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# Investigation on Prosthetic Leg using Design of Experiments (DOE)

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**Abstract**: Wearable technology for prosthetic limbs and replacement organs is a rapidly growing field. A prosthesis is indeed an artificial device intended to replace a missing bodily part caused by trauma, sickness, or a birth defect. Therefore, prostheses are typically intended to replace the missing body organ and restore its functions. The main issues with prosthetic technologies and practices were poor prosthesis comfort and durability. The creation of a prosthetic for people who are missing a lower limb is the aim of this project. This project entails designing and producing a lower limb prosthesis out of local materials to improve the product's affordability. By developing an inexpensive, cosy, and long-lasting prosthetic, this initiative intends to improve the quality of life for persons who have lost their lower limbs. This study research aims to identify the significant parameters and optimum setting for the spring of the shock absorber. The overall study research methodology consists of a few phases that correspond to the study research objectives, which are constructing a shock absorber pylon model in SOLIDWORKS environment, performing Design of Experiment (DOE) analysis on the spring of the shock absorber pylon and identifying the significant parameters and optimum setting for the spring of the shock absorber pylon.

**Keywords**: Design of Experiment (DOE), SOLIDWORKS, Finite Element Analysis

## 1. Introduction

An artificial lower limb known as a prosthetic lower limb can substitute a biological lower limb that has been amputated due to an injury or congenital defect. For instance, a person may not be able to move properly if they lost a lower limb in an accident. To go around, one would need to drive while using a cane or a wheelchair. A wheelchair or a walking cane, on the other hand, would not assist the individual in moving independently. It would necessitate the assistance of another person. Prosthetic legs were introduced to help with this situation. The individual would not need to rely on another person to move independently and freely with a prosthetic leg. Numerous companies introduced numerous

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designs of prosthetic legs. Among these designs, various prosthetic legs were created for specific purposes, such as running or exercising, while others were created for general use and walking. [1] This study's primary focus will be the shock absorber pylon because it is crucial to the prosthetic leg's shock absorber's functionality. By doing Design of Experiment (DOE) analysis on the prosthetic leg's mechanism, this study will assist to optimize shock absorber performance.

Furthermore, because it can produce the necessary number of runs to comprehend the behavior of the parameters under study, DOE’s is a well-known technique for planning large-scale studies. Identifying crucial tactics for boosting a system's efficiency is also made easier with DOE. [1] When diverse applied loads produce significant interface pressure and restrict the amputee's maneuverability, most prosthetic patient irritations happen. To guarantee a comfortable ride, the mechanism's functioning must be optimized.

This study research aims to identify the significant parameters and optimum setting for the shock absorber of the Prosthetic Leg. The study research methodology consists of a few phases corresponding to the study research objectives: constructing a Prosthetic Leg model in SOLIDWORKS, performing Design of Experiment (DOE) analysis on the shock absorber, and identifying the significant parameters and optimum setting. This study research is expected to achieve several outputs such as displacement and stress from the three parameters: material, ply angle and ply thickness.

## 2. Materials and Methods

### 2.1 Methods

Figure below shows the process of determining the best setting for each parameter in the shock absorber pylon experiment. The procedure begins with a shock absorber model in SOLIDWORKS 2021. The Minitab software then generates a data collection worksheet based on the parameters set for this experiment: material, ply angle, and ply thickness. Following that, the Design of Experiments (DOE) response will be determined. The Minitab charts are then used to generate data. Various charts will be used to determine the quantitative effect of each parameter. Finally, the best parameter settings for running the FEA for the spring in the shock absorber will be suggested.

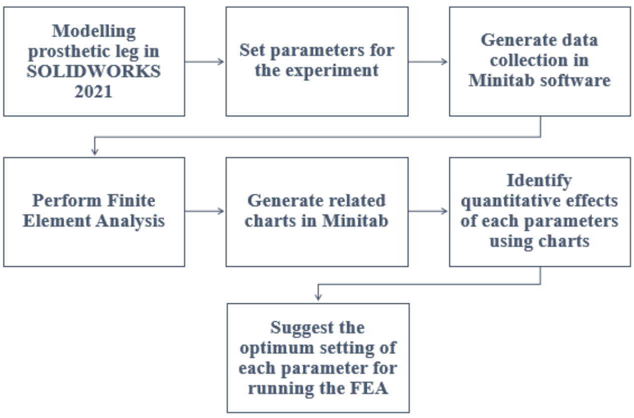


**Figure 1: Workflow of study research**

### 2.2 Materials

The model employed a widely manufactured shock-absorbing pylon design in this analysis. Since the model is similar to a real system, modelling the shock-absorbing pylon with SOLIDWORKS 2021 software aids in evaluating the effect of changes to the system. Figure 2 and 3 shows the SOLIDWORKS 2021-modelled prosthetic leg and shock-absorbing pylon.

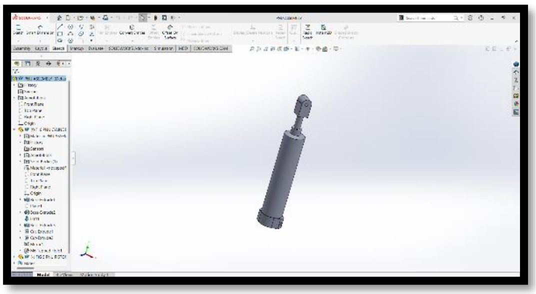

**Figure 2: Shock absorber pylon**

**Figure 3: Prosthetic leg**

2.3 Finite Element Analysis on the spring of shock absorber pylon

SOLIDWORKS Simulation is a collection of analytics software that use FEA to simulate CAD models and predict the physical actions of a product in the real world. FEA uses virtual simulation technology to test how well a product design response to physical effects such as heat, vibration, bending, fluid flow, and other impacts. [5] Using FEA simulation tools, users can analyse designs early in the design cycle, determine what will lead to premature failures, rapidly explore design measures to reduce cost and weight, and determine the product's safety factor. FEA methods for determining the behaviour of parts under load. Pressure, force, temperature, and gravity are all examples of loads. [2] The outcome can be represented by stress, displacement, and strain. Figure 4 below shows the FEA on spring.

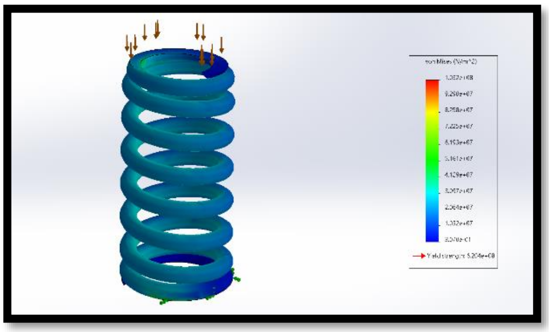

**Figure 4: Finite element analysis on spring**

2.4 Identification of Response for DOE Analysis

The first step in this study is to identify the responses before implementing DOE. The displacement, strain and stress are the responses. The goal function's value is an important aspect of the optimization process, and as stated previously, the lesser the value of the objective function, the greater the result. Table 1 describes the unit for each response.

**Table 1: Example of presenting data using a table**

| No | DOE Response | Unit |
|---|---|---|
| 1 | Displacement | mm |
| 2 | Stress | $N.mm^2$ |

2.5 Identification of Factors for DOE Analysis

The parameters for DOE analysis are stated in Table 2.

**Table 2: List of factors for each DOE analysis**

| Doe Analysis | Analysis Details | |
|---|---|---|
| | Number of parameters | Factor for each DOE analysis |
| Spring of shock absorber pylon parameters | 3 | 1. Materials<br>2. Ply Angles<br>3. Ply Thickness |

The DOE analysis, based on Table 2, helps to clarify the significance of spring parameters for optimizing the performance of the shock absorber spring. Furthermore, this analysis is critical for determining the optimum setting for each spring of shock absorber parameters in order to achieve the lowest objective function value. Decision-makers can calculate a specific parameter's impact on the optimization system's overall performance using the quantitative effect value. The optimal setting for each parameter is recommended in both DOE analyses.

2.5 Performing DOE Analysis using Minitab Software

Minitab 16 is used to conduct the DOE analysis in this study. As a result, this section will outline each step required to complete such a task. To begin, the features that will be used must be selected based on these studies; the features that will be used are DOE. To start a DOE analysis in Minitab, you'll need to create a factorial design. [4]

Minitab is a statistical analysis software tool with many features, as shown in Figure 3.13. The various sorts of DOE analyses are also shown in the diagram. On the other hand, if the count of runs is too large or too expensive to implement, the user can use the Fractional Factorials design. [4] Furthermore, using a fractional factorials design, the count of runs will be significantly reduced, but the results will still be acceptable. This is because the full run provides higher accuracy.

## 3. Results and Discussion

DOE Analysis was done to get the best results for the spring's parameters. The displacement and stress responses will be analyzed. The extent of the force needed to alter the length of a spring-like object is directly proportional to the spring constant and the spring displacement. In addition, stress is a measurement of the maximum yield strength that a material can withstand without deforming. As a result, it aids in the selection of acceptable materials for building based on the requirements.

3.1 Displacement

Figure below shows the Interaction Plot for Displacement. Material code 1 represents aluminium; material 2 is for stainless steel, followed by alloy steel as material 3.

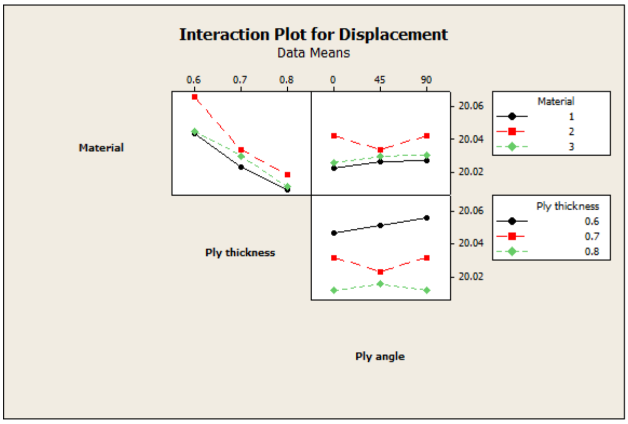


**Figure 5: The interaction plot for displacement**

This interaction plot for displacement in Figure 5 is shown as material vs. ply thickness at the top left. We can observe that as the value of ply thickness decreases, the value of displacement of every material increases. Stainless steel shows the highest displacement in all three values of ply thickness. While aluminium and alloy steel have almost the same value in 0.6 and 0.8, alloy steel has a slightly higher displacement in 0.7 ply thickness.

At top right of the interaction plot shows the displacement for material vs ply angle. Stainless steel shows a high displacement with similar values when the ply angle is set at 0º and 90º. The displacement value of stainless steel in 45º ply angle is lower than 0 and 90º and still manages to get higher than two other materials. Material 3, alloy steel, and material 1 aluminium have almost the same pattern displacement value in all 3 ply angles plotted, but aluminium is slightly lower than alloy steel with decimal differences.

Finally, the bottom plot shows the interaction plot for displacement is ply thickness vs ply angle. Ply thickness 0.6 has the highest displacement among all the other thickness, 0.7 and 0.8. Displacement value of ply thickness of 0.6 increases gradually as the angle increases. Ply thickness of 0.8 stays low in this plot showing the lowest displacement value on 0º and 45º compared to other thicknesses. As for 0.7 ply thickness shows a slight decline in the angle of 45º and increases back same value as 0 at angle of 90º.

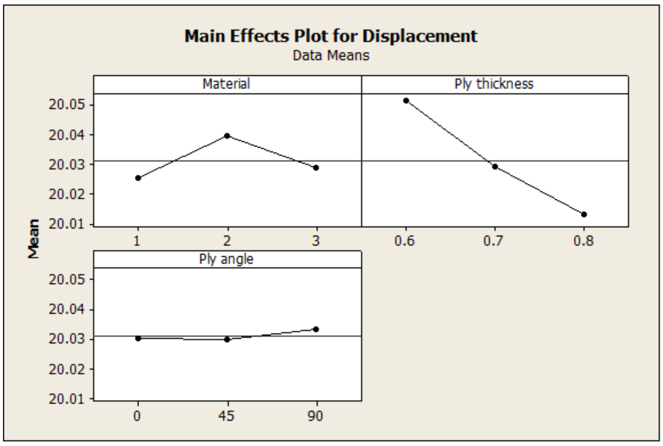


**Figure 6: Main Effects Plot for Displacement**

Figure 6 above shows the main effects plot for displacement. Material 2, stainless steel has the highest displacement value and aluminium has the lowest displacement value. Alloy steel takes the second place by being slightly higher than aluminium. As with ply thickness 0.6 makes sky scraping value of displacement compared to other materials. 0.8 ply thickness has the lowest displacement value. On the other hand, ply angle 0º and 45º have almost equal value of displacement and 90º shows slight increase in displacement. For displacement, the best optimum setting is material 1 aluminium, 0.8 ply thickness and $45^{oo}$ ply angle.

### 3.4 Stress

Figure below shows the Interaction Plot for Stress.

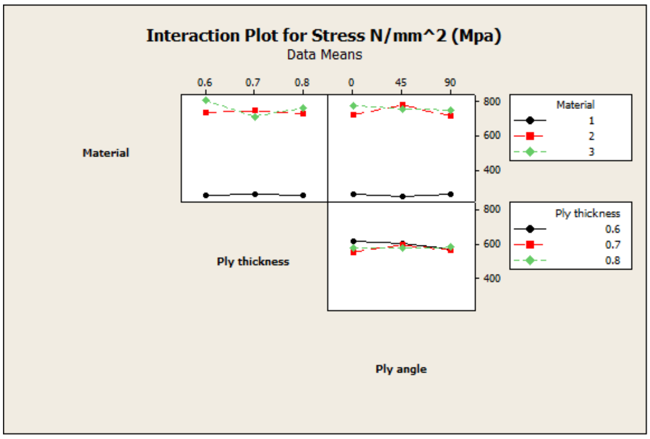


**Figure 7: Interaction Plot for Stress**

From the chart on the top left, we can see that material 1 aluminium has the lowest stress value obtained in every ply thickness set. However, Stainless steel as material 2 and alloy steel as material 3 are on top of the chart. Alloy steel on a thickness of 0.6 has the highest stress value. Stainless steel is slightly lower in stress value at 0.6 and 0.8. At thickness of 0.7, stainless steel's value is substantially higher than alloy steel's stress value. This occurs because a ply contained in a laminate has stronger shear strengths and transverse than a unidirectional ply. According to the graph, stainless steel, and aluminium all have lower stress values than alloy steel.

Top right chart now shows plotted values of materials against ply angle. Here it shows alloy steel has the highest stress value in $0^{o}$ ply angle. At $45^{o}$ angle, stainless steel and alloy steel have nearly the same values. The value of stainless steel drops at $90^{o}$ angle. Even so, aluminium has the lowest stress value compared to the others.

Moving on to the final chart on below express that all the materials have the same behaviour at angle of $45^{o}$ and $90^{o}$. Meanwhile, at $0^{o}$ angle the ply thickness 0.6 over takes the highest stress value over 600 Mpa following with 0.8 and 0.7.

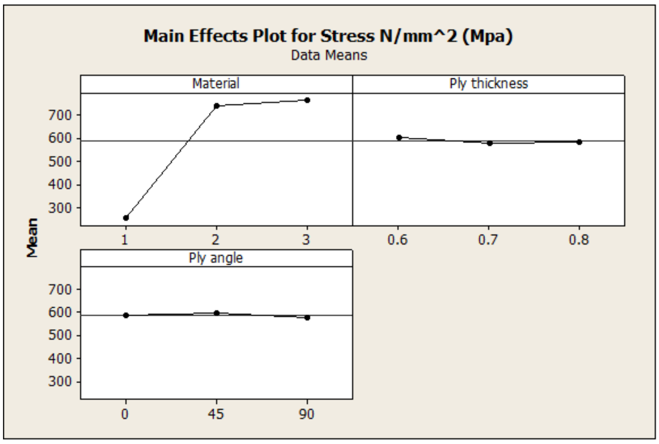


**Figure 8: Main Effects for Stress**

This graph shows the stress values obtained individually. Alloy steel has the highest ability to withstand such stress over 700 MPa. Following that, material 2 stainless steel has the second top spot in the graph with slight decline stress value compared to alloy steel. The ply thickness 0.6 has a slightly higher value by contrast with 0.7 and 0.8 ply thicknesses, which have the same stress value as shown in the graph. Ply angle's graph shows minor fluctuation through all the plotted angles. The angle of 45º has a higher value in decimals compared to the other two angles. In short, the parameters with the best setting are material 3 with ply angles of 45º and 0.6 thickness.

3.5 Results

The result for all the different parameters obtained to justify the displacement can been seen on Table 3.

**Table 3: Results for Displacement**

| Materials | | Ply Thickness | | Ply Angle | |
|---|---|---|---|---|---|
| Aluminium | Lowest | 0.6 | Highest | 0º | Same |
| Stainless steel | High | 0.7 | Low | 45º | Same |
| Alloy steel | Low | 0.8 | Lowest | 90º | High |

Table above shows the summarised result that obtained from the charts to identify the best optimum setting for the spring. Here we can conclude that the aluminium with 0.8 ply thickness following with 45º ply angle has the best displacement value compared to other combinations of parameters. The displacement is the distance between a point's original position and its final location on the distorted model. This set of parameters that has been chosen, performs the lowest displacement on spring which is more than enough on a shock absorber.

**Table 4: Results for Stress**

| Materials | | Ply Thickness | | Ply Angle | |
|---|---|---|---|---|---|
| Aluminium | Lowest | 0.6 | Same | 0 | Same |
| Stainless steel | High | 0.7 | Same | 45º | Same |
| Alloy steel | Highest | 0.8 | Same | 90º | Same |

For stress, the tables above convey the results gained in the observation from graphs. As we see, parameter setting with the combination of alloy steel, ply angle 0º, and ply thickness of 0.8 that been selected as the best setting that can withstand higher value of stress. Stress is a physical term that expresses the internal forces exerted on neighbouring particles of a continuous substance. In addition, strain is a measure of material deformation that is not a physical quantity. Setting with higher stress has stronger yield strength. Continuous motion of shock absorber requires optimum setting that could withstand higher stress value.

## 4. Conclusion

The prosthetic leg and the shock absorber have been drafted in SOLIDWORKS 2021 in order to carry out Design of Experiments (DOE) analysis on the shock absorber's spring. DOE was used to determine the important parameters and the best configuration for the shock absorber's spring. There are two responses that have been studied: displacement and stress, which operate as indicators to determine which materials are appropriate for the shock absorber's spring. From the results tabulated on tables, alloy steel has the lowest displacement effects on spring with ply thickness of 0.8 and ply angle 45º. On the other hand, aluminium with ply thickness of 0.8 and ply angle 0º was the best in value of stress. However, alloy steel has slightly similar value compared to aluminium. Same goes the ply angle 0º and 45º, it does not any bigger difference in both summarized tables. Thus, aluminium with ply thickness of 0.8 and ply angle 45º has concluded as the best optimum setting for this study to optimize the performance of shock absorber's spring. Finite Element Analysis (FEA) modelling and DOE provided an approximation for this complex engineering problem and determined the optimal design for these sorts of shock absorbers of prosthetic legs. It must be remembered that minor errors may have occurred during the implementation of these procedures.

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