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Parametric study of pedicle screw: Effect of stress transfer parameters on pullout strength

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Abstract

A pedicle screw is an important implant used to fix and stabilize a cervical spine when spinal alignment is needed. The size and characteristics of pedicle screws affect pullout strength of the screws when inserted into the cervical spine. The pullout strength is greatly affected by the quality and duration of cervical spine treatment. To aid orthopedic surgeons in choosing a suitable pedicle screw for Thai cervical spine patients, the pullout strength of pedicle screws had to be considered. Since pedicle screws are different in design, size and characteristics, a middle ground parameter- Stress Transfer Parameter (STP) obtained through formula and finite element analysis, was used to compare the screws. Nine commonly-used pedicle screws were studied under the chosen parameters namely Outer Diameter (OD), Core Diameter (CD), Pitch (P), Proximal Root Radius (PRR), and Distal Root Radius (DRR). Each type of screw was inserted into C3 C4 C5 C6 and C7 of Thai cervical spines to bear the axial load in order to analyze their pullout conditions using Finite Element Analysis and to evaluate the STP. The maximum STP occurred on Y I pedicle screw as follows: 0.57 at C3, 0.48 at C4, 0.43 at C5, 0.48 at C6 and 0.59 at C7. The maximum STP resulted from the large OD and CD which could bear more axial load. The large Pitch decreased the stress concentration on each screw thread and the small PRR and DRR increased the slope of the blade to resist the pullout load.

Keywords: Screw parameters, Pullout strength, Pedicle screw, Stress transfer parameter

1. Introduction

Cervical spine is the bone part that connected a body and a skull, which also protects a spinal cord and allow tilting and twisting the neck. To treat patients with cervical spine trauma or cervical disc problem, pedicle screw fixation is one of the treatments designed to fix and increase the stability of the cervical spine for the patients. Despite the fact that other posterior approaches in cervical spine surgery techniques such as Interspinous Wiring or lateral mass screws fixation can stabilize the cervical spine, the pedicle screw fixation yielded more durability and less chance of failure in mechanical testing [1-4]. Pedicle screws are inserted into two or three of the vertebrae and the short rod are used to connect the screws. The screw size, characteristics and design affect the pullout strength which helps to prevent the failure of screw fixation and yield satisfactory clinical result. Many research articles evaluated the pullout strength of pedicle screw. It can be classified into two groups as experiment testing [5-9] and simulation testing [8-11]. The researchers had compared the pullout strength by testing on human vertebrae with various screw types [12-15] but the uncontrollable human bone property of each tested sampling overshadowed the effect of screws the pullout strength. Finite Element Analysis is a commonly used method to predict the stress distribution on the bone-implant through varying shapes and parameters of implants with non-destructive specimens [10,16-21]. This study aims to evaluate the pullout strength of the popular nine pedicle screws fixation inserted into Thai cervical spines through a middle-ground STP and Finite Element Analysis in order to help orthopedic surgeon select suitable pedicle screws for Thai cervical spine.

2. Materials and methods

2.1 Three-dimensional Thai spine models

The cervical spine is made up of 7 vertebrae. C1 and C2 are unique and highly different from other vertebrae while C3 to C7 are considered classical vertebrae. Eight sets of C3 to C7 Thai spines were scanned with Computerized Tomography (CT) scanner. The CT data were reconstructed with ITK-SNAP program to adjust the image threshold value [18-22] as shown in Figure 1. The different thresholds were used to separate the inner and outer contour of cervical spine.

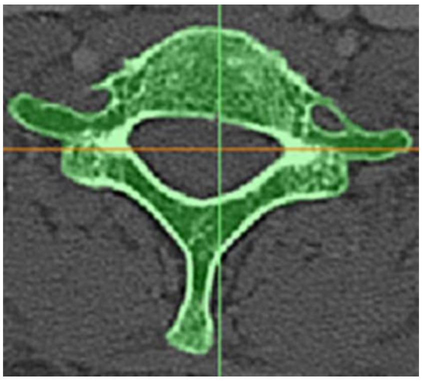

Figure 1 CT slices data of Thai cervical spine.

The completed three-dimensional cervical spine models were exported from the ITK-SNAP software as STereoLithography (STL) files. All cervical spine models were shown in Figure 2.

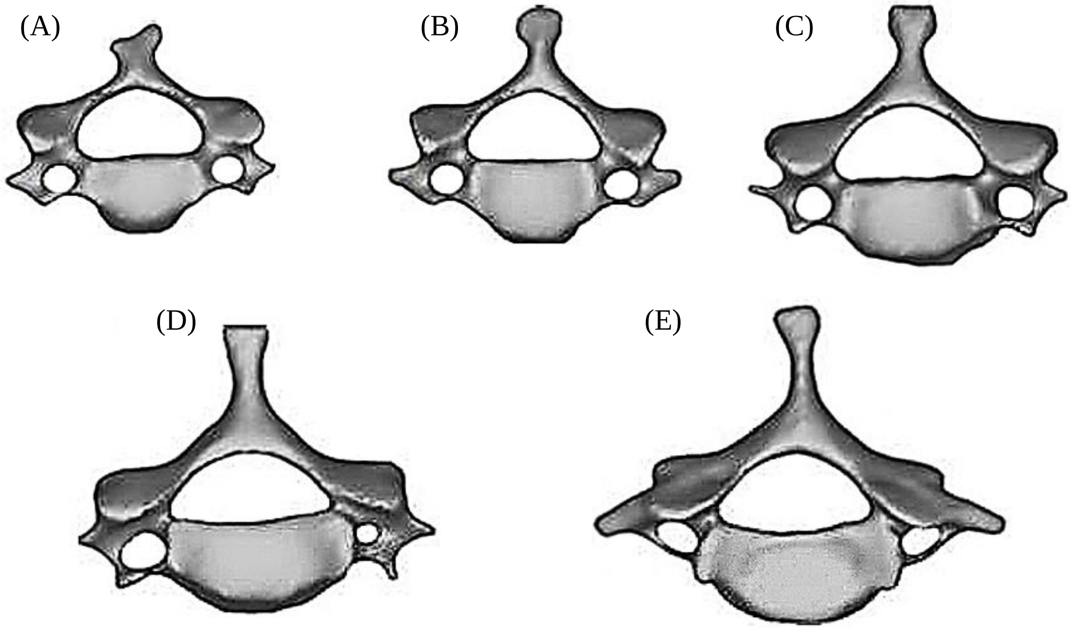

Figure 2 Three-dimensional cervical spine models: (A) C3, (B) C4, (C) C5, (D) C6 and (E) C7.

2.2 Three-dimensional screw models

Pedicle screws varied in characteristics and sizes such as Outer Diameter (OD), Core Diameter (CD), Pitch (P), Proximal Root Radius (PRR) and Distal Root Radius (DRR) as shown in Figure 3. These traits affected the pullout strength of pedicle screws when inserted into cervical spine [23]. The highest risk in regards to the pedicle screw insertion into the cervical spine was pedicle screws being pulled out from the pedicle region, causing injury to patients. The pullout strength of screw fixation depended greatly on the parameters of a pedicle screw.

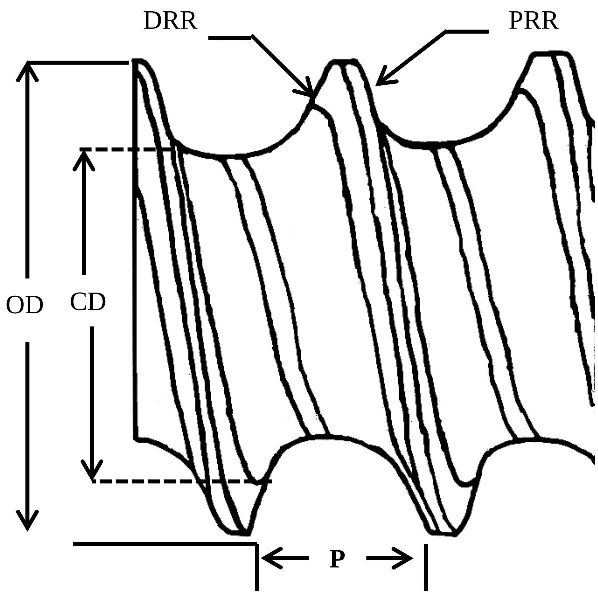

Figure 3 The pedicle screw parameters [24].

Three types of widely-used screws designated as screw X, screw Y and screw Z were recreated by SolidWorks software package based on actual screws' parameters [23]. Each type of screws was varied in three sizes as shown in Figure 4. The dimensions of the screws, the studied screw parameters, included OD, CD, P, PRR and DRR as shown in Table 1.

Figure 4 Three-dimensional models of pedicle screws: (A) Screw X, (B) Screw Y and (C) Screw Z.

Table 1 Screw dimensions/screw parameters [23].

Type	Outer diameter (mm)	Core diameter (mm)	Pitch (mm)	Proximal root radius (mm)	Distal root radius (mm)
Screw X I	7.50	4.92	2.80	0.81	1.27
Screw X II	6.50	4.10	2.80	0.88	1.20
Screw X III	5.50	3.84	2.71	0.81	1.23
Screw Y I	7.50	4.98	2.80	0.83	1.16
Screw Y II	6.50	4.32	2.80	0.84	1.18
Screw Y III	5.50	3.78	2.75	0.83	1.23
Screw Z I	6.90	4.50	2.98	3.31	3.31
Screw Z II	5.85	4.19	2.94	3.31	3.31
Screw Z III	4.87	3.03	2.48	2.54	2.54

2.3 Case analysis

Nine pedicle screw models were inserted into five cervical vertebrae (C3 to C7) to test the pullout strength of each case. Forty cervical spine samplings from eight origins were used in this study, namely model A, model B, model C, model D, model E, model F, model G and model H to evaluate the STP. Each vertebrate sampling was inserted with nine cervical screw models, amounting to 360 cases analyzed in this study. The cervical vertebrae samplings inserted with pedicle screw models were shown in Figure 5. According to Karaikovic *et al*., 2000, all screws were placed at starting landmarks lying in the center of pedicle region with the actual surgery position [25].

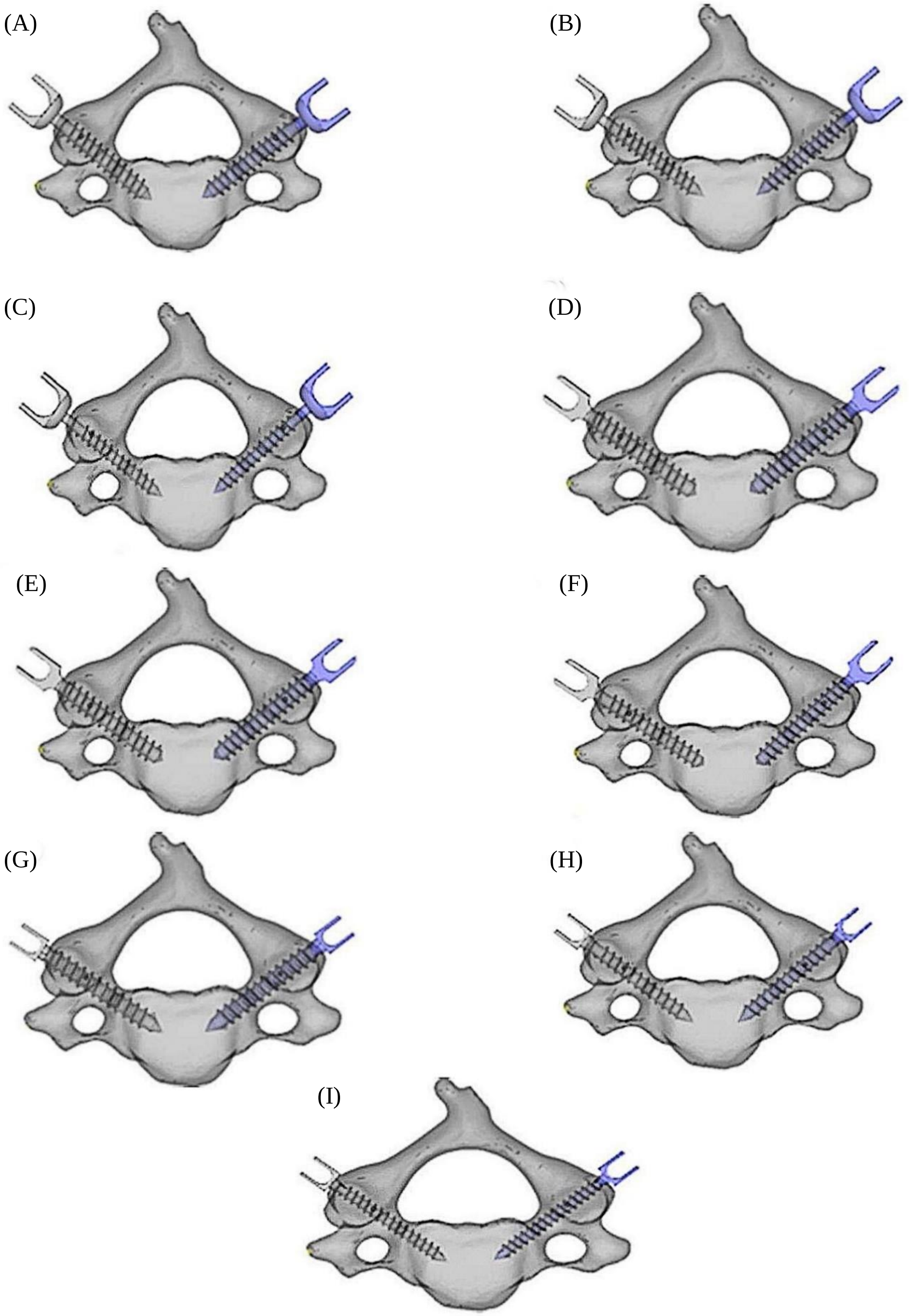

Figure 5 The cervical vertebrae samplings inserted with nine pedicle screw models: (A) Screw X I, (B) Screw X II, (C) Screw X III, (D) Screw Y I, (E) Screw Y II, (F) Screw Y III, (G) Screw Z I, (H) Screw Z II and (I) Screw Z III.

2.4 Stress transfer parameter (STP)

STP is a dimensionless parameter that characterized the load transfer between the pedicle screw and cervical spine. STP can be applied to test different types of screws classified under five parameters mentioned in 2.2 section. These five parameters provided an evaluation of the load sharing between a screw fixation and the bone surrounding. The maximum von Mises stress occurred at the first thread of all cases and STP was defined as follows:

$$\text{STP} = \frac{\sigma_{fb}}{\sigma_{ft}} \tag{1}$$

STP was calculated from the ratio of the maximum von Mises stress distribution on the bone over the first thread of pedicle screw and the maximum von Mises stress distribution on the first thread of pedicle screw as shown in Figure 6. This study eliminated the stress shielding. The values of the defined STP would approach an optimal magnitude of unity [26-28].

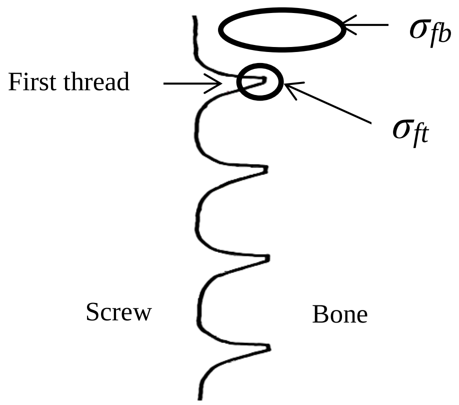

Figure 6 The position of all parameters to evaluate stress transfer parameter.

2.5 Material properties

All materials were assumed to be homogeneous, linear elastic, and with isotropic property. The material properties were shown in Table 2.

Table 2 Material properties of the cervical spine and pedicle screw [11].

Material	Elastic modulus (MPa)	Poisson's ratio	Yield strength (MPa)
Cervical spine	14,000	0.3	100
Pedicle screw	110,000	0.3	850

2.6 Convergence testing and mesh generation

All mesh models were generated by MSC Marc software. Four-node tetrahedral element was chosen in this research in order to reduce the calculating time. The previous results showed that there is a correspondence between tetrahedral element and hexahedral element [29]. The bone-implant had total nodes and elements as shown in Table 3.

Small mesh size increased the computational time in the analysis process. Convergence testing is a method used to find the smallest mesh size that took the least calculation time and gave the exact solution. Mesh model of cervical spine was varied in sizes from 0.5 to 1.3 mm. The results of the mesh size versus equivalent total strain on the cervical spine were shown in Figure 7 and the optimal mesh sizes used in this research were 0.9 mm. The illustrations of a pedicle screw and cervical spine mesh model were shown in Figure 8.

Table 3 Total nodes and elements of the cervical spine and pedicle screw.

Type	Nodes	Elements
Cervical spine (C3)	34,698	154,991
Cervical spine (C4)	37,282	167,836
Cervical spine (C5)	41,416	186,357
Cervical spine (C6)	45,590	205,874
Cervical spine (C7)	46,887	211,420
Screw X I	21,660	88,048
Screw X II	17,471	72,076
Screw X III	16,763	66,884
Screw Y I	12,382	47,683
Screw Y II	9,910	39,383
Screw Y III	5,175	18,827
Screw Z I	11,324	46,180
Screw Z II	10,232	42,212
Screw Z III	6,654	25,136

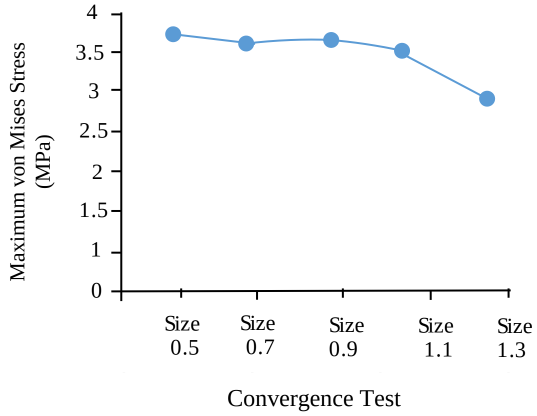

Figure 7 Mesh size versus equivalent total strain on cervical spine in convergence testing.

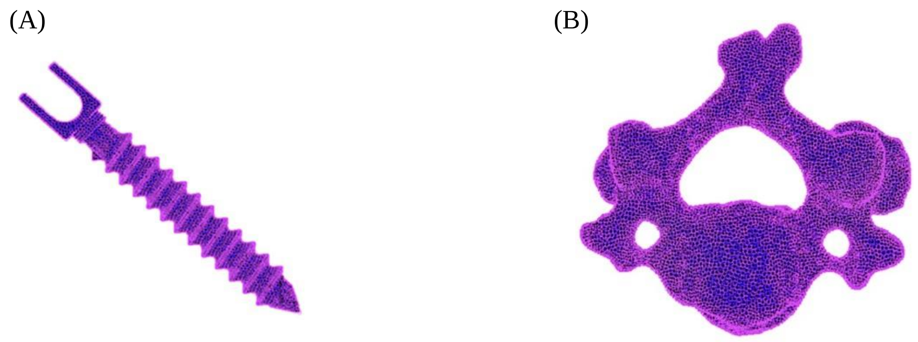

Figure 8 Mesh model: (A) Screw Z I and (B) Cervical spine 3.

2.7 Boundary condition

The cervical vertebrate was fixed in all directions and the pullout force, which made the maximum von Mises stress on each cervical bone reach the yield strength was acted on the top of the pedicle screw as the axial force using Multiple Point Constraint (MPC). The MPC pulled out the screw vertically by dispersing the force on several nodes to control the vertical motion of each node as shown in Figure 9. The contact between bone and screw was touching contact condition. The value of friction coefficient between the contact interface of screw and bone was selected as 0.2 [10, 30].

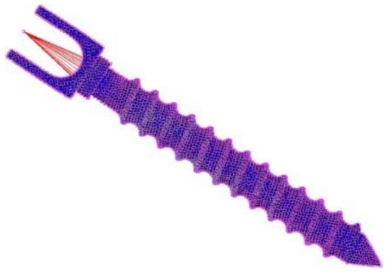

Figure 9 Multiple point constraints that pulled out the pedicle screw in the vertical movement**.**

2.8 Model validation

The implant model was validated with FE model to compare the von Mises stress distribution on the pedicle screw as shown in Figure 10 [10]. The stress distribution on the simulation model showed the same trend as that of the literature model.

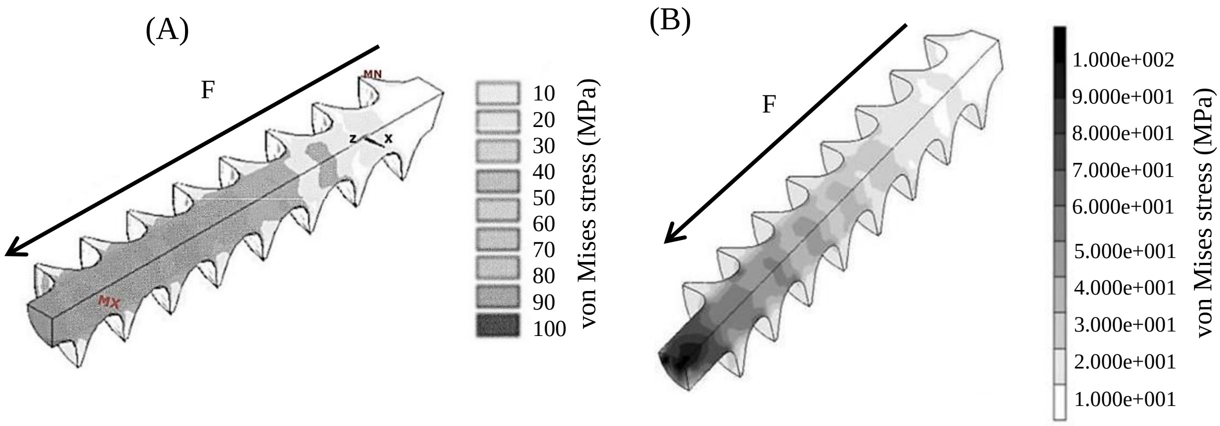

Figure 10 The comparison of von Mises stress distribution on the pedicle screw: (A) Literature model [10] and (B) Simulation model.

3. Results and discussion

MSC software package was used to analyze the von Mises stress on nine pedicle screws inserted into five cervical vertebrae using Finite Element Analysis. The maximum von Mises stress occurred at the first thread of screw in all cases because the first thread had less cortical bone contact that could resist the pullout load transferred from the cap. The selected data from 360 analyzed cases of maximum, minimum, mean and standard deviation of STP of pedicle screws inserted into cervical vertebrae were shown in Table 4.

Table 4 The maximum, minimum, mean and standard deviation of STP of screws inserted into C3 to C7.

Cervical vertebrae	Stress transfer parameter			
	Maximum	Minimum	Mean	Standard Deviation
C3	0.43	0.20	0.37	0.102
C4	0.48	0.16	0.28	0.078
C5	0.48	0.12	0.28	0.070
C6	0.57	0.15	0.29	0.069
C7	0.59	0.17	0.32	0.096

All the five cases of maximum STP of pedicle screws inserted into cervical vertebrae that occurred on screw Y I and their stress distribution was shown in Figure 11.

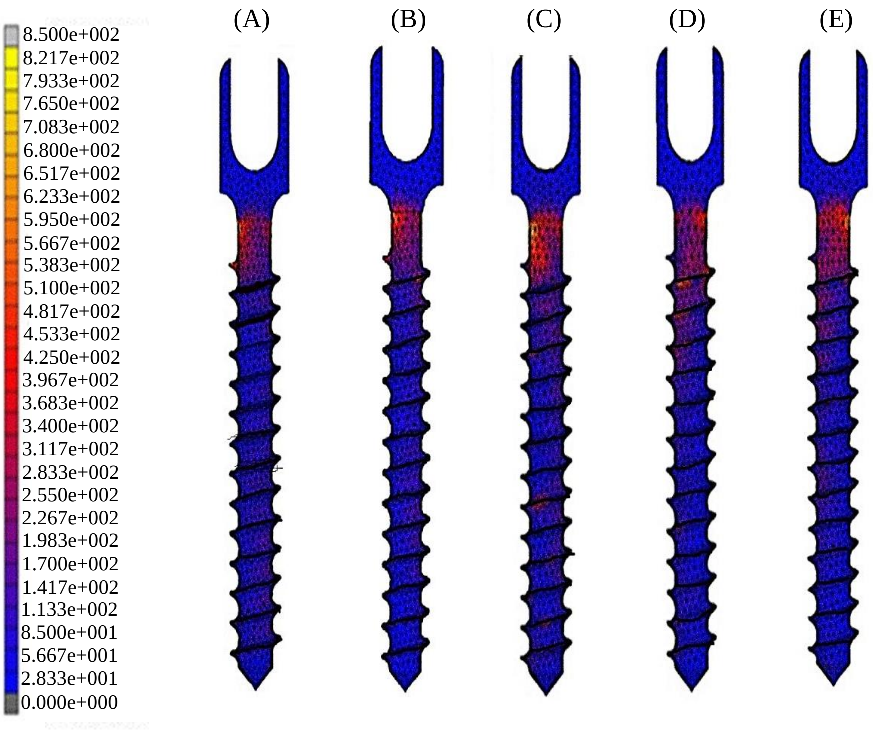

Figure 11 The stress distribution on the pedicle screws: (A) Screw Y I inserted into C3, (B) Screw Y I inserted into C4, (C) Screw Y I inserted into C5, (D) Screw Y I inserted into C6 and (E) Screw Y I inserted into C7.

The five parameters of pedicle screws affected the STP. Table 1 and 4 shows a comparison between the screw parameter of pedicle screws inserted into each vertebrate sampling and the maximum STP. The cross-sectional area of pedicle screws could receive the normal stress form the pullout load as shown in Figure 12 including the area of Outer Diameter and Core Diameter. The proximal root radius of pedicle screws could resist the pullout load due to load sharing onto vertebrae.

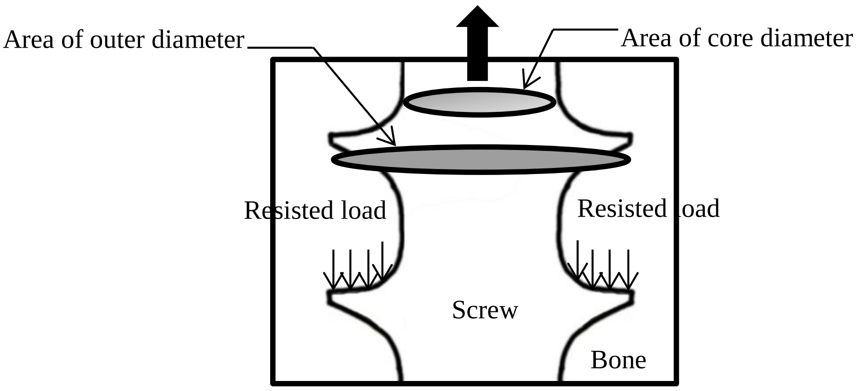

Figure 12 The section of pedicle screw showed that the area of Outer Diameter and Core Diameter received the pullout load and the proximal root radius resisted of pullout load.

To analyze the screw parameters that affected the STP, first, the large Outer Diameter gave more STP than other cases when compared under the same cervical vertebrae sampling. It increased the thread area of the pedicle screw to share more loading from the bone than the smaller diameter. Figure 13 shows the cross section of pedicle screws with different outer diameters.

Second, the Core Diameter affected the STP similarly to the outer diameter. The large core diameter increased the area to receive more axial load of pullout force than the smaller ones. Figure 14 shows the cross section of pedicle screws with different core diameters.

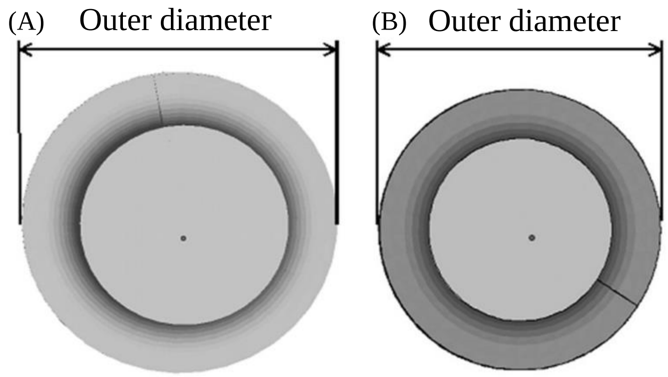

Figure 13 The cross section of two pedicle screws with different outer diameters: (A) Screw Y I and (B) Screw Z I.

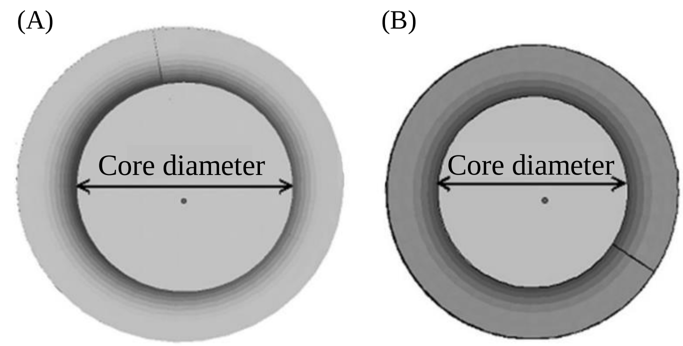

Figure 14 The cross section of two pedicle screws with different core diameters: (A) Screw Y I and (B) Screw Z I.

Third, the large pitch decreased the stress concentration on each thread. Last, the small proximal and distal root radius increased the slope of the blade to resist the pullout load. Figure 15 shows the pitch, proximal and distal root radius between screw Y I and screw Z I.

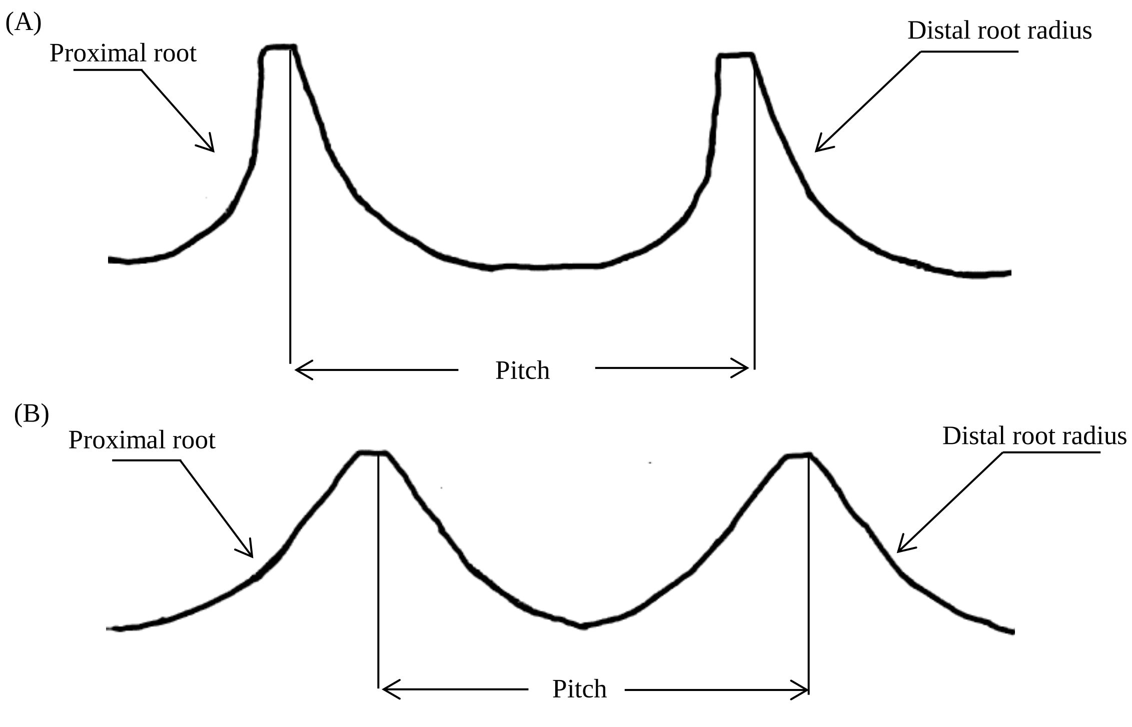

Figure 15 The position of pitch, proximal and distal root radius: (A) Screw Y I and (B) Screw Z I.

The large Outer Diameter and Core Diameter were the main causes of the high pullout strength [5,10] and the large Pitch, small Proximal Root Radius and Distal Root Radius helped distribute the stress concentration while resisting the pullout load. The pedicle screw was designed based on the force disperse between bone and screw for a good performance [17].

The conclusion could help orthopedic surgeons select the most suitable pedicle screws for Thai cervical spine patients.

4. Conclusion

This research analyzed the failure of pedicle screw fixation and cervical spine under the screw pullout process, and compared the results using STP of each screw to show how the screws' parameters affected the pullout strength. Screw Y I showed the best result among pedicle screws in this study when inserted into Thai cervical spine through STP analysis as it best resisted the pullout force.

5. Acknowledgments

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