individual vertebra. After stabilization of the vertebral bodies, the screws were extracted employing a material testing system using axial pull-out. The maximum axial forces were recorded at the time of the construct failure. The mean ultimate fixation strength (UFS) values after being adjusted for bone mineral density and vertebral body diameter

were 631, 711, and 1244 N for the three different constructs, respectively (screw alone, screw with an opposite washer, and screw with a suprapedicle claw). The difference in UFS was not significant for the first two constructs tested (screw alone and screw with an opposite washer). However, the difference in ultimate fixation strength between the claw and the other constructs was highly significant ($P < 0.0001$). Specimens with low BMD did not benefit as much from claw construct as the ones did with a normal BMD. The failure mode of each construct was described, but was in neither case judged dangerous for the spinal cord. This study shows that the suprapedicle claw construct improves the pull-out strength of an anterior vertebral body screw by 80%, and changes the mode of failure so as not to rely only on the screw characteristics or solely on the vertebral body. By adding a suprapedicle hook in a claw configuration, one may prevent superior screw pull-out in anterior spine surgery for scoliosis.

Keywords Spine · Pull-out strength · Biomechanics · Hook instrumentation · Scoliosis

Introduction

A common problem with anterior thoracic screws in scoliosis surgery, regardless of the implant system, is screw pull-out, and coronal body fracture [3–6, 8, 9]. Several variables can affect the strength of fixation, such as screw design, screw tapping, orientation and bone quality [3–5]. The use of a cancellous thread configuration, bicortical purchase in the vertebral bodies, and an upper purchase of the screw below the end plate may provide some solutions for a stronger purchase [3–6]. A further method to prevent pull-out is to add a pull-out stop in the form of a specially designed nut on the opposite side of the vertebral body [8]. Lieberman has shown that the addition of such a pull-out resistant nut to an anterior vertebral body screw improves the pull-out strength by 2-fold and changes the mode of failure to rely ultimately on the inherent vertebral body strength rather than the screw's characteristics [8]. However, the problem with this method is the need to expose the other side of the spine to apply the pull-out resistant nut and since the screw has to be longer to engage the nut, there is a theoretical risk of injury to the great vessels [10]. More recently, the addition of a 3 mm washer on the top vertebra that elevates the screw head to be in closer height alignment to the second most proximal screw has the favor of some authors [7]. Despite all these improvements proximal screw pull-out and pseudarthrosis remain a problem in anterior scoliosis correction [2, 11].

We therefore decided to test our new fixation concept (suprapedicle claw) against the other accepted methods of fixation. The suprapedicle claw is best described in the Technical Innovation which can be found in the current issue of this journal [1]. It consists of a hook and a screw inserted in the same vertebra. A supralaminar hook is inserted over the pedicle after disarticulation of the rib head, and the screw is inserted just above the inferior end-plate. Both implants are attached to the rod and loaded in compression making a claw construct (Fig. 1).

Materials and methods

Thirty-six single human vertebrae were obtained from six individuals (T4 to T9) with a mean age of 35 years old. The thoracic spines were kept frozen at -20°C until the day of testing, and were then thawed to room temperature. Muscles and soft tissue were removed. Bone mineral density (BMD) was measured for all specimen in an anteroposterior projection by dual energy X-ray absorptiometry (DEXA) scan (Lunar Radiation Corporation, Madison, Wisc, USA). Direct caliper measurements of the vertebral body width, depth, and height were taken as well as pedicle horizontal and vertical diameters (Table 1). The ultimate fixation strength (UFS) was determined for each specimen using a pull-out test described below. A linear model was used to assess the effects of BMD, vertebral dimensions and the implant group on fixation strength. A *P*-value of 0.05 was used as level of significance throughout. All statistics used the SAS software package (SAS Institute Inc., Cary, N.C., USA.).

To avoid differences among specimens and constructs we carried out a block randomization with respect to the individual and the level into three distinct implant groups of 12 samples each. The T4–T9 levels were chosen based on the fact that screw pull-out is more often observed at these levels than lower down. The same instrumentation (Universal spine System (USS) Synthes, Paoli, USA) was used in our three different configurations.

The implant constructs that were compared in this study were a bicortical screw, a bicortical screw with a pull-out washer on the opposite side of the vertebra, and the new suprapedicle claw construct (Fig. 1) that consists of a USS screw with a superior laminar hook over the pedicle.

Since the commonly used approach is for right thoracic scoliosis, screws were applied on the right side along the equator of the vertebra. For the claw construct, the appropriate size laminar hook was applied over the

Fig. 1 AP X-ray and saw bone representation of the superior claw construct. The claw construct consists of an anterior vertebral body screw attached to a rod, with a hook inserted just proximal to the screw over the pedicle. Compression between the screw and the hook forms a claw construct

Table 1 Experimental values are given as mean with standard deviation for each of the three experimental groups. *ap* antero-posterior, *BMD* bone mineral density, *VB* vertebral body

	Nut	Screw	Claw
ap BMD	0.809 ± 0.199	0.793 ± 0.212	0.795 ± 0.152
Coronal VB dimension	34.3 ± 4.3	34.2 ± 4.2	34.6 ± 4.2
Sagittal VB dimension	30.5 ± 4.2	28.9 ± 4.3	29.5 ± 3.4
VB height	24.8 ± 1.6	25.3 ± 2.5	25.5 ± 3.4
Pedicle height	13.8 ± 3.0	13.9 ± 2.7	13.9 ± 2.9
Pedicle width	8.9 ± 1.5	8.3 ± 1.8	8.4 ± 1.4
Ultimate fixation strength	721.7 ± 249.7	619.7 ± 393.0	1234.5 ± 579.9*

($P < 0.0001$)

pedicle and the screw was applied just above the inferior end plate to accommodate the required distance between the screw and the hook (Fig. 1).

The screws used were of 6 mm diameter for T7–T9 and 5 mm for T4–T6 to approximate the sizes that are commonly used clinically and to match the size of the vertebra. The hook size was determined by the size of the pedicle (smallest possible)

The 5 mm USS screw used for T4–T6 has a root diameter (minimal inner diameter of screw) of 3.71 mm, a thread diameter of 4.9 mm, and a pitch of 1.4 mm. The USS screw used for T7–T9 has a root diameter of 4.62 mm, a thread diameter of 5.9 mm, and a pitch of 1.6 mm. The spiked washer has 13.5 mm outer diameter (with custom-made nut). The hook blade thickness depending whether it is a small or a large laminar hook is 2.1 ± 0.1 mm.

The entry points for the screw were established with an awl followed by a probe from the USS set. The entry point was at the junction between the middle and posterior third of the vertebra with four threads protruding

outside the cortex. For the claw construct, the screw was inserted through the posterior third and just above the inferior end plate to accommodate the hook

Each construct was connected to a stiff titanium rod so the pull-out tests for the claw construct and the other two screw constructs would be identical. (Fig. 2)

The fixation strength was evaluated by a pull-out test performed on material testing system (MTS model 858.01 table-top; mini-Bionix). Specially designed pneumatic holding clamps with small spikes anchoring the endplates were manufactured to hold the vertebra and resist the axial pull-out forces of the MTS machine (Fig. 2). The holding clamps were used to avoid embedding the vertebral body in acrylic cement mass which is a commonly used fixation with a tight form fit. The concern was that the acrylic cement might artificially strengthen the construct and/or vertebral body, especially in the case of the screw and washer construct where the vertebra is expected to burst during the pull out test. A constant holding force of 400 N was used. To test the resistance against pull-out forces of the claw construct, it was necessary to pull on the two sides of a 50 mm long rod where the claw had been fixed (Fig. 2). This was therefore done in a similar fashion to the other two constructs (screw alone and screw + washer). A gimbel was used to hold either end of the short rod. Initially, the gimbel could be adjusted in all directions and angles to hold the short rod unconstrained but was then fixed in this starting position throughout the test. Therefore, strict axial pull-out force was applied while the lower platform of the testing machine still allowed for free horizontal movement in all directions. The axial pull-out test on the MTS machine was done with a displacement control mode (monotonically increasing displacement at a constant rate of 0.5 mm/s), ensuring that loading was applied along the axis of the implant. The failure forces in Newtons were documented along with the failure mode. Failure was defined as the point at

Fig. 2 Each instrumented vertebra was gripped with pneumatic holding clamps. The constructs were mounted on a rod in order to apply axial pull-out forces at the two ends of the rod (see arrow *a*). The pull-out test was performed with a material testing machine. *VB* vertebral body

which maximum load was recorded in the load displacement curves for each specimen.

Results

There were no significant differences in BMD or in any of the size measurements between the three experimental groups. (Table 1)

In the load displacement curves recorded for each specimen, the first load peak was always the highest followed by a significant drop in load. Standard deviation (SD) and peak values are listed in Table 1. Data is derived from a normally distributed population, and therefore means and standard deviations (SD) are used to describe variables as listed in Fig. 3. Multilinear models were used to assess the effects of instrumentation, BMD and anatomical dimensions on the UFS (Fig. 3). First, stepwise regressions were used to select significant explanatory variables. The multi-linear model used for final data evaluation included as explanatory variables the implant group, the BMD, the coronal vertebral body dimension and the first order interaction term for BMD and implant group. The model ($P < 0.0001$) as derived from the adjusted (r^2) value, explains 88.6% of the variation in UFS data, leaving only 13.6% unexplained as a random variation. All explanatory variables were significant with the BMD and BMD-implant group interaction at $P < 0.0001$, the implant group at $P = 0.0065$ and the coronal dimension at $P = 0.0282$. Based on the variance component estimates, the most important explanatory variable was BMD, followed by implant group and lastly by the coronal vertebral body dimension. BMD, coronal diameter and instrumentation were all highly significant (regression: $P < 0.0001$, $r^2 = 0.886$) explaining UFS. Means for UFS adjusted for BMD and diameter

were 1244, 711, and 631 N, for the claw, screw with washer and single bicortical screw, respectively (Fig. 3). As determined with post-hoc test, the claw was significantly stronger (Bonferroni, $P < 0.0001$) than with screw alone, or screw with washer. There was no statistically significant difference between the screw, and screw with washer (Bonferroni $P = 0.88$).

When studying the effects of the bone mineral density on the different constructs, the first order interaction term for BMD and instrumentation was significant ($P < 0.0001$), indicating that specimens with low BMD did not benefit as much from claw construct as those with a normal BMD (Fig. 4). From the graph in Fig. 4, it is obvious that the claw construct provides a significant improvement in UFS for samples that have a high BMD, but fails to provide additional strength in specimens with a low BMD (BMD less than 0.7 g/cm^2). The later statement was an incidental finding, and this type of fixation is used mainly for young patients with scoliosis, not for patients with osteoporosis.

The failure mode of each construct was recorded. The screw alone construct failed with shearing at the bone screw interface. The screw with the opposite washer construct failed by imploding the vertebral body around the nut, in a similar fashion to what has been described in the literature [8]. For the claw construct, two modes of failure were identified: fracture of the lamina posteriorly in the midline observed in one-third of the case or a fracture through the lateral wall of the pedicle observed in two-thirds of the cases. In no instance was this failure mode judged dangerous to the spinal cord as the spinal canal remained identical in size or even enlarged. The fracture of the lamina happened in the case where a large blade hook was used, the fracture of the pedicle occurred when a small blade hook was used.

Fig. 3 Ultimate fixation strength (UFS) plotted for each implant group, and adjusted for bone mineral density (BMD) and coronal vertebral body dimension

Fig. 4 The effect of BMD on the pull-out forces of the three constructs. Significant first order interaction term exists between BMD and the three constructs group. With low bone mineral density the axial pull-out forces tend to be the same

Discussion

The results of this biomechanical study show an almost 2-fold increase in pull-out resistance when using the claw construct, in comparison to a conventional bicortical screw or a screw with nut augmentation. The screw and nut construct has added strength, but this was not statistically significant. This later finding does not match the results of Lieberman [8]. This can partially be explained by the differences in the levels being tested and probably by the differences in the testing setup. Lieberman studied the pull-out of the USS with a pull-out resistant nut in the lumbar spine, whereas our study was concentrated on the thoracic spine. Is any other anterior fixation superior to our claw technique in resisting pull-out forces? Although the use of two screws has been shown by Ogon [9] to increase the pull-out force of an anterior system especially in triangulation, this does not seem possible in the upper thoracic spine, where the vertebral bodies are too small to accommodate two screws without the risk of coronal body fracture.

Our concept does not seem to be valid when the bone mineral density is low, as pull-out forces tends to be similar among the three different constructs. The effect of BMD was already studied by Breeze in anterior spine fixation where the difference between monocortical and bicortical screw fixation was attenuated in specimen with low mineral density [3]. This has a very important bearing in that there is no advantage to using such construct in osteoporotic patients, but rather it should be reserved for the upper vertebra of young scoliotic patients.

The failure mode of our different constructs is interesting. Looking at the different specimens, obviously the screw with an opposite washer seemed to be the most concerning for the vertebra and the neural structure as the failure mode is an implosion of the vertebral body along the nut. As the nut measured 13.5 mm in diameter, this left a large hole in the vertebral body after failure. As the vertebral body height measures 25 mm on average, one would think that the vertebral body would be very significantly weakened. Conversely, the failure mode of the claw construct was either a fracture of the lamina (large blade hook) or a fracture of the pedicle (narrow blade hook) with no spinal canal narrowing.

This biomechanical study was very encouraging regarding the use of a suprapedicle claw to prevent proximal screw pull-out in scoliosis surgery. Future designs of new suprapedicle hooks should naturally fit anatomically the upper aspect of the pedicle with a

mildly concave curve blade to fit the inner canal. The blade should be large as the preferred failure mode is a lamina fracture in the midline as opposed to a pedicle fracture.

It is important to recognize that our biomechanical model describes the pull-out failure in-line with the direction of the screw, as this method is reproducible, and is the method used by most of the similar studies reviewed in the literature [3–6]. However, in scoliotic deformity, the resultant of forces on the superior thoracic screw are different. There is an axial pull-out force along the direction of the screw as the scoliotic vertebra is reduced to the rod, and a vertical force along the direction of the rod. The vertical force is easy to understand, as correction of the scoliosis requires closing and compression of the convex disc space. Naturally, it is easy to understand that the suprapedicle claw resists better these vertical forces as the hook over the pedicle will resist these vertical forces better than any other known constructs. We therefore think that the suprapedicle claw is even stronger in resisting the moment failure of the upper anterior scoliosis construct than what our biomechanical study has shown.

Fatigue testing of our system was not done. However, the adjunction of a suprapedicle hook should logically prevent screw loosening at the bone screw interface as the hook will prevent shearing forces to act on the screw. Further biomechanical studies will therefore test the vertical sharing forces of such claw constructs compared to other available constructs and the different fatigue testing of such a construct.

As to the possible intercostal nerve damage of the hook in the foramen, it is best discussed in the clinical application of the suprapedicle hook construct in this journal issue [1].

Conclusions

The suprapedicle claw construct improves by 80% the pull-out strength of an anterior vertebral body screw, and changes the mode of failure so as not to rely only on the screw characteristics or solely on the vertebral body. By adding a suprapedicle hook in a claw configuration one may prevent superior screw pull-out in anterior spine surgery for scoliosis.

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References

1. Arlet V, Shilt J, Ouellet J (2005) The suprapedicle hook in anterior scoliosis surgery. *European Spine Journal* (in press)
2. Betz RR, Harms J, Clements DH III, Lenke LG, Lowe TG, Shufflebarger HL, Jeszenszky D, Beele B (1999) Comparison of anterior and posterior instrumentation for correction of adolescent idiopathic scoliosis. *Spine* 24(3):225–239
3. Breeze SW, Doherty BJ, Noble PS, LeBlanc A, Heggeness MH (1998) A biomechanical study of anterior thoracolumbar screw fixation. *Spine* 23(17):1829–1831
4. Chapman JR, Harrington RM, Lee KM, Anderson PA, Tencer AF, Kowalski D (1996) Factors affecting the pullout strength of cancellous bone screws. *J Biomech Eng* 118(3):391–398
5. Decoster TA, Heetderks DB, Downey DJ, Ferries JS, Jones W (1990) Optimizing bone screw pull-out force. *J Orthop Trauma* 4:169–174
6. Horton WC, Blackstock SF, Norman JT, Hill CS, Feiertag MA, Hutton WC (1996) Strength of fixation of anterior vertebral body screws. *Spine* 21:439–44
7. Lenke LG (2003) Anterior endoscopic discectomy and fusion for adolescent idiopathic scoliosis. *Spine* 28(15S):S36–S34
8. Lieberman IH, Rabi K (1998) Terence Woodside. Anterior vertebral body screw pullout testing. A comparison of Zielke, Kaneda, universal spine system, and universal spine system with pullout-resistant nut. *Spine* 23:908–910
9. Ogon M, Haid C, Krismer M, Sterzinger W, Bauer R (1996) Comparison between single-screw and triangulated, double-screw fixation in anterior spine surgery: a biomechanical test. *Spine* 21(23):2728–2734
10. Sucato DJ, Duchene C (2003) The position of the aorta relative to the spine: a comparison of patients with and without idiopathic scoliosis. *J Bone Joint Surg [Am]* 85A(8):1461–1469
11. Sweet FA, Lenke LG, Bridwell KH, Blanke KM, Whorton J (2001) Prospective radiographic and clinical outcomes and complications of single solid rod instrumented anterior spinal fusion in adolescent idiopathic scoliosis. *Spine* 15;26(18):1956–1965