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Comparison of the bending performance of solid and cannulated spinal pedicle screws using finite element analyses and biomechanical tests

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ABSTRACT

Spinal pedicle screw fixations have been used extensively to treat fracture, tumor, infection, or degeneration of the spine. Cannulated spinal pedicle screws with bone cement augmentation might be a useful method to ameliorate screw loosening. However, cannulated spinal pedicle screws might also increase the risk of screw breakage. Thus, the purpose of this study was to investigate the bending performance of different spinal pedicle screws with either solid design or cannulated design. Three-dimensional finite element models, which consisted of the spinal pedicle screw and the screw's hosting material, were first constructed. Next, monotonic and cyclic cantilever bending tests were both applied to validate the results of the finite element analyses. Finally, both the numerical and experimental approaches were evaluated and compared. The results indicated that the cylindrical spinal pedicle screws with a cannulated design had significantly poorer bending performance. In addition, conical spinal pedicle screws maintained the original bending performance, whether they were solid or of cannulated design. This study may provide useful recommendations to orthopedic surgeons before surgery, and it may also provide design rationales to biomechanical engineers during the development of spinal pedicle screws.

1. Introduction

Posterior pedicle screw and rod fixation systems have been widely used for the treatment of degenerative diseases of human spines and the stabilization of fractured vertebrae [1–3]. In clinical applications, spinal pedicle screws are the key components of pedicle screw and rod systems [4]. However, patients might have non-union or other complications when breakage, loosening, or pulling out of spinal pedicle screws occurs [5–7]. A breakage of spinal pedicle screws should be avoided because a broken screw fragment trapped in the vertebral body is difficult to remove and may impede subsequent revision surgeries [8]. The interfacial strength of pedicle screw fixation in an osteoporotic spine can be improved by the addition of bone cement [9]. One of the injection techniques is cannulated pedicle screws with bone cement augmentation. To reduce the risk of pedicle screw breakage, past studies investigated the bending performance of traditional solid pedicle screws using biomechanical tests and/or finite element analyses [10–12]. However, there is little research on the bending performance of cannulated pedicle screws. To our knowledge, past research studies were mainly focused on the pullout strength of cannulated or expandable pedicle screws [13–16]. In fact, the risk of pedicle screw breakage may become more serious, especially when cannulated pedicle screws were used. In the present study, three-dimensional finite element models were first constructed to calculate the bending performance of spinal pedicle screws. Next, samples of each type of spinal pedicle screws were fabricated and tested to validate the results of the finite element simulations. Finally, both the numerical and experimental results were compared and discussed. The purpose of this study was to investigate the bending performance of solid and cannulated spinal pedicle screws using finite element analyses and biomechanical tests.

2. Materials and methods

2.1. Designs of the spinal pedicle screws

Most spinal pedicle screws have either a cylindrical or conical core. To investigate the effects of different screw design, two groups

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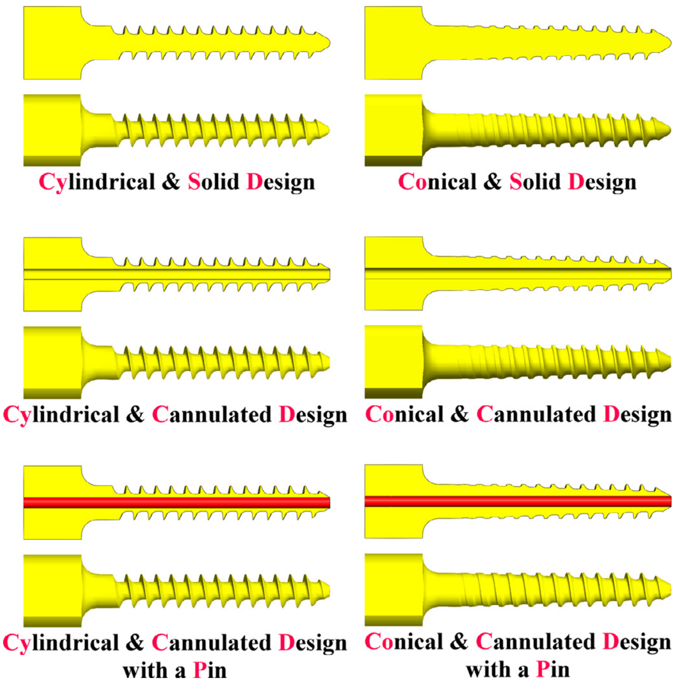

Fig. 1. Six designs of the spinal pedicle screws.

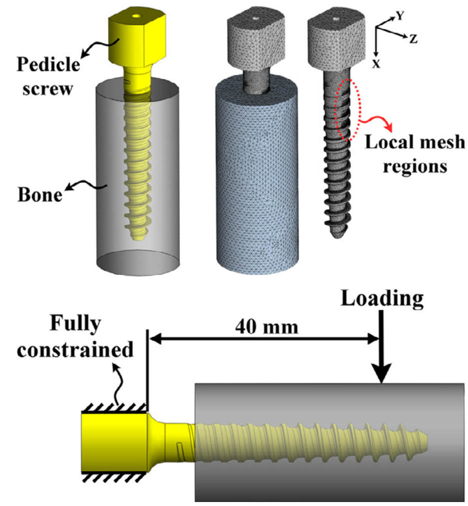

Fig. 2. Loading and boundary conditions of the finite element model.

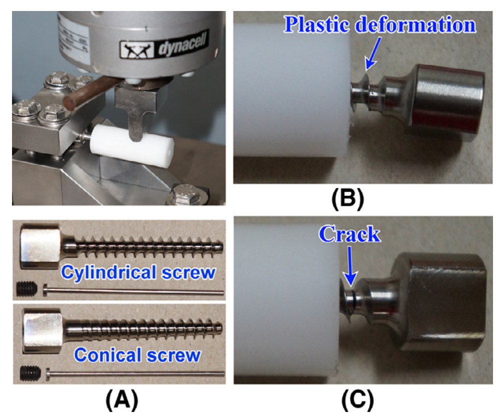

Fig. 3. (A) The experimental setup. (B) A specimen after the monotonic tests. (C) A specimen after the cyclic cantilever bending tests.

of spinal pedicle screws were considered in the present study, including the cylindrical design group and the conical design group. For each design group, solid and cannulated spinal pedicle screws were considered. In addition, a cannulated spinal pedicle screw with an additional 2-mm pin was also considered to restore its biomechanical performances. Thus, six types of spinal pedicle screws were designed and considered: cylindrical and solid design (Cy-SD), cylindrical and cannulated design (Cy-CD), cylindrical and cannulated design with a pin (Cy-CDP), conical and solid design (Co-SD), conical and cannulated design (Co-CD), and conical and cannulated design with a pin (Co-CDP) (Fig. 1). All of the spinal pedicle screws have the same screw thread and their geometry and dimension were referred to the design ranges of commercial products. The area moment of inertia at the centroid for each spinal pedicle screw was calculated.

2.2. Finite element models

The solid models of the spinal pedicle screws and the screw's hosting materials were constructed and assembled using SolidWorks 2013 (SolidWorks Corporation, Concord, MA, USA). The geometry and dimension of the spinal pedicle screws were as follows: outer diameter of 6.5 mm; inner diameter of 3.3 mm; cannulation diameter of 2 mm; pitch of 2.83 mm; proximal root radius of 0.4 mm; distal root radius of 1.2 mm; thread width of 0.1 mm; proximal half angle of 5°; distal half angle of 25°; conical angle of 2.04°; and screw length of 45 mm. The screw's hosting material was simplified as a cylinder with a diameter of 20 mm and a length of 45 mm [10]. The solid models of the spinal pedicle screw and the bone were converted into parasolid format and transferred to the ANSYS Workbench 14.5 (ANSYS, Inc., Canonsburg, PA, USA). The spinal pedicle screws were made from titanium and their material properties were set as 110 GPa for the elastic modulus and 0.3 for the Poisson's ratio. For the material properties of the bone, the elastic modulus was set as 2.6 GPa and Poisson's ratio was set as 0.3 [4]. The material properties of the bone were referred to the material of the testing specimens used in this study. All solid models were free-meshed using 10-node tetrahedral elements (SOLID 187). A convergent study was conducted by decreasing the element size of the local mesh regions. The interfacial condition between the spinal pedicle screw and the screw's hosting material was assumed to be in contact without any frictional force. In addition, the interfacial condition between the metallic pin and the screw was also assumed to be in contact. The boundary condition was fully constrained at the surfaces of the pedicle screw head. In the loading condition, a vertical load of 220 N was applied on the bone (Fig. 2). This loading was determined by averaging the cyclic loading of 40∼400 N. During post-processing, the maximum displacement of the numerical model was used to represent the yielding strength, and the lower maximum displacement reveals the higher yielding strength. In addition, the maximum tensile stress of the spinal pedicle screw was chosen to represent the fatigue strength, and the lower maximum tensile stress reveals the better fatigue strength.

2.3. Monotonic tests of the spinal pedicle screws

The testing specimens used in this study consisted of the spinal pedicle screw and the bone. High-molecular-weight polyethylene cylinders were used instead of real bones in the present study. The cylinders had a diameter of 20 mm and a length of 45 mm. The diameter of the predrilled holes was 3.3 mm. The spinal pedicle screw was inserted into the predrilled hole, and the insertion length of the pedicle screws was 40 mm. In this study, six types of the spinal pedicle screws were manufactured and tested. The pedicle screw head of the testing specimens were gripped in a specially designed jig (Fig. 3A). Monotonic tests were conducted by applying a static load at the distal part of the spinal pedicle screws using a materials