Medical Engineering & Physics 36 (2014) 1218–1223

Contents lists available at ScienceDirect

Medical Engineering & Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Biomechanical evaluation of bending strength of spinal pedicle screws, including cylindrical, conical, dual core and double dual core designs using numerical simulations and mechanical tests

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ARTICLE INFO

Article history:
Received 15 January 2013
Received in revised form 10 June 2014
Accepted 28 June 2014

Keywords:
Pedicle screw
Bending strength
Double dual core screw
Finite element analysis
Fatigue

ABSTRACT

Pedicle screws are used for treating several types of spinal injuries. Although several commercial versions are presently available, they are mostly either fully cylindrical or fully conical. In this study, the bending strengths of seven types of commercial pedicle screws and a newly designed double dual core screw were evaluated by finite element analyses and biomechanical tests. All the screws had an outer diameter of 7 mm, and the biomechanical test consisted of a cantilever bending test in which a vertical point load was applied using a level arm of 45 mm. The boundary and loading conditions of the biomechanical tests were applied to the model used for the finite element analyses. The results showed that only the conical screws with fixed outer diameter and the new double dual core screw could withstand 1,000,000 cycles of a 50–500 N cyclic load. The new screw, however, exhibited lower stiffness than the conical screw, indicating that it could afford patients more flexible movements. Moreover, the new screw produced a level of stability comparable to that of the conical screw, and it was also significantly stronger than the other screws. The finite element analysis further revealed that the point of maximum tensile stress in the screw model was comparable to the point at which fracture occurred during the fatigue test.

1. Introduction

Pedicle screws have been used over the last several decades for treating degenerative spine diseases and trauma. Together with rods and plates, they are used to form intrapedicular fixation or transpedicle screw devices [1–6] for effective stabilization of the spine of patients. However, screw breakage and loosening have been reported, which may create post-surgery problems [7–9]. Three major factors that affect the strength of the fixation are the design of the pedicle screw, the insertion technique, and the bone quality. Indeed, several studies have been conducted to develop screws that are more effective than the original cylindrical type, and conical and dual core designs have been proposed [10–12]. The screw proposed in this paper is based on the concepts of the dual inner core (DIC) screw, the dual outer core (DOC) screw, and the conical screw, and combines the advantages of the three.

Lill et al. originally proposed the dual core screw in 2006 and evaluated its pullout strength [12]. The results of their study—the only one to have focused on the dual core design—showed that the dual core screw had a higher pullout strength than the cylindrical screw under both fully inserted and backed out conditions. However, the bending strength is also an important property that affects post-surgery failure of a pedicle screw.

The primary purpose of the present study was the investigation of the bending performance of all types of currently available pedicle screws and a newly designed one by finite element analysis (FEA) and biomechanical tests. The secondary purpose was the development of an effective FEA model for comparing the bending strengths of different types of pedicle screws, and which can also be effectively used to optimize the design of such screws. It is our hope that the results of this study could be referenced by surgeons in choosing suitable pedicle screws for their patients.

2. Materials and methods

2.1. Pedicle screw designs

Eight pedicle screws were used for this study, namely, cylindrical with small inner diameter (CYSID), cylindrical with large inner diameter (CYLID), conical type I with small inner diameter

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http://dx.doi.org/10.1016/j.medengphy.2014.06.014
1350-4533/

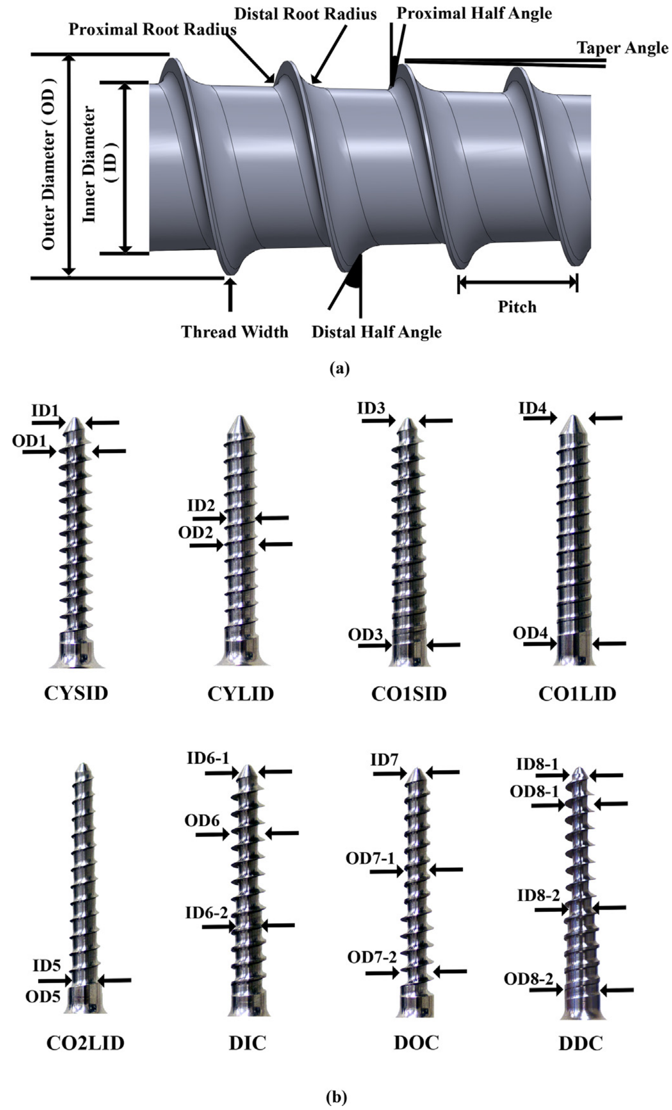

Fig. 1. (a) Definitions of the design parameters of spinal pedicle screws. The proximal root radius, proximal half angle, distal root radius, distal half angle, thread width, and pitch were 0.4 mm, 5°, 1 mm, 25°, 0.1 mm, and 3.3 mm, respectively. (b) Designs of the eight different screws used for this study, namely, cylindrical with small inner diameter (CYSID), cylindrical with large inner diameter (CYLID), conical type I with small inner diameter (CO1SID), conical type I with large inner diameter (CO1LID), conical type II with large inner diameter (CO2LID), dual inner core (DIC), dual outer core (DOC), and double dual core (DDC). The inner diameter (ID) and outer diameter (OD) of each screw are given in Table 1.

(CO1SID), conical type I with large inner diameter (CO1LID), conical type II with large inner diameter (CO2LID), dual inner core (DIC), dual outer core (DOC), and double dual core (DDC, the new screw). The parameters of each type of screw and their values are shown and listed in Fig. 1 and Table 1, respectively. To reduce the variation due to the interactions among the different parameters, some factors were fixed. The proximal root radius, proximal half angle, distal root radius, distal half angle, thread width, and pitch were 0.4 mm, 5°, 1 mm, 25°, 0.1 mm, and 3.3 mm, respectively (Fig. 1(a)). The outer diameter (OD) of all the screws was fixed at 7 mm, with the exception of CO2LID, DOC, and DDC. CYSID and CYLID were cylindrical but had different inner diameters (IDs). Both CO1SID and CO1LID were conical screws with fixed ODs (conical type I screws), whereas CO2LID was a conical screw with varying OD and ID along its length (conical type II screw). The distal part of the DIC, DOC, and DDC screws was 30 mm long (Fig. 1(b) and Table 1). The thread length of all the screws was 45 mm. All the screws were

Table 1
Inner diameter (ID) and outer diameter (OD) of each screw. The different screw types are shown in Fig. 1(b).

Screw type	OD (mm)	ID (mm)
CYSID	7.0 (OD_1)	3.8 (IDi)
CYLID	7.0 (OD_2)	5.5 (ID:)
COISID	7.0 (OD_3)	3.8 (ID_3)
COILID	7.0 (OD_4)	5.5 (ID_4)
C02LID	7.0 (OD_5)	5.5 (ID_5)
DIC	7.0 (OD_6)	3.8 ($ID_{6\text{-}1}$), 5.5 ($ID_{6\text{-}2}$)
DOC	5.3 ($OD_{7\text{-}1}$); 7.0 ($OD_{7\text{-}2}$)	3.8 (ID_7)
DDC	6.0 ($OD_{8\text{-}1}$), 7.0 ($OD_{8\text{-}2}$)	3.0 ($ID_{8\text{-}1}$), 5.5 ($ID_{8\text{-}2}$)

made from titanium alloy Ti6Al4V according to the specifications of the American Society for Testing and Materials (ASTM) number F136-02a.

2.2. Mechanical test

A cantilever bending test is widely used for conducting bending tests on pedicle screws under clinical conditions [13–15]. High molecular weight polyethylene cylinders (Universal Plastic, Auckland, New Zealand) with OD of 20 mm and length of 50 mm were used to simulate the human vertebrae. Young's modulus of the polyethylene cylinders was 2.6 GPa. Polyethylene was used because of its stable properties and resistance to deformation and breakage during the test [9,16,17]. A hole the size of the initial ID of the screw was drilled into the polyethylene cylinders using cylindrical drills, and the screws were inserted 43 mm into the holes. The screw heads were fixed and a vertical point load was applied by a 45 mm level arm (Fig. 2). An Instron 8872 material testing machine (Instron Corporation, Norwood, MA, USA) was used to conduct the yielding and fatigue (or cyclic) tests. The yielding tests were performed by applying a displacement load of 2.5 mm/min until the total displacement was 20 mm, which was beyond the elastic limit of the titanium alloy screws. The yielding test was repeated five times for each type of screw. The load and deformation data were acquired at a rate of 100 Hz. The yielding load for each screw type was calculated by the 0.2% offset method.

In the fatigue test, a sinusoidal load with a frequency of 10 Hz was applied using two maximum values, namely, 200 and 500 N. A stress ratio, *R*, of 10% was used to define the range of each cycle of the loading. The tests were stopped after 1,000,000 cycles or when the maximum displacement exceeded 10 mm, which indicated fatigue breakage of the screw. The fatigue test was repeated seven times for each screw type. The data for each cycle, such as the number of cycles, load, and deformation were recorded using a data acquisition rate of 100 Hz.

2.3. Finite element analyses (FEA)

All the 3D models, including those of the screws and the polyethylene cylinder, were created using SolidWorks 2010 software (SolidWorks Corporation, Waltham, MA, USA). The screw models were inserted into the polyethylene cylinder model (PCM) to a depth of 43 mm. The models were then imported into the finite element software ANSYS WORKBENCH 11 (ANSYS Inc., Canonsburg, PA, USA). The important FEA settings were as stated in our previous works [13,17]. Fig. 2(a) is an illustration of the FEA settings for this study, including the meshing and the boundary and loading conditions. The external PCM was meshed using 20-node hexahedral elements type, whereas the internal PCM and screw model were meshed using 10-node tetrahedral elements type (Fig. 2(a)). The global element size (body mesh size) was 1.2 mm. The size of the