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Effect of thread profile variation on pullout and bending strength of a pedicle screw

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Abstract. Pedicle screw is an important instrument in treatment of spinal degeneration or disease. However, the pedicle screw failure still occurs due to the screw loosening, fracture and pullout. There are few factors that affected the pedicle screw performance as reported by previous research but still lacking study related to the pedicle screw thread profile. Thus, the aim of this research is to investigate the effect of variation of thread pitch on the pullout and bending strength of pedicle screw. The research is carried out by constructing 3D pedicle screw models (model 1-6), importing the models into ANSYS, meshing and post processing analysis. The equivalent or Von-Mises stress used to compare the bending and pullout performance of the pedicle screws. Based on the obtained finite element analysis result, the single thread pedicle screw (model 3) has the optimum performance in bending while the model 4 is the optimum in pullout performance. While, for the dual threaded pedicle screw, the model 6 which has coarse thread pitch at screw tip is better than model 5 (fine thread). Thus, it can be conclude that both the single and dual threaded pedicle screw with coarse thread pitch has lower maximum equivalent stress than fine thread pitch, which is means it has better bending and pullout performance.

Keywords: Pedicle Screw; Finite Element Analysis; Pedicle Screw Thread Profile; Loosening.

1. Introduction

Pedicle screw is a surgical implant that used to stabilize the spinal segments in the spinal fusion surgery. A pedicle screw has played an important role in the treatment of spinal degeneration to limit the movement of the spine parts to assist the affiliation between broken bones by providing support and strength to the bony structures since the 1960s [1-4]. However, the failure of pedicle screw due to the fracture, loosening and pullout of screw still occurs although the pedicle screw contributes in long-term human lumbar spine segments stability in more than 90% cases, stated by W Qi *et al.* [5]. Many studies did on different pedicle screw designs to prevent screw loosening. Various designs such as screw with different outer diameter or length of the body of screw, thread profiles, cylindrical or conical core, expanding screws and cannulated screws are studied constantly [6-10]. The improvement of this medical device is getting more important in the medical industry.

The mechanical performance of the pedicle screw can evaluated by Finite Element Analysis (FEA) software as practised by other researchers [1-10]. The real condition and performance of pedicle screw during implantation can simulated by the FEA software. It allows the designers to predict and optimize the physical properties and implantation of the pedicle screw before applied on the patients in the surgery especially for the elderly patients. Nowadays the number of the population of elderly is rising gradually in the whole world. Biswas *et al.* (2019) stated that the spinal degeneration caused by the age becomes a serious problem for the older generation and brings intense pain to them. Fortunately, the spinal degeneration problem can reduced via the spinal surgery with the help of the pedicle screw [2]. However, screw loosening and pullout may happen due to insufficient interfacial strength between the surfaces of bone and screw.

Therefore, there are many studies done on the different pedicle screw designs to improve the structure of screw and to reduce the probability of screw loosening [1-10]. The designs on the outer diameter, length, thread profiles, core of the screw are studied. Although lot of studies related to the pedicle screw are done but the nightmare of pedicle screw (loosening) still happened till this date which shown that there is still no gold standard to overcome this main problem of pedicle screw performance. Thus the aim of this study are to investigate the effect of thread pitch variation on the pullout strength of single threaded pedicle screw using FEA and to investigate the difference in the bending strength of solid pedicle screws designed with different thread pitch by FEA.

2. Methodology

This project began with constructed two 3D models of the pedicle screw which it dimensions based on the published journal using SolidWorks software [6]. Next, the models were simulated using ANSYS software with the boundary conditions and load referred from the published journals. They then validated by comparing the results in the published journal to check whether the model can be used as the references for other modified models. After that, the proposed design of the pedicle screw (focused on thread profile) were constructed using SolidWorks software too. The models then imported into the ANSYS software to carry out simulation with the same boundary conditions and load. The table 1 below is the summarised dimensions of the constructed pedicle screws.

Table 1. Structures of pedicle screws.

Parameters	Pedicle Screw from Previous Research by Chao *et al.* [6]		Proposed Design of Pedicle Screw			
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Length	45					
Outer Diameter (mm)	6.5					
Inner Diameter at Screw Tip (mm)	3.9	4.9	3.9			
Thread Pitch (mm)	2.8		1.8	3.8	-Screw tip to half-length of screw body: 1.8 -Rest of screw body length: 3.8	-Screw tip to half-length of screw body: 3.8 -Rest of screw body length: 1.8
Thread Width (mm)	0.2					
Proximal Half Angle (degree)	14					
Distal Half Angle (degree)	25					
Conical Angle from the Screw Tip (degree)	1.655	1.018	1.655			

Figure 1 shows the important structures/parameters of a pedicle screw.

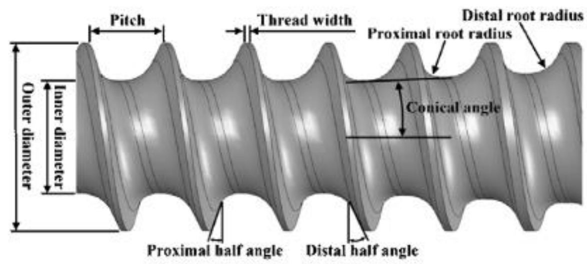

Figure 1. Structures of the pedicle screws (thread part).
Source: Chao *et al.* [6].

While figure 2 till figure 5 shows the pedicle screws from the previous published research (model 1 and 2) and the proposed design of pedicle screw (model 3-5) [6].

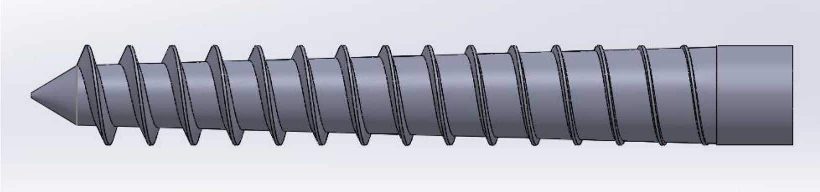

Figure 2. Model 1.

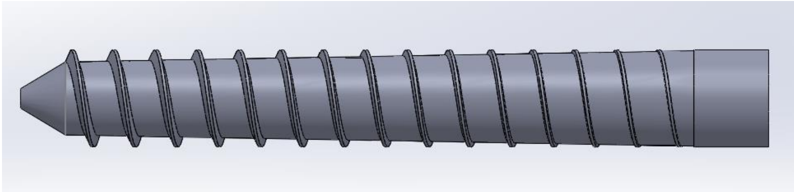

Figure 3. Model 2.

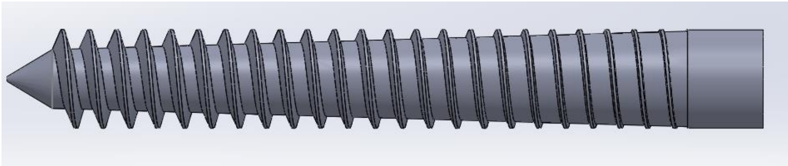

Figure 4. Model 3.

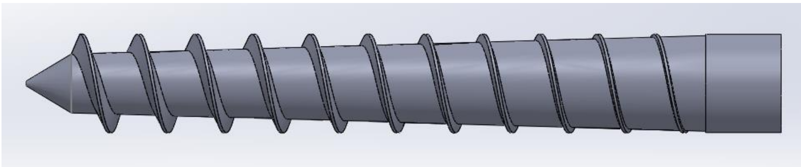

Figure 5. Model 4.

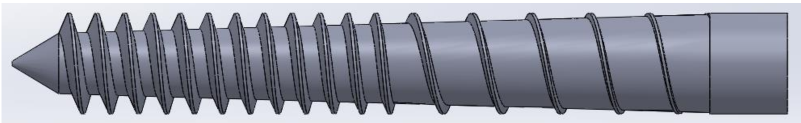

Figure 6. Model 5.

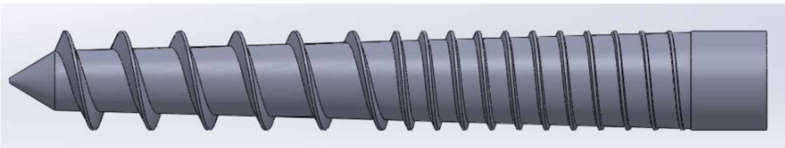

Figure 7. Model 6.

The models of the pedicle screw then saved as IGES file for imported to ANSYS software for finite element analysis. The material that used in finite element analysis for the pedicle screws is titanium alloy (Ti-6Al-4V) according to the specification of American Standard of Tested Materials (ASTM) F136-96. Chao *et al.* stated that two important parameters to describe the mechanical properties of the titanium alloy are elastic modulus (E) and Poisson's ratio (v) [6]. The titanium alloy chosen because of its superior biocompatibility and mechanical strength if it is compared to stainless steel based on the statement of Shea *et al.* [12]. According to the Chao *et al.*, the titanium alloy has the Young's modulus of 114 GPa and the Poisson ratio of 0.3

[6]. Therefore, in ANSYS, the Ti-6Al-4V in the additive manufacturing materials added into the contents of engineering data. The material then added to the body of the pedicle screws.

2.1 Boundary Condition

There are two situations of screw for the simulation: 1) the screw is bent; 2) the screw was pull by given load. Therefore, the boundary conditions of the pedicle screw in both situations are different. For the situation when the screw is bent, the screw head fixed in all direction while a force of 330N is applied to the body of the screw in negative y-direction as shown in figure 8. Next, for the situation when the screw is pull, the screw head also fixed in all direction but the displacement of 0.01mm applied to the screw tip in positive z-direction as shown in figure 9.

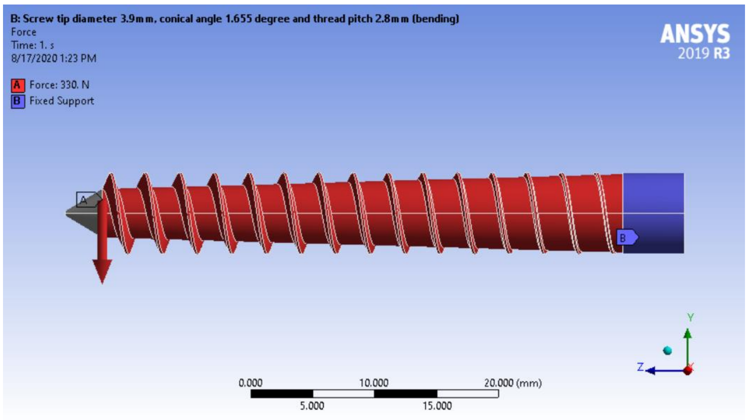

Figure 8. Boundary conditions of pedicle screw (bending).

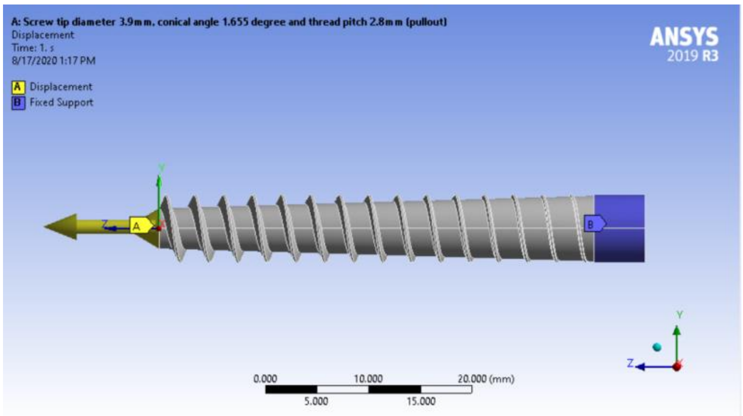

Figure 9. Boundary conditions of pedicle screw (pullout).

2.2 Meshing

The titanium alloy has been add as the material of the pedicle screws and the 3D meshes were then generated at the body of the pedicle screw. The size of mesh on the body of the pedicle screw is controlled using edge sizing method as shown in figure 10. All of the edge sizing are using the type of number of divisions. For the first three-edge sizing, the number of divisions is set at 30. For edge sizing 4, the number of divisions is set at 10 while the number of divisions for edge sizing 5 is set at 5. The details of number of nodes and elements of each models can be refer to the table 2. One of assumption made in our Finite Element Analysis (FEA) was that the mesh used was not too course or too fine but it is still converged. A mesh with more nodes would have improved the accuracy of the computational results because it would account for more points on the sample. This was not done however, because more elements means more calculations for the program to do and there is limited time in lab. Some other assumptions that did in our FEA such as materials were consider as linear and forces were apply slowly and did not change direction in time.

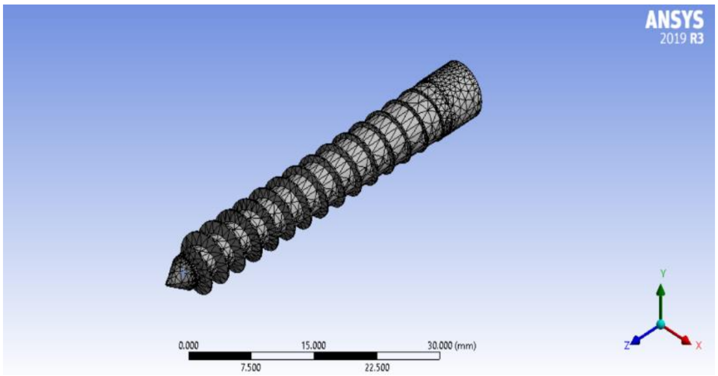

Figure 10. Meshing on the body of pedicle screw.

Table 2. Number of nodes and elements for each model.

Model No.	3D Models of Pedicle Screw Conditions	Nodes	Elements
1	Screw tip diameter 3.9mm, conical angle 1.655 degree and thread pitch 2.8mm	19618	10570
2	Screw tip diameter 4.9mm, conical angle 1.018 degree and thread pitch 2.8mm	20740	11272
3	Screw tip diameter 3.9mm, conical angle 1.655 degree and thread pitch 1.8mm	19421	10414
4	Screw tip diameter 3.9mm, conical angle 1.655 degree and thread pitch 3.8mm	17165	9395
5	Screw tip diameter 3.9mm, conical angle 1.655 degree and thread pitches 1.8mm (half-length of screw body starting from screw tip) and 3.8mm (rest of length)	20514	11287
6	Screw tip diameter 3.9mm, conical angle 1.655 degree and thread pitches 3.8mm (half-length of screw body starting from screw tip) and 1.8mm (rest of length)	20086	10796

3. Results and discussion

Finite element analysis result (maximum equivalent stress) of pedicle screw model 1 shown in figure 11 and 12 for both situation bending and pullout. The maximum equivalent stress of other models are as shown in table 3 and 4.

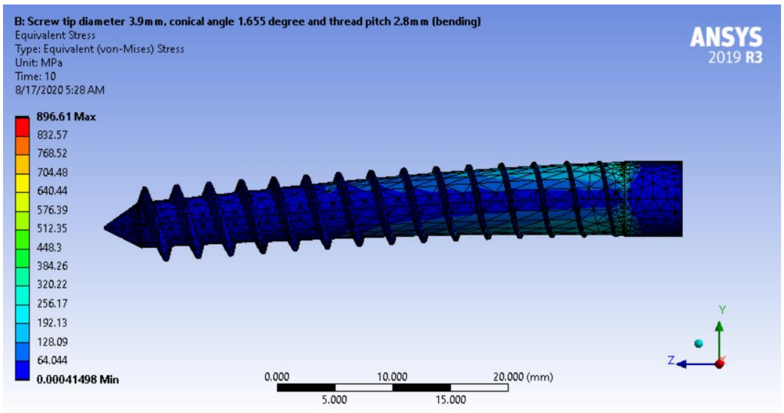

Figure 11. Equivalent (von-Mises) stress (bending) for model 1.

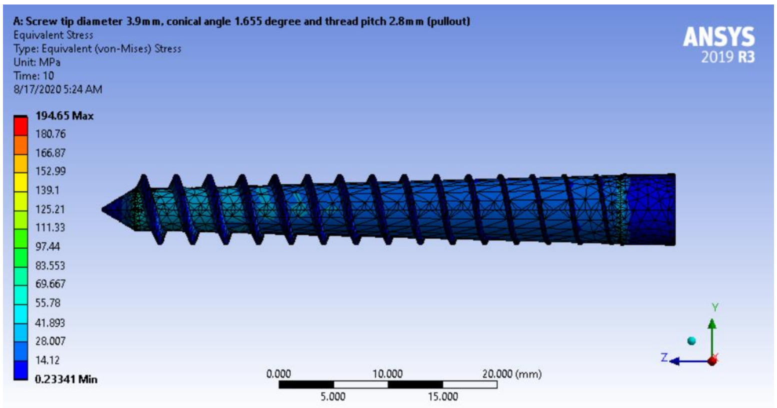

Figure 12. Equivalent (von-Mises) stress (pullout) for model 1.

Table 3. Maximum equivalent stress (bending).

Model	Maximum Equivalent Stress (MPa)
Reference model 1 [6]	896.61
Reference model 2 [6]	892.65
Proposed model 3	1097.4
Proposed model 4	709.05
Proposed model 5	1067.9
Proposed model 6	732.91

Table 4. Maximum equivalent stress (pullout).

Model	Maximum Equivalent Stress (MPa)
Reference model 1 [6]	194.65
Reference model 2 [6]	150.62
Proposed model 3	172.47
Proposed model 4	186.05
Proposed model 5	198.65
Proposed model 6	176.32

When the force applied on the body of pedicle screw models to let it bend, the model 4 has the lowest maximum equivalent stress, which is 709.05 MPa while model 3 has the highest maximum equivalent stress, 1097.4 MPa (table 3-4). Based on the theoretical, the higher maximum equivalent stress the easier to fail. In the bending test, model 3 fail first while model 4 (with the highest value of thread pitch) has the best bending performance compared to other pedicle screw models. Thus, it is proof that the thread pitch affects the performance of the pedicle screw in bending and has effect on pullout performance as proof by Gausepohl *et al.* [13]. The higher value of thread pitch of pedicle screw has better performance in bending. However further investigation especially by experiment should be done to verify this finding as did by Lee *et al.* [14].

When the load displacement is applied on the screw tip of the pedicle screw models, the model 5 has the highest maximum equivalent stress which is 198.65 MPa but model 2 (reference model) has the lowest equivalent stress, 150.62 MPa as shown in table 4. Thus, model 5 show the worst pullout performance. Based on the stress value in table 4, we found that the model 3 (a single threaded pedicle screw) has the optimum pullout performance among the proposed design of the pedicle screw. It is also better than the model 1(reference model). While, for the dual threaded pedicle screw, the model 6 is better than model 5 in term of pullout performance.

Model 1, 3, 4, 5 and 6 has the same inner diameter but various thread pitch. Based on table 3 and 4, when comparing the bending and pullout performance of the models which have same inner diameter but different thread pitch, model 4 and model 6 have lower maximum equivalent stress than model 1 which is a reference model in both bending and pullout tests. The model 1 fail faster than model 4 and 6 when bending and pullout are applied. Therefore, it can be conclude that the model 4 and 6 is the optimum design of pedicle screw thread since it is better than the model 1(reference model that currently available in the market).

4. Conclusion

As a conclusion, the pedicle screw with lower maximum equivalent stress has better performance in bending and pullout. Comparing the model 1, 3, 4, 5 and 6, model 4 is the best in bending performance since it has the lowest maximum equivalent stress. For pullout, the model 3 has the optimum performance even though it has the worst bending performance. To compare all proposed pedicle screw models with the reference model (model 1) in both bending and pullout aspects, model 4 and model 6 are better than model 1. Therefore, it can be conclude that the pedicle screw with coarse thread pitch has better pullout and bending performance. For the dual threaded pedicle screw, the pedicle screw with coarse thread pitch at the screw tip is better than the pedicle screw with fine thread pitch at the screw tip. This findings have potential in assisting the optimum design of pedicle screw in the future although still need to do further investigation to support this finding.

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