The biomechanics of pedicle screw-based instrumentation

There are three basic concepts that are important to the biomechanics of pedicle screw-based instrumentation. First, the outer diameter of the screw determines pullout strength, while the inner diameter determines fatigue strength. Secondly, when inserting a pedicle screw, the dorsal cortex of the spine should not be violated and the screws on each side should converge and be of good length. Thirdly, fixation can be augmented in cases of severe osteoporosis or revision.

A trajectory parallel or caudal to the superior endplate can minimise breakage of the screw from repeated axial loading. Straight insertion of the pedicle screw in the mid-sagittal plane provides the strongest stability.

Rotational stability can be improved by adding transverse connectors. The indications for their use include anterior column instability, and the correction of rotational deformity.

Biomechanics of the pedicle screw

Studies on the biomechanics of the pedicle screw can be divided into three types: those that concern the characteristics of the screw itself, those that address how they are inserted and those that deal with augmentation techniques.

Screw characteristics. Definition. The parts of a pedicle screw are shown in Figure 1: each is of biomechanical importance. The screw consists of a head, neck and body. The body may be conical or cylindrical. It has a major (outer) and minor (inner) diameter. The difference between the two is the thread depth. The pitch of the thread is the distance between the crests of two adjacent threads.

Pullout strength. When a pedicle screw is pulled out, the bone between the crests of the thread is typically fractured. Therefore, the quantity as well as the quality of the bone is important. It is generally thought that a larger outer diameter, a smaller inner diameter, shorter pitch, and stronger bone increase the pullout strength. Among them, the outer diameter is the most important factor in determining pullout strength. Tapping, however is thought to reduce the pullout strength.

The morphology of the pedicle also affects the pullout strength of the screw. Hirano et al have shown that the pedicle of the spine is more important in resisting pullout than the vertebral body. About 60% of the screw pullout strength and 80% of the longitudinal stiffness depend on the pedicle rather than the vertebral body. In osteoporosis, however, the cortex of the pedicle is thinner and the bone mineral density (BMD) is reduced. The use of a larger screw does not increase the stability of the construct and may result in cortical cut out
of the pedicle. Misenhimer et al also found that pedicle screws do not gain purchase in cortical bone within the pedicle because the pedicle deforms first. Therefore, a pedicle screw with a diameter larger than the endosteal diameter of the pedicle will either fracture the pedicle or cut out. Insertional torque. Many surgeons prefer a pedicle screw with high insertional torque because it gives good tactile feedback of bony purchase. For the same thread design and size, insertional torque is directly related to BMD which, in turn, is directly related to pullout strength. It would seem reasonable to conclude that insertional torque is directly related to pullout strength. In one study, the investigators showed insertional torque to be directly related to the number of cycles to pullout. However, since the publication of that study, no other study has shown a strong correlation between insertional torque and pullout strength. By contrast, although there is a strong correlation between insertional torque and BMD, screw loosening is not objectively predicted by insertional torque in the clinical setting. Inceoglu, Ferrara and McLain have confirmed that there is no correlation between insertional torque and pullout strength. In order to explain this paradox, we need to pay attention to the kind of screw being tested. The insertional torque is very sensitive to thread design while the pullout strength is not. Taking into account the differences in thread design, there appears to be no correlation between insertional torque and pullout strength.

Fatigue strength. The inner diameter is the most important dimension of the pedicle screw when considering its fatigue strength. In one study, fatigue strength increased 104% following a 27% increase in inner diameter. The neck is the weakest part of a monoaxial screw and Fogel et al have shown that the coupling between the polyaxial head and the screw is its weakest part.

Different designs. A number of different designs of screw have been developed over the years in an attempt to improve screw biomechanics. Bushing augmented screws in order to improve load-bearing capacity, screws with dual core in which the inner diameter thickened around the neck to improve fatigue strength, and double threaded screws to facilitate faster insertion, all yielded promising biomechanical results. There are other screws on the market such as the screw with double lead and dual thread near the pedicle area (OteoGrip, Medtronic, Memphis, Tennessee). Double lead and dual thread near the pedicle area can provide the higher insertional torque which many surgeons believe can lead to higher pullout strength. However, higher pullout strength has not yet been proven.

The inner core of the pedicle screw can be conical or cylindrical. Which is biomechanically better, is still controversial. The biggest concern of using the conical screw is decreasing pullout strength when it needs to be backed out. Kwok et al and Abshire et al advocated the use of conical screws. Kwok et al described that, in terms of insertional torque, the conical screw is superior but the pullout strength is the same. Abshire et al described that even up to 360° back out is safe with the conical screws as there is no pullout strength loss. However, Lill et al described that even with a half turn of back out of 180° significantly reduced the pullout strength.

Still, whether the conical screw can be backed out up to 360° is controversial. Many researchers tried to find the answer in the different design of the screws in terms of outer diameter, inner diameter and pitch distance. The biggest difference between the studies of Abshire et al and Lill et al was that one involved porcine lumbar vertebrae and one cadaver spines. We support the view of Lill et al since the study was conducted in a real operative field and believe that the conical screw will loosen if backed out for 360°.

Insertion technique

Screw hole preparation. When inserting pedicle screws, keeping the dorsal cortex intact is important for solid fixation. Many surgeons tap the screw hole before inserting the screw and it has been shown that tapping improves trajectory. However, screws placed into untapped holes have a higher pullout strength. Generally, same-size tapping is not recommended as it reduces the purchase of the screw, but undertapping by 1 mm is thought to be safe and conserves the same pullout strength as an untapped screw hole. The most important point is not to manipulate the screws excessively because insertion, back-out, and reinsertion of the screws lead to a decrease in insertional torque and pullout strength.

Trajectory. Convergence of pedicle screws by 30° in the coronal plane can increase the pullout strength by 28.6% (Fig. 2). Insertion of the screws without convergence, however, is more stable in terms of longitudinal linkage.

More recently, a laterally-directed cortical bone trajectory was advocated by Santoni et al and was found to have similar biomechanical characteristics to the more traditional medial trajectory (Fig. 3). This cortical trajectory is especially effective in poorly trabeculated osteoporotic bone. It has also been used for extrapedicular vertebroplasty and has been found to be biomechanically effective.

Insertion depth. About 80% penetration depth or passing the neurocentral junction is considered sufficient. Krag et al showed that 80% penetration is 32.5% stronger than
50% penetration. Up to 75% of maximum insertional torque can be achieved with engagement of the neurocentral junction.32

Salvage (pedicle screw augmentation)
Indications and options. Various methods of augmentation can be used for revision or in severely osteoporotic patients, including cement augmentation, additional hooks and wires, and larger, expandable hydroxyapatite-coated screws.35

Recently, other options such as extrapedicular screws, double pedicle screws, and injecting cement through an appropriate implant have been advocated.

Even though most of these are biomechanically sound, there are only a few studies that have compared the different options. Kiner et al compared the larger screw and polymethylmethacrylate-(PMMA) augmented screw and showed that the larger screw had higher construct stiffness than the PMMA-augmented screw. The use of cement in the spine is becoming more popular.

Cement (PMMA or bioabsorbable). PMMA is still widely used, but the dangers of using it in the spine have prompted the development of bioabsorbable cement which has the same favourable biomechanical properties and high osteoconductivity while discharging less heat than PMMA.40

Linhardt et al found that pullout strength was improved if the screw was inserted while the PMMA was in its doughy state rather than after it had hardened. The pullout strength from bioabsorbable cement at different timings showed that augmentation power increases up to four minutes after the injection of calcium phosphate cement but decreases after four minutes.42 Screw removal was safe whenever the screw had been introduced.43

Pedicle screw construct
Pedicle screw constructs versus other constructs. Many biomechanical studies have compared pedicle screw constructs with other constructs. Kallemeier et al showed that posterior pedicle screw fixation with anterior plating and a strut graft gives the most rigid fixation. Less rigid constructs were posterior pedicle screw fixation with anterior strut grafting but without plating, followed by posterior pedicle screw fixation alone and then anterior plating with a strut graft. Wang et al have suggested that pedicle screws alone do not provide sufficient stability if the anterior column is compromised, like, for example, in thoracolumbar fractures.

The biomechanical properties of different pedicle screw constructs. There have been many studies that have compared different methods of assembling the construct itself. Yücesoy et al compared the angular range of movement (ROM) and neutral zone of six different types of construct and showed that unilateral short fixation was the least stable. After extending the construct by one more level above and below, the mean ROM across the pathological level was decreased by 56%. Yousef et al studied the bending movements of the pedicle screw as a function of the sagittal angle of insertion and concluded that screws angled cephalad developed a greater mean intrapedicular bending moment when compared with screws inserted caudal or parallel to the superior endplate. This suggests that cephalad insertion should be avoided because of an increased risk of early fatigue or failure. The axial insertion angle was also studied: straight screw insertion with no convergence provided a more stable longitudinal construct. The authors advocated that the trajectory of the pedicle screw should be parallel to the mid-sagittal line rather than along the axis of the pedicle.

A few studies have compared the different construct designs as well. Chen et al compared the use of polyaxial and monoaxial screw systems with an anterior cage and found that the polyaxial screw system gave greater rigidity in the lumbosacral spine.

New pedicle screw construct designs. There are a small number of innovative constructs that include pedicle screws as a method of fixation such as the polyethyetherketone rod system, and the transpedicular plate fixator. While they appear to be biomechanically sound, their clinical efficacy has yet to be confirmed.

Insertion techniques of transverse connectors. Biomechanical testing has shown that only axial rotational stability improves significantly with the addition of transverse connectors. The greatest stability can be obtained with two transverse connectors. Lim et al advised that the ideal position is “one in the middle and the other at the proximal 1/8 position of the longitudinal rods”. Lim et al also studied the technique of placing transverse connectors and concluded that diagonal transfixation can hold the construct more rigidly in flexion and extension but not in lateral bending or axial rotation, when compared to horizontal-transfixation. Furthermore, the pedi-
cle screws bear greater stresses in the diagonal transfixation model.

Kuklo et al.53 studied transverse connectors in the thoracic spine and showed that they can significantly decrease axial rotation. The addition of one transverse connector had some effect, but the addition of two provided more rigidity. **Indications for transverse connectors.** Lim et al.51 showed a significant difference in ROM between the intact spine and that instrumented with a transverse connector after total discectomy, suggesting that transverse connectors have a measurable effect on the spine with an unstable anterior column. Chutkan et al.54 demonstrated that facetectomy can increase axial rotation and transverse connectors can restore it, but that the amount of restoration of axial stability was minimal. They concluded that the use of a transverse connector is not justified.

Based on these findings, we suggest that the indications for using transverse connectors should be: 1) in all cases of anterior column instability including fracture, anterior disectomy or anterior corpectomy, and 2) when correcting rotational deformity.

**Supplementary material**

An illustration showing six different construct designs, compared in terms of the angular range of movement (ROM) and neutral zone (reproduced after permission from Yücesoy K, Yiiksel KZ, Baek S, Sonntag VK, Crawford NR. Biomechanics of unilateral compared with bilateral lumbar pedicle screw fixation for stabilisation of unilateral vertebral disease. *J Neurosurg Spine* 2008;8:44-51) can be seen with the online version of this article on our website at www.jbjs.org.uk

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

**References**


