Biomechanical arrangement of threaded and unthreaded portions providing holding power of transpedicular screw fixation

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ABSTRACT

Background: Failure of pedicle screw is a major concern in spinal surgery. The threaded and unthreaded portions of the pedicle screw provide the ability to anchor and squeeze the surrounding bone, respectively. This study aimed to investigate the anchoring and squeezing effects of different design of the threaded/unthreaded portions of a pedicle screw to vertebrae.

Methods: Four variations (one fully and three partially threaded, with a 1/3, 1/2, and 2/3 unthreaded designs at the proximal portion) of screws were used to measure pullout strength and withdrawn energy using synthetic and porcine specimens. The tests were conducted in static and dynamic fashions, in that the screws were axially extracted directly and after 150,000 cycles of lateral bending. The load-displacement curves were recorded to gain insight into the peak load (pullout strength) and cumulative work (withdrawn energy).

Findings: The two testing results of the synthetic and porcine specimens consistently showed that the 1/3 unthreaded screw provides significantly higher pullout strength and withdrawn energy than the fully threaded screw. The withdrawn energy of the three unthreaded screws was significantly higher than that of the threaded counterpart.

Interpretation: The holding power of a pedicle screw was the integration of the anchoring (cancellous core) and squeezing (compact pedicle) effects within the threaded and unthreaded portions. The current study recommends the 1/3 unthreaded screw as an optimal alternative for use as a shank-sliding mechanism to preserve the holding power within the pedicle isthmus.

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1. Introduction

Transpedicular fixation has been widely used in spinal surgery to correct deformity and stabilize the spine. However, loosening at the bone-screw interfaces and breakage at the screw threads are common failure modes (Phdlajamaki et al., 1997; Davne and Myers, 1992; Lonstein et al., 1999; Okuyama et al., 2000; Kwok et al., 1996; Hsu et al., 2005). Failure of pedicle screws often leads to loss of fixation, symptomatic pseudarthrosis, and possible reoperation. To eliminate these complications, several concepts have been investigated, including shape modification of the threads, surface coating of the screws, and polymethylmethacrylate (PMMA) augmentation within screw holes (Krenn et al., 2008; Choma et al., 2011; Hashemi et al., 2009; Hasegawa et al., 2005; Sandén et al., 2001). These aim to enhance holding power at the bone-screw interfaces and fatigue resistance at the thread-shank junction, which have been reported to be stress-concentrated sites that jeopardize screw strength (Chao et al., 2008).

The pedicle screw is inserted to hold the bone through a pedicle isthmus and vertebral core (Fig. 1). The anchoring ability of the threaded shank comes from the shearing cut of the sandwiched bone chips along the cylindrical surface, formed by the thread tips (Tsai et al., 2009). However, slipping resistance at the unthreaded shank-bone interfaces results from the increased friction of the bone chips that were squeezed onto the surrounding zone (Chapman et al., 1996). The current study proposes two hypothetical, optimal arrangements of screw threads within two bony regions. The first uses the unthreaded shank to suppress the stress-concentrated effect, thus reducing the breakage risk within the pedicle isthmus (Chao et al., 2008). Furthermore, the greater diameter of the unthreaded shank can squeeze the surrounding

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bone onto the peripheral wall of the predrilled hole, thus increasing the frictional resistance and the holding power of the inserted screw. The second is to preserve the deeper threads near the screw tip to anchor the cancellous bone of the vertebral core. Static and dynamic tests were used to evaluate the outcome of the different threaded strategies within the two bony regions.

In this study, specially manufactured pedicle screws with varying lengths of unthreaded designs at the proximal portion were tested. The peak load (pullout strength) and cumulative work (withdrawn energy) of the load-displacement curve were used as the comparison indices of the four screws. The measured pullout strength and withdrawn energy are discussed to investigate the holding characteristics of the threaded and unthreaded designs. The results of the testing were aimed to provide insight into the bone-screw interaction at the vertebral core and pedicle isthmus.

2. Methods

2.1. Pedicle screws

There were four variations of the threaded and unthreaded screws in this study: (1) threaded design along the full shank, (2) unthreaded design in the proximal one-third of the shank: 1/3 unthreaded, (3) unthreaded design in the proximal half of the shank: 1/2 unthreaded, and (4) unthreaded design in the proximal two-thirds of the shank: 2/3 unthreaded (Fig. 2a). The fully threaded screw was used as a control. The specifications of the four screws were the same, including outer and core diameters, pitch, depth, and profile of the threads, and screw length. All screws were 5.5-mm in diameter and 45-mm in length, and were made of titanium alloy (Ti6Al4V). The sample size was six for each of the groups in each test.

2.2. Biomechanical tests

The testing protocol used for pullout strength and withdrawn energy of the pedicle screws was based on the ASTM F543 standard and previous studies (Tsai et al., 2009). Two types of synthetic and porcine specimens were used to measure the biomechanical behaviors of holding power for the bone-screw constructs. The synthetic specimen served as the representative to avoid individual variation of the mechanical properties while using cadaveric bones. The adapted bricks had porosity of 0.16 g/cc which were made of cellular polyurethane foam (Sawbones, Pacific Research Corporation, Vashon, Washington, USA). Each brick of polyurethane foam was equally segmented into cubic blocks, 6 × 6 × 6 cm in size. The testing blocks were prepared by pre-drilling pilot holes, and followed by pedicle screw insertion perpendicularly into the center of the testing block without pre-tapping. The porcine specimens were used as a control group that could mimic the bony properties of the vertebral core and pedicle isthmus. Porcine specimens were isolated from porcine lumbar spine obtained from a local slaughterhouse. Before experimentation, all intervertebral disc tissues and subjacent soft tissues were cleaned, and bony vertebral structure was isolated individually. Application of the pedicle screw into synthetic and porcine specimen is all performed by a spine surgeon to avoid man-
made interference. The intersection of the superior articular process and transverse process of the porcine vertebrae was identified as the entry point of the pedicle screw. A special designed bone awl (US patent 20120323242A), which consists of a leading drill portion (5 mm length) and a tap portion (10 mm length), is used to create the pilot hole of 4 mm. After the drill forms a hole in the bone, the tap threads create an internal screw thread in the bone along the surface of the hole formed by the drill. The pedicle screw was inserted following the created screw tract in each vertebra.

The static and dynamic tests were performed using an Instron 4467 servo-hydraulic testing system (Instron Norwood, MA, USA). The synthetic and porcine blocks were completely seated in the fixture frame mounted to the testing platform (Fig. 2a). The insertion depth into the synthetic and porcine specimens was kept constant (40 mm) for all screw variations (Fig. 2b). After a screw was inserted into the pilot hole, the static tests were performed only with axial tension at the screw head by means of the jig that was connected to the Instron actuator. For the dynamic tests, cantilever bending tests were initially performed to simulate clinical loads, with cyclic compression applied to the screw head and aligned vertically to the screw axis. The cantilever bending was initiated in the form of a sinusoidal wave with 5-Hz frequency and 10–100 N until 150,000 cycles were achieved (Sterba et al., 2007; Lu et al., 2004; Ferrara et al., 2003). The pulling load was then steadily applied to the screw head and along the screw axis with an actuator speed of 5 mm/min.

The static tests were performed for both the synthetic and porcine specimens. However, only the synthetic specimens were used for the dynamic tests due to the technical problem of fixing the porcine vertebrae and applying the cantilever loads. During testing, the load-displacement curves of the Instron sensors were recorded. The pullout load was defined by the first change in the slope from a positive to a negative value in the load-displacement curve. The area beneath the load-displacement curve was defined as the withdrawn energy to extract the screw from the specimen completely. The withdrawn energy was calculated using Origin 8.5.1 software (OriginLab, Massachusetts, USA). Student’s t-test was used to analyze the differences in pullout strengths and withdrawn energy among the bone-screw variations (Fig. 2b). From the initial to the final withdrawal, the two stages of screw pullout can be defined as peak (0–2.5 mm) and loosening (2.5–30 mm) regions. Within the peak region, the peak value of the 1/3 unthreaded screw was the highest, followed by the fully threaded, the 1/2 unthreaded, and the 2/3 unthreaded with the least. Within the loosening region, however, the pullout resistance of the fully threaded screw decreased more rapidly than the unthreaded designs. Beyond the peak region, the fluctuant loads of the 1/2 and 2/3 unthreaded screws were more compatible and gradually higher than that of the 1/3 unthreaded design toward the final withdrawal. The 2/3 unthreaded shank provided more enduring resistance to the screw pullout than the other unthreaded screws. Beyond the peak load, the pullout load of the 2/3 unthreaded screw was about three times that of the fully threaded screw.

3. Static tests

The pullout strengths of the static tests of the synthetic and porcine specimens were compared (Fig. 4). The differences in pullout strength between the synthetic and porcine specimens were 193.1% for the fully threaded, 196.3% for the 1/3 unthreaded, 330.7% for the 1/2 unthreaded, and 224.3% for the 2/3 unthreaded screws. This was attributed to the difference in material property of the synthetic (osteoporotic foam) and porcine (compact pedicle) specimens. The highest pullout strength of the synthetic specimen was achieved by the 1/3 unthreaded screw, followed by the fully threaded screw and the 1/2 unthreaded screw; the 2/3 unthreaded screw had the least. The pullout strength of the 1/3 unthreaded screw was statistically different from those of the others (P = 0.0004 for the 1/3 unthreaded, and P = 0.0003 for the 2/3 unthreaded) (Fig. 4a). The differences between the fully threaded and partially unthreaded screws were also significant (P = 0.0098 for the 1/2 unthreaded, and P = 0.0043 for the 2/3 unthreaded). However, there was no significant difference between the 1/2 and 2/3 unthreaded screws (P = 0.1372). For the porcine specimen, the pullout strength of the 1/3 unthreaded screw was higher than that of the fully threaded (P = 0.0176), 1/2 unthreaded (P = 0.3444), and 2/3 unthreaded (P = 0.0662) screws (Fig. 4b).

3.3. Dynamic tests

The pullout strengths and withdrawn energy of the dynamic tests of the synthetic specimens were compared (Fig. 5). Similar to the static test, the pullout strength of the 1/3 unthreaded screw was the highest, followed by the fully threaded screw and the 1/2 unthreaded screw; the 2/3 unthreaded screw had the least (Fig. 5a). The pullout strength of the 1/3 unthreaded screw was statistically higher than those of the others (P = 0.0004 for the fully threaded, P = 0.0001 for the 1/2 unthreaded, and P = 0.0003 for the 2/3 unthreaded). The differences between the fully threaded and the other two partially unthreaded screws were also significant (P = 0.0098 for the 1/2 unthreaded, and P = 0.0043 for the 2/3 unthreaded). The withdrawn energy of the three unthreaded screws was significantly higher than that of the threaded counterpart (Fig. 5b). The withdrawn energy was the highest for the 1/2 unthreaded screw, followed by the 2/3 unthreaded screw, the 1/3 unthreaded screw; the fully threaded screw had the least. Except for the 2/3 unthreaded screw (P = 0.9858), the withdrawn energy of the 1/2 unthreaded screw significantly differed from those of the others (P = 0.03998 for the 1/3 unthreaded, and P = 0.00298 for the fully threaded).

4. Discussion

Weinstein et al. (1992) reported that the stability of transpedicular fixation depends 60% on the pedicle isthmus, 15–20% on the vertebral
core, and 20–25% on the penetration of the opposing cortex. However, detailed information on the unthreaded effect on the holding power of a pedicle screw within the pedicle isthmus has not been extensively provided. This study proposed two hypotheses of the holding effects of threaded and unthreaded shanks on the bone-screw construct (Fig. 6a). When applying the pullout load, the threaded shank provides the ability to anchor the sandwiched bone until the shearing strength of the bone chips is beyond their peak load (point d). This study used the thread-shearing mechanism to describe the rapid decay of the holding ability of the fully threaded screw (Fig. 6b). Rapid laceration then potentially occurs along the cylindrical surface formed by the thread tips (line aa) (Tsai et al., 2009; Chapman et al., 1996). This accounts for the results that the pullout resistances of all screws drastically decayed within the peak region (Fig. 3). Moreover, interfacial laceration severely decays the pullout resistance of the fully threaded screw within the loosening region (Fig. 3). This results in the lowest value of withdrawn energy absorbed by the fully threaded screw due to the decayed ability of the anchoring bone chips (Fig. 5b).

According to Wang et al. (Chen et al., 2005), the most stressed site of a pedicle screw is the junction of shank and threads and the model of threads inside the screw/bone interface tended to be less stressed than threads outside the interface. For the unthreaded screw, the shank-thread junction is moved into the vertebral body, the insertion of the smooth shank can squeeze the cancellous bone between the pilot hole and the shank surface into the peripheral region; thus increasing the shearing strength of the squeezed bone chips (Tsai et al., 2009; Chapman et al., 1996). This simulates the “broaching” process in femoral canal preparation during total hip replacement and produces the proximal-fit effect in pedicle isthmus. The conical segment of the pedicle screw removes cancellous bone in front of the screw and around the thread while approaching, and then creates an osseous envelop to support the unthreaded shank segment and promotes intimate contact between the screw and host bone for bony ingrowth. This offers a positive fit and fill of the screw in the pedicle isthmus, even in osteoporotic bone. Although the anchoring force of the screw action at the distal end of the screw is responsible for the press fitting of the proximal unthreaded section, this may cause shearing of the spongy bone and possibly fracture the compact pedicle. Reports of McLain et al. (Inceoglu et al., 2007) showed the cortical bone at the pedicle has material properties different from those of typical cortical bone in long bones. The more ductile pedicle cortex with a lower yield strain allows a larger safety margin in the lumbar pedicle for expansion prior to gross fracture. There was no fractured pedicle during screw insertion in our study.

Furthermore, frictional resistance at the bone-shank interfaces (line bb) constantly exists during screw pullout. This study assumed that the shank-sliding mechanism provides a more stable value of pullout

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**Fig. 4.** Pullout strengths of the static tests. (a) Synthetic specimen. (b) Porcine specimen. The symbol *** denotes that the difference between the compared groups is statistically significant (P < 0.05).

**Fig. 5.** Pullout strengths and withdrawn energy of the dynamic tests. (a) Pullout strength. (b) Withdrawn energy. The symbol *** denotes that the difference between the compared groups is statistically significant (P < 0.05).
resistance after the peak load (point c) is achieved (Fig. 6b). This assumption can be validated by the higher values of the pullout strength for the three unthreaded screws within the loosening region (Fig. 3).

The static test results of the synthetic and porcine specimens consistently support the squeezing effect of the unthreaded shank (Fig. 4). The 1/3 unthreaded screw consistently yielded significantly higher ($P < 0.001$) pullout strength than the fully threaded and the other two partially threaded screws. The pullout strength of the fully threaded screw was second only to the 1/3 unthreaded screw, but significantly better than the 1/2 and 2/3 unthreaded screws ($P < 0.05$). This finding reveals that the unthreaded shank occupies the pedicle isthmus and requires a higher pullout load to cause screw loosening, and provides positive evidence for the hypothesis that the squeezing ability of the unthreaded shank within the pedicle is more critical than the anchoring effect of the screw threads. However, the threaded shank was shortened beyond half of the entire screw length, so the pullout strength was remarkably reduced (Figs. 4 and 5). This indicates the significant role of the screw threads in the anchoring of the cancellous bone of the vertebral core. Our results suggest that the 1/3 unthreaded screw provides the optimal trade-off of threaded and unthreaded portions of the four variations.

Some limitations are still inherent in this study. Even though the well-accepted synthetic blocks were considered as standard specimens (Krenn et al., 2008; Hashemi et al., 2009; Tsai et al., 2009; Chapman et al., 1996; Zdero et al., 2007), foam density in this study was 0.16 g/cm$^3$, which is generally believed to be comparable to the osteoporotic property of human cancellous bone. The dynamic results of the porcine specimens were not provided in this study due to the technical problem of fixing the vertebrae while applying lateral cantilever bending. The differences in the holding ability of the compact pedicle and the cancellous core were deficient in this study. The porcine specimens were the healthy bone and the static results of pullout strength were consistent with those of the synthetic specimens. However, this study cannot provide definite information on the squeezing effect of the unthreaded shaft on the osteoporotic pedicle. Testing and clinical studies using human cadaveric bones are still required to validate the positive findings for the 1/3 unthreaded screw. For screw implantation, stress-relaxing behavior should be cautiously estimated to ensure the press-fitted effects of the proximal unthreaded screw on the long-term stability of the bone-screw construct.

In this biomechanical test, there was not enough time for stress relaxation of the press-fitted section. The test in human vertebrae will be performed in future study to observe the loosening phenomenon over time. The insertion torques of the screws were not recorded in this study.

5. Conclusions

The current study took the insight into the thread-shearing (anchoring) and shank-sliding (squeezing) mechanisms at the threaded and unthreaded portions, respectively. The holding power of a pedicle screw was the integration of the anchoring (cancellous core) and squeezing (compact pedicle) effects within those two portions. Two tests of both specimens consistently showed that the 1/3 unthreaded screw provides higher pullout strength and withdrawn energy than the fully threaded screw, and avoids the decayed pullout strength of the 1/2 and 2/3 unthreaded screws. In the situation of osteoporotic bone, the thread-shearing mechanism potentially fails to anchor the weakened bone of the vertebral core. The current study recommends the 1/3 unthreaded screw as an optimal alternative for use as a shank-sliding mechanism to preserve the holding power within the pedicle isthmus.

Competing interests

The authors declare that they have no competing interests in connection to this study.

Authors’ contributions

CJC and FYT conceived, designed the study, and interpreted the data. CHC, LCW and YJK carried out the study and drafted the manuscript. SCL analyzed the data. All authors approved the final manuscript to be submitted.

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