Investigation into the differences of pull-out resistance between normal and osteoporotic cancellous bone

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Abstract. Pedicle screw loosening or pullout has occurred from time to time in patients with poor bone quality. However, there have been no rigorous mechanical analysis of the pullout process, and the resistance region to pullout force remains under-investigated. The objective of the current study was to investigate the stress state of cancellous resistance to pullout in normal and osteoporotic conditions using plane finite element method. The pull-out model was simplified to a simpler two dimensional axisymmetric model by symmetry. A prescribed axial displacement of 2 mm was imposed on the screw head and a fixed boundary condition was set on edge nodes of the bone to simulate the pullout process. The results of numerical simulation showed that the high-stress area of normal bone was clearly larger than that of osteoporotic bone, and the normal bone provided the higher pullout force of 86.09 N, which was about 3 times than that for osteoporotic bone. From the study it was found that osteoporosis would diminish the active region of resistance to pullout around the screw and decrease the pullout strength about threefold. The results of the current study can be used for screw augmentation techniques.

1. Introduction

Spinal surgery has been significantly improved by using pedicle screws. These screws are placed into cancellous bone to provide rigid fixation and load transmission. Screw pullout strength is closely associated with material properties of cancellous bone, such as bone density, elastic modulus, plastic yield stress and strain, and so on. Therefore, pedicle screw loosening or pullout has occurred from time to time, especially in patients with poor bone quality [1]. Orthopaedic surgeons often face clinical situations where improved screw holding power in cancellous bone is needed. However, the enhancement of screw fixation strength in osteoporosis patients is challenging. It is essential to study the stress state during pullout process in cancellous with different bone properties.

Researchers have long been interested in the investigation of fixation strength of pedicle screw. The holding power of a screw is directly influenced by the number of threads and their depth and for a given length of the screw, and screws fail most commonly on the bone side of the bone screw interface [2,3]. Tests using polyurethane foam blocks with different mechanical properties reported by Ramaswamy et al [4] suggest that the fixation strength of screw is directly correlated to bone density, thread design and number of threads engaging the bone. To overcome difficulties of fixing screws in poor quality cancellous bone, the injectable bone cement was used in clinic. Various biomechanical tests and clinical studies have confirmed that an appropriate use of cements can generally significantly increase the
pullout forces of bone screws and improve stability [5-8]. In addition, other studies have investigated the effects of screw orientation to the axis of pullout in osteoporotic bone [9,10]. To date, work on screw pullouts has focused mainly on pull-out tests using cadaveric and animal bone and synthetic materials. There have been no rigorous mechanical analysis of the pullout process, and the resistance region to pullout force remains under-investigated.

The objective of this study was to investigate the resistance behavior of cancellous bone to screw pullout. The maximal axial pull-out strength and stress distribution in cancellous bone with normal and osteoporotic properties were predicted and expected to help understand the mechanical behavior of the pullout process. The findings are intended to determine the resistance region of bone around the screws for application of screw augmentation techniques.

2. Methods
In order to accurately and visually determine the resistance region with stress distribution, plane finite element method was used to simulate the pullout process.

2.1. Simplified finite element model
The screw model is based on the universal lumbar pedicle screw manufactured by Weigao Orthopaedic Materials Co. LTD (5.5 mm major diameter, 32 mm thread length, 2.75 mm thread pitch). The cancellous bone block was generated by entity model (50 mm×50 mm×37 mm). According to symmetry, it was rational to simplify the pull-out model to a simpler two dimensional axisymmetric model (figure 1). There's little research on the mechanical property of cancellous bone. Earlier reports said cancellous bone had showed viscoelasticity and rate-dependence [11], but the depth of its theoretical research is still far from enough. In the current research, an elastoplastic model was employed to describe the stress-strain behavior of the cancellous bone under the axial pullout load. Material parameters associated with the stress-strain behavior of the cancellous bone, in its normal and osteoporotic conditions, are grouped in table 1 [12]. Young’s modulus (E) and the plastic yield stress (σp) and strain (εp) were deduced from density values based on empirical relations [13,14].

![Figure 1. Model simplification of pullout.](image)

Table 1. Material properties for normal and osteoporotic bone.

|          | ρ (g/cm³) | E (MPa) | ν | σp | εp (%) |
|----------|-----------|---------|---|-----|-------|
| Normal bone | 0.2       | 100     | 0.2 | 3   | 4     |
| Osteoporotic bone | 0.13     | 75      | 0.2 | 1.5 | 4     |

2.2. Mesh generation and boundary conditions
The linear axisymmetric 4-node quadrilateral elements were opted in the mesh partition. Simplification of the finite element model and selection of the element type were based on a previous literature [15]. Mesh generation characterized by a minimal element size of 0.2 mm was implemented, leading to a total number of nodes and elements of 15,753 and 15,631, respectively (figure 2). The grid quality items that has a greater impact on the calculation were checked, such warpage, aspect ratio and jacobian. The comprehensive quality indicator value (comp.QI) was 58.01 and the poor quality elements ratio was
0.2%, largely because of the threads form. In consideration of no relative displacement between screws and bone in screw fixation, the screw-bone interfaces were defined binding constraints. To simulate the pullout condition, a prescribed axial displacement of 2 mm was imposed on the screw head via a multipoint constraint coupling condition, and a fixed boundary condition was set on edge nodes of the bone. The finite element calculation is performed by the default Abaqus standard solver after pre-processing.

Figure 2. Finite element mesh generation.

3. Results
The stress nephograms of cancellous bone in normal and osteoporotic conditions were depicted in figure 3, showing that the bone quality had cast obvious impact on the resistance to pullout. The high-stress area of normal bone showed clearly larger than that of osteoporotic bone. The maximum shear stress resistance to pullout in normal bone was 3.95 MPa, while the value is 2.0 MPa in osteoporotic model. The load-displacement curves showed that the normal bone provided the higher pullout force of 86.09 N, and that for osteoporotic bone was 26.9 N (figure 4).

Figure 3. Stress distribution in (a) osteoporotic and (b) normal bone.

Figure 4. The load-displacement curves. (a) Result of the present study and (b) experimental result by Varghese.

4. Discussions
Cancellous bone plays a major role in the holding power of pedicle screw fixation. The magnitude and range of resistance will change with the change of bone quality. Patients needing internal fixation surgery often have the varying degree of the osteoporosis. This study used finite element technique to simulate the effect of changes in bone quality on the holding power qualitatively. To the best of the authors’ knowledge, no previous study has attempted to investigate the matter by numerical calculation method.

This paper studied the resistant performance of cancellous bone to screw pullout in normal and osteoporosis conditions. The compacting structure of normal bone contributed more bone tissue to resist screw pullout. The high stress area spread to the intact screw channel, and the radial range affected by high stress was 6.7 mm. In comparison, the osteoporotic bone showed the weak ability to form solidity. The high stress area was rarely distributed in the area of the first screw thread and screw tip. The exact scope of resistance defined by the stress distribution results can provide adjustment reference for the application of technique in screw augmentation, such as the valid range of cement injection.

Pullout strength is a persuasive biomechanical parameter to demonstrate the screw fixation strength. The load-displacement curves showed that the pullout force reached the peak value first in osteoporosis model. The main reason for this was that osteoporosis decreased the deformation resistibility capacity. For our simplified two-dimensional axisymmetric model, the resultant pullout values were 86.09 N and 26.8 N for normal and osteoporotic bone respectively. As might be expected, the calculation results were far less than researches done by others. Pullout tests in which polyurethane foam with varying-density was used to represent normal and osteoporotic bone were performed by Varghese et al [11], the obtained mean pullout values of the foam model were 1100 N and 300 N for normal and osteoporotic bone respectively. From the above, it can be seen that the pullout strength for normal bone was more than 3 times for osteoporotic bone in the current research as well as in Varghese's tests. Besides, the computed load-displacement curves in our research had followed the same trend in comparison with the experiment results by him (figure 4). Therefore, using cement augmentation to increase bone density in osteoporotic patients can improve screw fixation, and consequently improve surgical outcome.

5. Conclusion

From the study it was found that bone quality is an important factor in pedicle screw fixation. Osteoporosis will diminish the active region of resistance to pullout around the screw and decrease the pullout strength about threefold. The results of the current study can be used for screw augmentation techniques.

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