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Investigation on Pullout Strength between Different Design of Cannulated Pedicle Screw and Osteoporosis Bones to Obtain an Optimum Design

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Abstract:

Cannulated Pedicle Screw (CPS) is the tools implemented in the biomedical sector to strengthen the structure of the bones and to increase the pullout strength in osteoporotic patients. The cement is injected from the top of cannulated screw to bone which the radial hole plays the main role in ensuring uniform cement distribution to bone for the enhanced fixation between CPS and bone, leading to higher pullout strength. This paper is aim to investigate on pullout strength between different design of cannulated pedicle screw and osteoporosis bones to obtain an optimum design of CPS in focusing on its radial holes. Four designs were constructed using SolidWorks software where one of it is the current model of CPS with 2 radial holes, 1.5 mm diameter whereas the proposed design 1 with 1 radial holes-1 slot, design 2 with 1 double radial hole-1 slot and design 3 with 1 double radial hole and 1 double slot. ANSYS software is used for the Finite Element Analysis (FEA). The Finite Element Models were verified with the previous research FEA result. The FEA results of stress von mises for current and proposed design were then compared to investigate their pullout strength whereby the yield strength of CPS is 820 MPa and 130MPa for osteoporosis bone. The FEA results show 19.26 MPa maximum stresses for the current design and 18.69 MPa, 22.3 MPa and 22.48 MPa for proposed design 1, 2 and 3 respectively. Thus, the current Cannulated Pedicle Screw seem can be improved by the proposed design 1 which is with 1 radial hole (1.5 mm) and 1 slot (1.5 mm x 3 mm) due to its gain the lowest average maximum stress. It can be concluded that the pullout strength of the Cannulated Pedicle Screw were not depends directly on how many the number of radial hole/slot in improving pullout strength since the single hole and slot is considered the optimum design of CPS due to its lowest average of maximum stress on the critical region.

Keywords: *cannulated pedicle screw, finite element method, optimization, pullout strength*

I. INTRODUCTION

Cannulated pedicle screw (CPS) is specifically designed for an osteoporotic cases which is allowed cement augmented to be injected through CPS as a solution for osteoporotic patients by increasing its pullout strength [1]. Pure Titanium and Ti-6Al-4V alloy have been mainly used as implant material. V-free titanium alloys like Ti-6Al-Nb have been developed to be another option due to the toxicity that might release by V in long term implantation [2]. By considering the factor of biomechanical safety of the pedicle screw, the best material of CPS is Ti-6Al-7Nb with high strength, good toughness and ductility. Another property of the Titanium alloy

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Ti-6Al-Nb is corrosion resistance which attribute to a stable and protective layer that has been obtained its reaction with the body fluid [3].

Besides types of materials, few parameters need to be considered to obtain the proper design of CPS for osteoporotic patients. Patel et. al. reported that the high value of diameter and length of the screw were able to produce larger pullout forces although will face with the risk of fracturing around surrounding bone [4]. Tapering the screw also is believed able to help compress surrounding bone, which may increase the screws fixation [5]. Different thread designs also could be considered as the important parameter to increase screw pullout strength [6]. Design alteration is a topic of interest in the literature and the pros and cons of altering each design characteristic are individually discussed as did by previous researchers in altering the implant design [7-9]. The performance of the altered design is evaluated by using finite element method which is quite popular method among previous researchers [10-14].

The high bonding contact between bone and CPS is important in increasing the pullout strength. In order to increase bonding contact between bone and CPS, radial holes could be an option which allows cement augmented flow through it. Another useful study about radial holes was done by Mckoy and An. on osteoporotic human vertebrae. They compared the pullout strengths of CPS and normal pedicle screw. They reported that radial holes increased the amount of the cement flow through it and concluded that the CPS gave 2.78 times higher pullout strength than standard pedicle screw [15]. Whereas Chao KH et al. investigation by implanted the cannulated screw designed with nine 1mm diameter radial holes that located around the distal one-third of screw. It is then demonstrated with cement-augmented and the result shows that the pullout strength of the screw is stronger over 300% [16].

Chen et al. summarize that the higher the number of radial hole does not makes the pedicle screw perform well, instead pedicle screw with high number of radial hole gives lower strength than a number of radial hole [17]. While other researcher found it oppositely where as the number of radius holes do affected the CPS performance [15]. By other words, either number of radial holes or pattern of hole still can be debated. Thus, the aim of this paper is to investigate on pullout strength between different design of cannulated pedicle screw and osteoporosis bones to obtain an optimum design of CPS in focusing on its radial holes.

II. METHODOLOGY

A. Construction of the CPS 3D Model

The current CPS was constructed using SolidWorks software which its dimension is based on the previous research CPS in order to validate our FE model by comparing the FE simulation result with the previous FE simulation result done by Teyfik Demir and Başgül [18]. The current design of CPS is with 2 radial holes (1.5 mm) is shown in Fig. 1 while another three designs are the proposed design with different number of hole and slot (1.5 mm x 3 mm) as shown in Fig. 2.

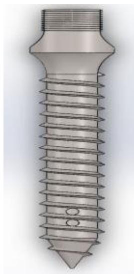

Fig. 1. Front view of current model of CPS with 2 radial hole.

Fig. 1 shows the front view of CPS with 2 radial hole. The dimensions and parameter each of the current CPS is fixed with 60 mm length, 7 mm outer diameter of the screw head, 2 mm inner diameter, 1.5 mm radial hole, and length of screw thread of 45 mm. While, there are three proposed designs of the CPS are designed with different number of hole and size. The proposed designs were constructed with 1.5 mm radial holes diameter and 1.5 mm x 3 mm slot size. The three proposed cannulated pedicle screws are;

i. One radial hole one slot
ii. One radial double holes one slot
iii. One radial double holes one double slot.

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(a) (b) (c)

Fig. 2. 3D model of proposed CPS with (a) Single hole and slot (b) Double holes and single slot (c) Double holes and slots

All the cannula diameters were 2 mm and radial slots were milled with 1.5 mm. holes were drilled with 1.5 mm width and height 3 mm. All slots and holes were drilled or milled unilaterally. The outer diameter and length of the proposed CPS is the same with the current one which is 7 mm for outer diameter and 60 mm length.

B. Material selection

There were two types of materials used in this study which are titanium alloy (Grade 23) for CPS and polyurethane foam (PU) block (Grade 10) for the synthetic spine bone [15, 19]. Table I shows the properties of titanium alloy and polyurethane foam respectively.

Table I: Properties of titanium alloy (Grade 23) and Polyurethane

Properties	Titanium alloy	Polyurethane
Young's modulus, E (Gpa)	104.5	0.78
Tensile strength, σ_x (Mpa)	860.0	33.0
Yield stress, σ_y (Mpa)	820.0	133.0
Poisson's ratios, ν	0.3	0.3

C. Finite Element Model

Finite Element Model was setup based on validated Finite Element Model which the bottom of the bone was completely fixed (Fig. 3) and a maximum force of 500 N was applied to the body of the CPS as shown in the Fig. 4.

Fig. 3. Fixed Support at Bottom of Bone

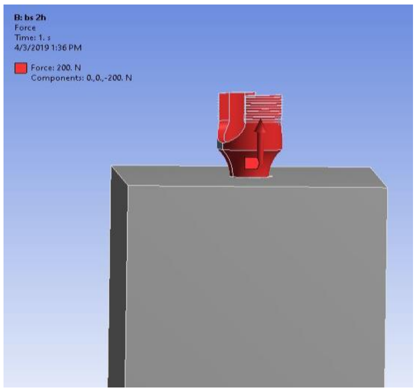
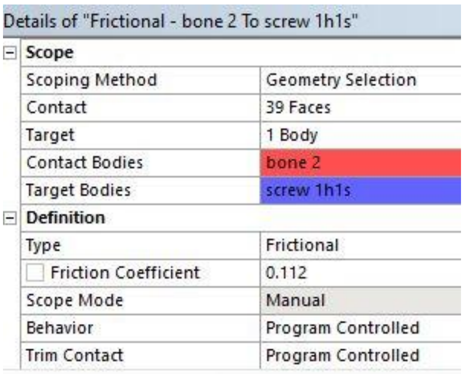


Fig. 4. Force Applied at Head of Screw

The contact type of connections between CPS and bone are assigned as friction. This is to represent the PMMA augmentation as the cement to bone. Fig. 5 shows the details connection of screw and bone material.



Details of "Frictional - bone 2 To screw 1h1s"

Scope	
Scoping Method	Geometry Selection
Contact	39 Faces
Target	1 Body
Contact Bodies	bone 2
Target Bodies	screw 1h1s
Definition	
Type	Frictional
Friction Coefficient	0.112
Scope Mode	Manual
Behavior	Program Controlled
Trim Contact	Program Controlled

Fig. 5 Details connection of screw and bone material

While, the geometry of CPS need to be mesh before it is proceed into the finite element analysis.

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Fig. 6 shows the geometry of CPS that already meshed. For this study, the total element that was being created was 69622 and a total of 123285 nodes. There is no need for higher nodes because design was fairly a simple design.

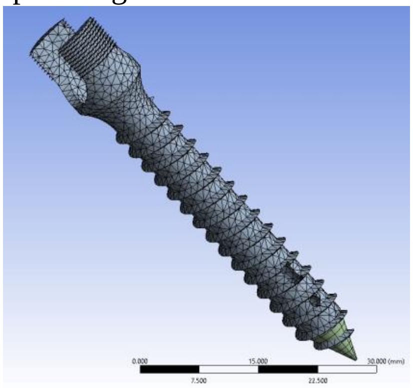


Fig. 6 Meshing of the Cannulated Pedicle Screw

III. RESULTS AND DISCUSSION

Based on the FE simulation result obtained as shown in the Fig. 7, the maximum Von Mises stress of the current design of CPS 47.521 MPa.

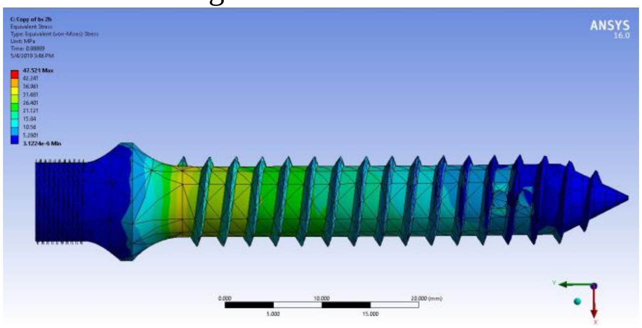
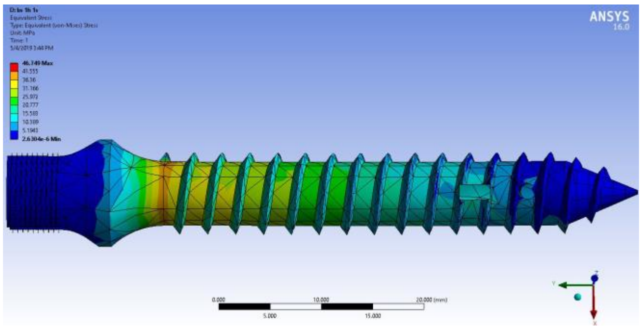


Fig. 7. Equivalent Stress (Von Mises Stress) of CPS with 2 radial holes

A. FE Simulation Results of Proposed Design of CPS

The Cannulated Pedicle Screw with 1.5 mm radial hole diameter and 3 mm x 1.5 mm slot size of the proposed design also been analyzed to obtain the optimum design. From the FE analysis result, the maximum stress on it is 46.749 MPa when load of 500 N is applied (Fig. 8).



IV. UNITS

Fig. 8. Equivalent Stress (Von Mises Stress) of CPS with 1 radial hole 1 slot

While, the second proposed design of CPS with double 1.5 mm radial hole diameter and 3 mm x 1.5 mm slot size gave the maximum stress of 53.455 MPa when the load of 500 N is applied (Fig. 9).

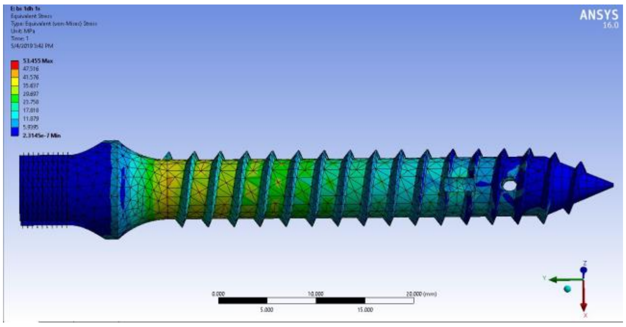


Fig. 9. Equivalent Stress (Von Mises Stress) of CPS with 1 double radial hole 1 slot

The third proposed design of CPS with double 1.5 mm radial hole diameter and double 3 mm x 1.5 mm slot size of the proposed design gave the highest maximum stress, 53.715 MPa as shown in Fig. 10.

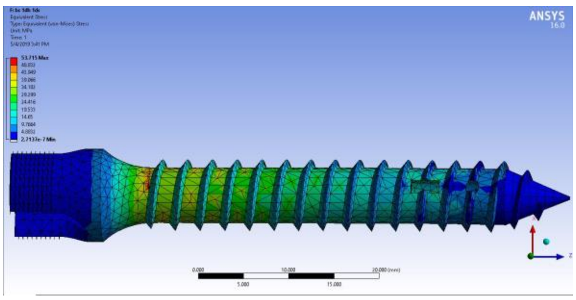


Fig.10. Equivalent Stress (Von Mises Stress) of CPS

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with 1 double radial holes 1 double slot design.

B. Comparison between Current and Proposed Design of CPS

In order to find the optimum design screw, the maximum stress around the critical region gain by each CPS design is compared. This critical region is the region that every design of CPS has different size and number of holes and also was considered as the main contact surface between CPS and bone. This region also is considered critical as reported by previous researcher [18]. Five spot points/nodes at highest maximum stress were choose to obtain the average of the stress. The detailed of the average maximum stress at critical region is as shown in Table II.

Table II: Load and Average Maximum stress at critical region between the current design and the proposed design

Load (N)	Average Maximum Stress (Mpa) at Critical Region			
	Current design	Proposed design		
	2 H	1 H 1 S	1 DH 1 S	1 DH 1 DS
500	19.26	18.69	22.3	22.4 8

The FE simulation results obtained also represented as a graph (Fig. 11.) for comparison purposed. The blue bar on the graph represents current CPS while for the proposed CPS, CPS design 1 with one radial hole (1.5 mm) one slot (3 x 1.5 mm), 1H1S represented by the orange bar. CPS design 2 with one double radial hole (1.5 mm) one slot (3 x 1.5 mm), 1DH1S represent by grey bar and CPS design 3 with one double hole one double slot, 1DH1DS represent by yellow bar.

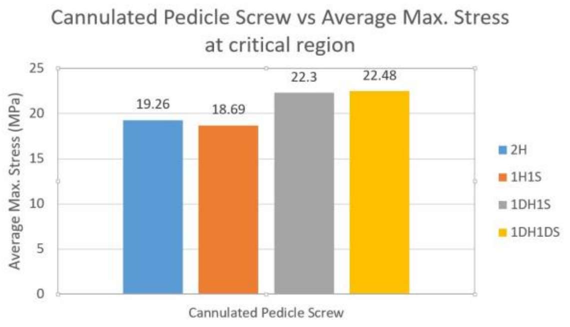

Fig. 11. Graph of comparison on the pullout strength of CPS between the current designs and the proposed design.

By referring to the graph Fig. 11, we can summarize that the proposed design 1 of CPS, 1H1S gave the lowest average maximum stress 18.69 MPa. While the CPS of design 3, 1DH1DS is gained the highest average maximum stress, 22.48 MPa. However, all the designs shown the reading of average maximum stress are still below than yield strength of the CPS and bone 860 MPa and 130 MPa respectively. But one thing that surprisingly regarding on this founding is the number of hole/slot did not decrease the maximum stress around the critical region since both proposed design with more hole/slot were gained high stress although at first thought it will reduce the stress since more hole/slot means more PMMA cement will be injected to increase the pullout strength between CPS and bone. Nevertheless, we can concluded that the proposed design 1 of CPS can be considered the optimum design since it can potentially has higher pullout strength due to the concept of the lower the value of maximum stress on the critical region, the higher pullout strength can be generated.

V. CONCLUSION

It can be concluded that the pullout strength of the Cannulated Pedicle Screw were not depends directly on how many the number of radial hole/slot in improving pullout strength since the single hole and slot is considered the optimum design of CPS. The proposed design of CPS with 1H1S is considered an optimum design since it gains the lowest average stress on the critical region. This optimum design is potential to be used as improved CPS since its pullout strength increased due to its lower stress on the critical region. However, the fabrication of CPS based on the optimum design still needed for physical testing of its performance before it can be used in real life. Beside the investigation on the size of radial hole is in list for the future research since based on the concept, the lower size of hole, the lower the possibilities of the fracture to occur around the radial hole therefore will affected the pullout strength and performance of the CPS.

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