A FINITE ELEMENT ANALYSIS OF ELBOW JOINT IN DAILY ACTIVITIES

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ABSTRACT

3-Dimensional elbow implant was built with SOLIDWORKS 2014 and the finite element analysis was performed with ANSYS. Designs of elbow implants were compared based on the linked, semi-constrained elbow implant design that was chosen and built in this study. The daily activities was said to be achieved within range of 30 degrees to 130 degrees of angle of flexion. Three common angles were picked to perform analysis, which are 30 degrees, 90 degrees and 130 degrees. Three types of materials were chosen for the metal components of the elbow implant which is Titanium, Copper and Stainless Steel. Polyethylene was chosen as the material for bushing. Values 0.1kg, 0.5kg, 1.5kg and 2.5kg were given to objects involved in daily activities. Results of stress from "Equivalent (von-Mises) Stress" and "Maximum Principal Stress" were compared. After the analysis, it was discovered that Titanium is the best material for elbow implant production, and failure of implant will likely to occur at the lower part of the humerus component and mid-ulnar component. The maximum values of the stress for all three materials of elbow implant were lower than the Ultimate Tensile Strength of the material. Therefore, the implant will provide a proper stress distribution when the individual perform his or her daily activities.

Keywords: elbow implants, load, stress, materials, angle of flexion.

INTRODUCTION

The elbow implant is used on patients with elbow pain and disabilities. Examples of conditions causing the disability are Rheumatoid Arthritis and Osteoarthritis. Rheumatoid Arthritis is a diseased in which the synovial membrane located in between the humerus and the radius and ulna, which surrounds the joint becomes inflamed and thickened. This will cause damage to the cartilage and eventually, pain. Osteoarthritis is most commonly referred as "wear-and-tear" arthritis. This disorder happens due to repetitive movement of the joint, causing the cartilage cushioning the two bones forming the hinge movement to wear away. As the cartilage becomes thinner, the humerus and the radius and ulna may rub against each other, causing pain to the elbow.

Total Elbow Arthroplasty (TEA) is a surgical procedure performed to restore the functions affected by the rheumatoid arthritis. The joint area of the elbow is severely damaged due to the effects of wear-and-tear. This will induce pain and stiffness. Thus, the individual suffering from rheumatoid arthritis may not be able to perform its daily functions well. To restore the functionality of the elbow, the scarred tissue has to be removed while maintaining the muscle balance. The elbow implant will then be inserted into the damaged elbow (Warme and Matsen, 2015). The humerus part of the elbow implant is inserted inside the humerus arm bone while the ulna part of the elbow implant is inserted into the ulna arm bone. The 2 parts will be connected by a hinge mechanism using a hinge pin. Figure-1 shows the x-ray image of the elbow implant.

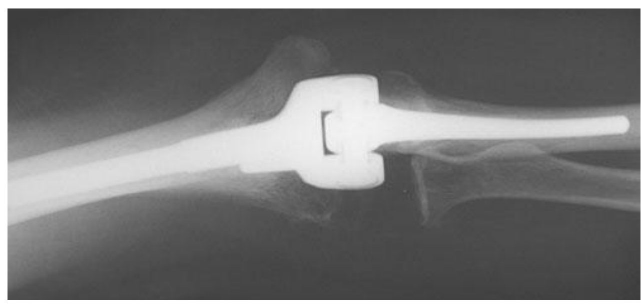

Figure-1. X-ray image of elbow implant (Warme and Matsen, 2015).

The main aim of this project is to analyze the linked semi-constrained elbow implant with influences of weights held and determining the best material for the elbow implant. A finite element analysis will be performed on the designed elbow implant to determine the force distribution on the implant when performing daily activities

LITERATURE REVIEW

Selecting a template

There are two common types of elbow implants used in the current medical field for TEA. They are the linked, semi-constrained elbow implant and the unlinked, unconstrained elbow implants. The feature of the implant that distinguishes the type of implant is the style of linking of the two implant components, the humerus and ulnar. The different linkings have different ways of preventing dislocation during surgery. Most of the linked implants are semi-constrained, which means the linking mechanism only allow some rotational and varus-valgus play which shows minor limitation when compared to the

VOL. 11, NO. 8, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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normal elbow (Sotelo, 2011). It is differentiated from the unlinked elbow implant through the articulation of the humeral and ulnar components (Ramsey, 2010). The unlinked implants are minimally constrained and not mechanically linked (Sotelo, 2011). They do not require a hinge pin as used by the linked implants. The most common linked implant is Coonrad-Morrey prostheses and the most common unlinked implants available during surgery are the Souter-Strathclyde and Kudo prostheses (Sotelo, 2011). The advantages and disadvantages were compared for selection and the linked semi-constrained elbow implant was chosen. Table-1 shows the advantages and disadvantages of both designs.

Table-1. Advantages and disadvantages for both linked and unlinked elbow implant.

Linked Semi Contrained Implant	
Advantages	**Disadvantages**
Joint stability	Constraint increases tension, causing higher failure risk
Can be performed on patient with insufficient ligament	Complicated surgery
Can be used for patient with severe bone loss	Cannot be done for hemiarthroplasty
Better ranged motion	
Unlinked Minimally Constrained Implant	
Advantages	**Disadvantages**
Less constrained, lower wear risk	Need higher accuracy in component positioning
Less bony invasive	Can dislocate joint
Better revision for surgery	Difficult to perform if severe bone loss or insufficient ligament
Can be performed for hemiarthroplasty	Limited ability for soft tissue release

Range of motion (ROM)

The range of motion (ROM) of an elbow joint is in the range from full extension to full flexion. Figure-2 shows the angle of flexion, illustrating the range of motion of the elbow.

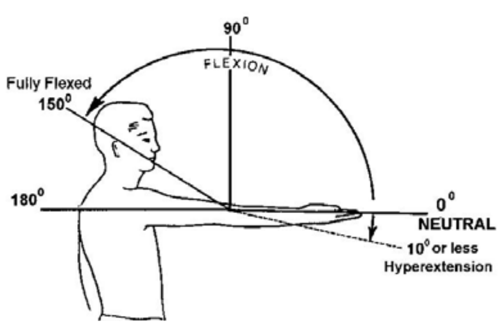

Figure-2. Range of motion of elbow (Ramsey, 2010).

A study was conducted to determine the range of motion of an elbow joint for contemporary tasks such as using a cellphone or eating and drinking. Types of range of motion included were flexion-extension, pronation-supination and varus-valgus angulation. Without taking into account the elbow implant, a healthy elbow should have a maximum flexion arc of 130° ± 7° with a minimum value of 23° ± 6° recorded and a maximum value 142° ± 3° recorded (Sardelli *et al.* 2011).

To determine the angle of flexion for the elbow joint during daily activities, a study was conducted using 33 normal patients to test the normal kinematics of the elbow and the total elbow motion on the 15 activities done during daily living. From the study, it was determined that most activities performed on daily basis can be achieved within 100º of elbow flexion, from 30º to 130º (Desai *et al.* 2014).

METHODOLOGY

There are two main stages that involved in this study. The stages are; (a) 3D Elbow Implant Drawing (b) Finite Element Analysis. The complete process flow is shown as in Figure-3.

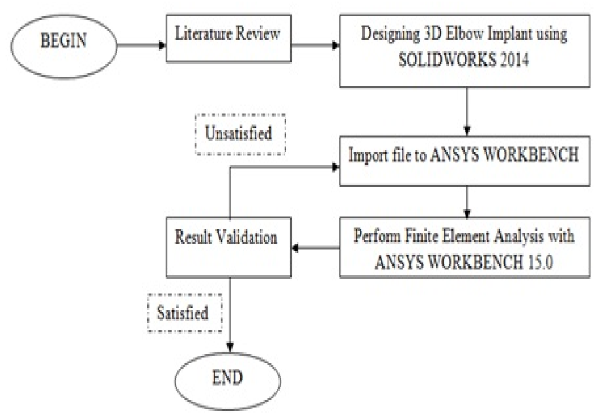

Figure-3. Flowchart of the study.

3D elbow implant drawing

The 3D development of the elbow implant was done with SOLIWORKS 2014. The design specification was determined based on previous study. Each part of the elbow implant (humerus, ulnar, bushing and hinge) was drawn separately. The components were then compiled using the "assembly" function of SOLIDWORKS 2014. The format saved was .SLDASM in order to be exported to ANSYS WORKBENCH 15.0 for Finite Element Analysis. Figure-4 shows the complete overall elbow implant design drawn on SOLIDWORKS 2014.

VOL. 11, NO. 8, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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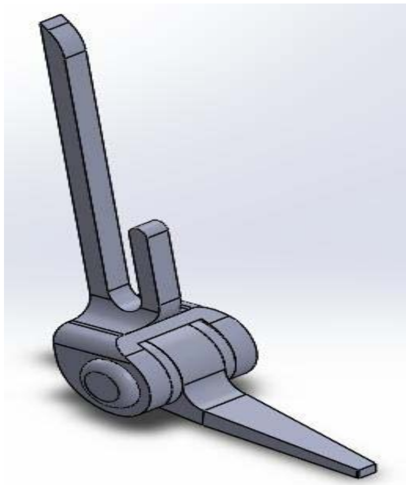

Figure-4. Overall elbow implant from SOLIDWORKS 2014.

Finite element analysis

Finite Element Analysis was performed using ANSYS WORKBENCH 15.0. Figure-5 shows the flow of Finite Element Analysis using ANSYS.

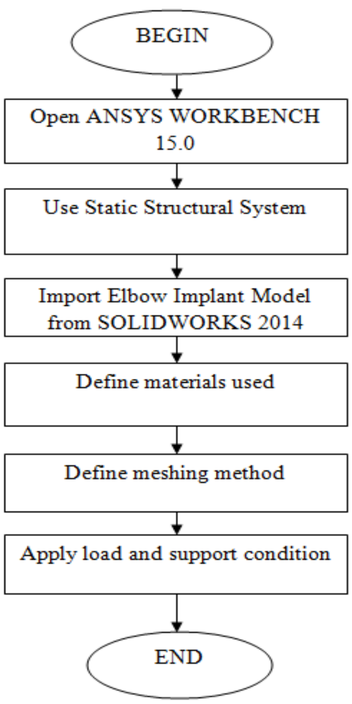

Figure-5. Flowchart of finite element analysis using ANSYS.

The "Static Structural" option from the ANSYS WORKBENCH 15.0 toolbox was chosen to perform the analysis. The drawing from SOLIDWORKS was exported into ANSYS and displayed on the 'Model' tab. Figure-6 shows the Elbow Implant in ANSYS.

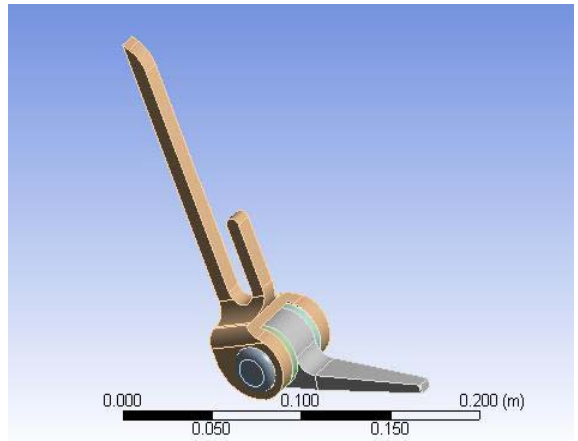

Figure-6. Elbow implant in ANSYS after exported from SOLIDWORKS.

Each component in the elbow implant was assigned a material from the ANSYS library. The bushing had a fixed component of Polyethelene while the humerus, ulnar and hinge component have variable materials, Titanium, Copper and Stainless Steel.

Three standards angles of flexion were selected, 30º, 90º and 130º. The load of object acted onto the elbow implant was set to be 0.1kg, 0.5kg, 1.5kg and 2.5kg. The forces applied to the elbow implant follow the free-body diagram of the elbow joint shown in Figure-7.

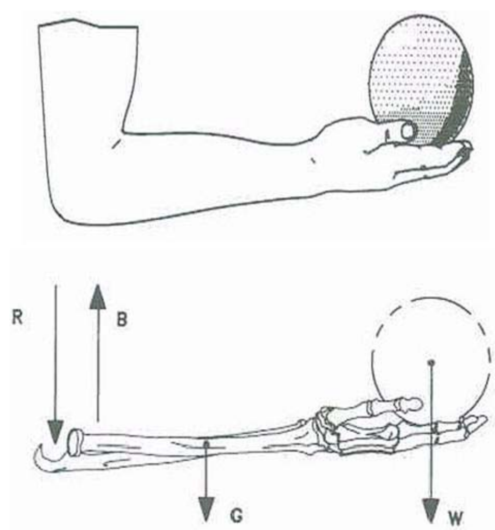

Figure-7. Free body diagram of elbow (Shahid *et al.* 2015).

After applying all forces onto specific locations, the result of the analysis was obtained from the Equivalent (von-Mises) Stress and the Maximum Principal Stress. Figure-8 and 9 shows the result from Equivalent (von-Mises) Stress and Maximum Principal Stress respectively.

VOL. 11, NO. 8, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

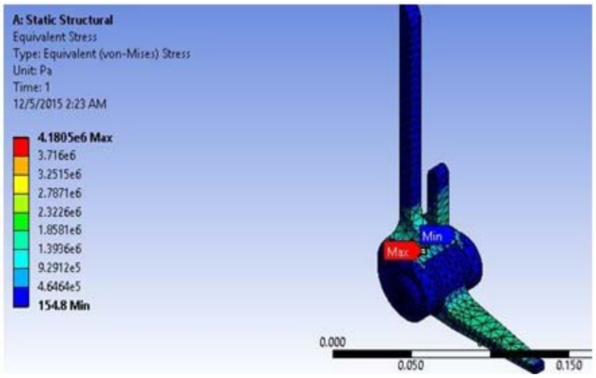

Figure-8. Equivalent (von-Mises) stress.

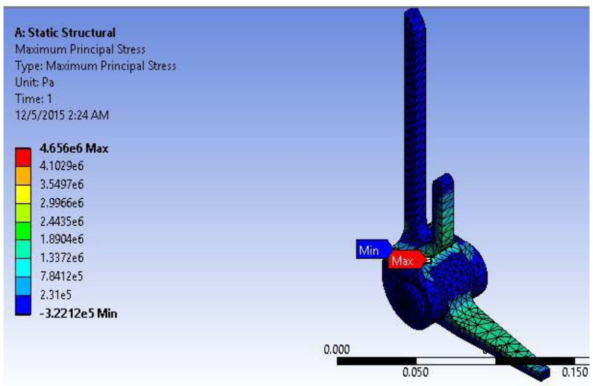

Figure-9. Maximum principal stress.

From the analysis above, the maximum value of stress was recorded and the stress distribution of the elbow implant was taken into consideration for data analysis. The finite element analysis was then repeated with different angle, followed by different load and then different material.

Equations

From the free body diagram in Figure-7, several equations were derived in order to calculate all four forces to be put in finite element analysis. The derived equations were;

Moments about Elbow joint = 0,

$$(\mathbf{B} \times \mathbf{D1}) - (\mathbf{G} \times \mathbf{D2}) - (\mathbf{W} \times \mathbf{D3}) = 0 \qquad (1)$$

D1, D2, D3 are perpendicular measured distances from the elbow joint**.**

After the force acted by the biceps was calculated, the sum of moment in the 'y-axis' direction will be taken as zero.

Sum of moments on 'y-axis' = 0,

$$-\mathbf{R} + \mathbf{B} - \mathbf{G} - \mathbf{W} = 0 \qquad (2)$$

G is the weight of the forearm with account to the gravitational force, acting vertically downwards. **B** is the force acted by the biceps, W is the weight of the object and **R** is the reaction force of the joint.

All four forces were calculated and compiled for ease of access during finite element analysis. Table-2, 3 and 4 shows the forces applied for all three materials.

Table-2. Forces applied to the copper elbow implant.

Conditions	Forces, N			
	G	W	B	R
0.1kg, 30°	8.829	0.981	61.671	42.051
0.1kg, 90°	8.829	0.981	30.835	21.025
0.1kg, 130°	8.829	0.981	40.253	27.447
0.5kg, 30°	8.829	4.905	106.522	79.054
0.5kg, 90°	8.829	4.905	53.261	39.527
0.5kg, 130°	8.829	4.905	69.527	51.599
1.5kg, 30°	8.829	14.715	218.650	171.562
1.5kg, 90°	8.829	14.715	109.325	85.781
1.5kg, 130°	8.829	14.715	142.714	111.979
2.5kg, 30°	8.829	24.525	330.778	264.070
2.5kg, 90°	8.829	24.525	165.389	132.035
2.5kg, 130°	8.829	24.525	215.900	172.360

Table-3. Forces applied to the stainless steel elbow implant.

Conditions	Forces, N			
	G	W	B	R
0.1kg, 30°	6.867	0.981	50.458	34.762
0.1kg, 90°	6.867	0.981	25.229	17.381
0.1kg, 130°	6.867	0.981	32.934	22.689
0.5kg, 30°	6.867	4.905	95.309	71.765
0.5kg, 90°	6.867	4.905	47.654	35.882
0.5kg, 130°	6.867	4.905	62.209	46.481
1.5kg, 30°	6.867	14.715	207.437	164.273
1.5kg, 90°	6.867	14.715	103.719	82.137
1.5kg, 130°	6.867	14.715	135.395	107.222
2.5kg, 30°	6.867	24.525	319.566	256.781
2.5kg, 90°	6.867	24.525	159.783	128.391
2.5kg, 130°	6.867	24.525	208.582	167.602

Table-4. Forces applied to the titanium elbow implant.

Conditions	Forces, N			
	G	W	B	R
0.1kg, 30°	6.867	0.981	50.458	34.762
0.1kg, 90°	6.867	0.981	25.229	17.381
0.1kg, 130°	6.867	0.981	32.934	22.689
0.5kg, 30°	6.867	4.905	95.309	71.765
0.5kg, 90°	6.867	4.905	47.654	35.882
0.5kg, 130°	6.867	4.905	62.209	46.481
1.5kg, 30°	6.867	14.715	207.437	164.273
1.5kg, 90°	6.867	14.715	103.719	82.137
1.5kg, 130°	6.867	14.715	135.395	107.222
2.5kg, 30°	6.867	24.525	319.566	256.781
2.5kg, 90°	6.867	24.525	159.783	128.391
2.5kg, 130°	6.867	24.525	208.582	167.602

VOL. 11, NO. 8, APRIL 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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RESULTS AND DISCUSSION

For this study, two criterions were viewed from the ANSYS WORKBENCH 15.0, which are the Equivalent (von-Mises) Stress and the Maximum Principal Stress. The Equivalent (von-Mises) Stress proposes that yielding of the material occurs when the distortion of the component exceeds the yield point. The Maximum Principal Stress proposes that failure of the material will occur when the maximum principal stress of the material reaches the maximum stress at elastic limit in simple tension.

The stress distribution of the elbow implant was determined from the images of Equivalent (von-Mises) stress and Maximum Principal Stress. The common area for stress concentration on Equivalent (von-Mises) stress was on the lower humeral part of the component and on the top of the ulnar component. Figure-10 shows the stress concentration on all three common angles.

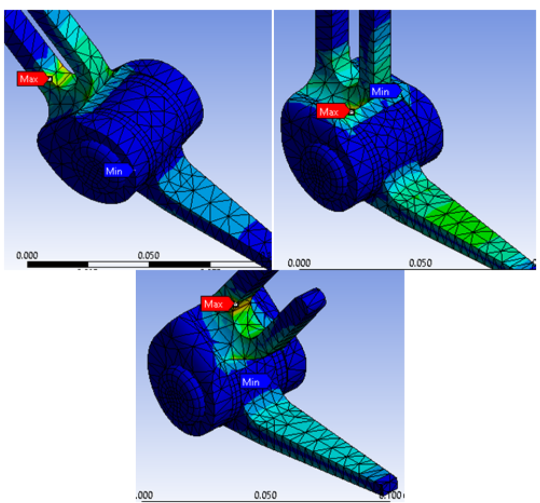

Figure-10. Close up of stress concentration on angles (clockwise) 30º, 90º and 130º.

From the Figure-10, it shows that the stress concentration was located at the lower humeral and anterior flange part of the humeral component. There are also stress concentrations on the ulnar component. Those are the areas that will occur failure after prolonged use of the elbow implant.

Also, the Ultimate Tensile Strength (UTS) of Copper, Stainless Steel and Titanium were taken from the ANSYS "Engineering Data" and compared with the highest value of the Maximum Principal Stress. From the ANSYS "Engineering Data";

UTS of Copper = 430 MPa.
UTS of Stainless Steel = 586 MPa.
UTS of Titanium = 1070 MPa.

The highest values for Maximum Principal Stress for the three materials are;

Copper = 41.638 MPa.
Stainless Steel = 40.416 MPa.
Titanium = 39.299MPa.

After comparing the highest values for Maximum Principal Stress and UTS, it was found out that the UTS of all 3 materials are a lot higher compared to the Maximum Principal Stress values. Therefore, the elbow implant for all three materials will not have a failure when performing daily activities with load up to 2.5kg.

A simple analysis was performed on the humeral component of the elbow implant. Two types of humeral components were analyzed, the humeral component with and without anterior flanges. A 100N force was applied to both the humeral components and Figure-11 shows the comparison of stress distribution between the two humeral components.

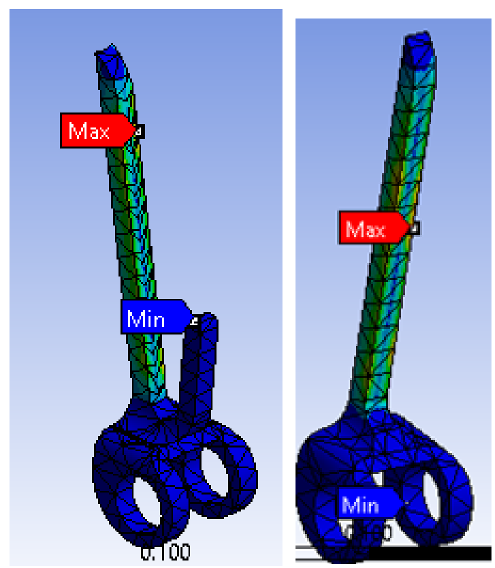

Figure-11. Humerus component. Left : With anterior flange. Right: Without anterior flange.

Based on the analysis done, the humerus component with the anterior flange shows 0.168MPa for the highest Equivalent (von-Mises) stress value while for the humerus component without the anterior flange, the highest Equivalent (von-Mises) stress is 0.172MPa. Therefore, the anterior flange does not provide much assistance as there is only a 0.004MPa difference between the two humerus components, but there may be a bigger difference as the load increases.

All three materials were compared for their Equivalent (von-Mises) stress and Maximum Principal Stress. Based on Table 4.1, the ranges of values for all three materials in both criterions are;
Equivalent (von-Mises) stress, Titanium:
1.909MPa - 42.365MPa.
Equivalent (von-Mises) stress, Stainless Steel:
2.976MPa - 45.048MPa.

Equivalent (von-Mises) stress, Copper:
3.603MPa - 45.755MPa.
Maximum Principal Stress, Titanium:
2.125MPa - 39.299MPa.
Maximum Principal Stress, Stainless Steel:
3.280MPa - 40.416MPa.
Maximum Principal Stress, Copper:
3.995MPa - 41.638MPa.

From the values stated above, Titanium showed the lowest value for Equivalent (von-Mises) stress and Maximum Principal Stress. It is then followed by Stainless Steel and Copper for both criterions. Therefore, Titanium is the most suitable among the three materials to produce the elbow implant as it is able to withstand forces applied to the elbow implant better than Stainless Steel and Copper.

CONCLUSIONS & FUTURE WORKS

Summary

Several conclusions were derived from this project. The first is that the stress distribution was concentrated on the lower humerus component, which is connected to the hinge of the elbow implant. There is also a stress concentration on the mid ulnar component. These stress concentrations will cause the failure of the elbow implant if the applied force is prolonged.

The next conclusion is that the anterior flange does not provide much assistance in terms of reducing stress distribution on the humeral component. However, there is a slight difference in the maximum value of Equivalent (von-Mises) stress. Therefore, it is still useful.

The last conclusion for this study is that the best material to be used for elbow implant is titanium. This is because it shows the least value for Equivalent (von-Mises) stress at 1.909MPa and Maximum Principal Stress at 2.125MPa. Therefore, the elbow implant will be able to withstand more force applied to the elbow implant during daily activities.

Future works

Further researches and improvements need to be done on the forces applied to the elbow joint during daily activities to acquire the accurate database for the project. Furthermore, questionnaires need to be done to have a deeper knowledge on the angle of flexions and weights used during daily activities. Moreover, a motion study can be conducted in the future to determine the stress distribution in animation. This will give a better knowledge on the stress applied during the elbow implant with coverage of all angles.

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