Material Analysis on Orthopedic Knee Brace Beams

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***Abstract*—The purpose of this study was to explore various materials to design a beam for a knee brace by evaluating them based on the requirements of being lightweight, cost-friendly and having a high shear modulus. Numerical experiments with Abaqus, a Finite Elements software, was also conducted for 7075 aluminum, 316 stainless steel, and T800 carbon fiber to generate the von mises stress plot and (U) deformation plot for further analysis of the material properties of each candidate. Through the research and numerical experiments, the data was subjected into a decision matrix with the established requirements to evaluate the best material for the beam. T800 carbon fiber scored the highest on the decision matrix and was concluded to be the best suited material for the beam of a knee brace.**

I. Introduction

A knee brace is a tool that manages discomfort in the knee. It reduces pain as it keeps the knee supported to speed up the recovery process and helps individuals move around with more comfort and confidence. It is important to select the best material to create the beam of the knee brace in order to create an effective and long lasting device. Establishing requirements helps evaluate the options based on a standard criteria to ensure the best decision is made.

The purpose of this report was to select the best material for the beam of a knee brace on the basis of three requirements of being lightweight, cost-friendly and having a high shear modulus. Elastic modulus was the first factor in identifying the best material out of the three selections. To prevent as much twisting motion as possible to protect the knee from injury, high modulus was crucial as the material needs to deform as little as possible. With high modulus, the material will deform less compared to other materials with lower modulus if the same stress is applied. Weight was another factor for evaluation. It is important that the material is lightweight to reduce straining the muscle when used for extended periods of time. If the material is heavy, it may injure the patient even more. Cost was the last factor to decide which material was best fit for the knee brace. It is important that many people can have access to health devices, hence reducing the cost by choosing a relatively cheap material will increase accessibility of the device. These requirements define the fitness of purpose for the beam and correlate with important factors for this product such as comfort, durability and effectiveness.

The three materials that were explored for the beam design during this analysis were 7075 aluminum, 316 stainless steel, and T800 carbon fiber. Biocompatibility was identified as the umbrella factor and the basis for the selection of materials for the knee brace beams. As direct skin contact was possible, it was crucial that any material considered for the device did not cause adverse skin reactions, especially after long periods of contact. The first material chosen was 7075 aluminum alloy. Aluminum is a common light metal used frequently in the biomedical field. It has high resistance to corrosion, high workability, relatively cheap price, and is not magnetic. An alloy from the 7000s series was chosen due to its high strength [1]. The second material chosen was 316 stainless steel. It is a type of austenitic stainless steel, which has an FCC structure and is nonmagnetic. They are commonly used for non implanted medical devices, and have the best corrosion resistance out of types of stainless steel [2]. The final material chosen was T800 Carbon Fiber. It is strong in tension, lightweight, and has a very high strength-to-weight ratio [3]. It also has high temperature and chemical resistance. T800 carbon fiber is the strongest out of the T series [4]. The values used for analyzing the other requirements were gathered from online research and looking at material properties from the Total Material database via the UW library. These three materials were then compared using the established requirements to decide the best material to use for the beam of the knee brace.

There are three types of range of motion for the knee joint; flexion/extension, abduction/adduction, and internal/external rotation [5]. Out of these three, only internal/external rotation was assumed to cause “twisting” of the knee. To evaluate the best material for the beam, numerical analyses were conducted to understand in which material the greatest shear stress and deformation are experienced from that internal/external rotation.

Finite element software are a powerful tool that can predict the structural integrity of a product in the real world without having to use resources to create as many real prototypes. Abaqus was used as the finite elements software for conducting numerical experiments in this exploration. This numerical simulation software was chosen based on prior familiarity with it that allowed the analysis to be done more efficiently. Additionally, Abaqus was chosen based on the criteria of its ability to model physics, set model parameters and boundary conditions. After initial research into the different software, Abaqus met all the necessary functionality for this assignment. There was also great documentation on how it defines the quantities and on how to navigate its various functions.

It was predicted that aluminum will be the best material for the beam since it was found from initial research that it is largely used in orthopedic materials due to its low weight, low cost, high strength as well as it being known to be abrasive resistant [6].

II. Results and Discussion

To conduct the numerical analysis, three separate models of the beam were built on Abaqus with the provided measurements of 15 cm in depth, with a 1 cm x 2 cm cross section. Each model was assigned one of the three materials being explored in this assignment. The materials were defined using the material properties in Appendix I**.** Through the free-body diagram in Appendix II, it was established that the force (F) of the leg turning creates a torque at the knee joint. The value for the average torque experienced by a man at a 70 degree knee angle was used for the analysis [7]. The highest average torque was used instead of the highest maximum torque because evaluating a material based on prolonged wear over the most force it can withstand serves as a better criteria in this case of regular use of a knee brace, along with its relation to other factors such as comfort. The average torque at a 70 degree knee angle for men of 280 Nm was used because it indicated the higher end of the spectrum of torque users may experience, thus is a safer parameter to design for [7]. This value was inputted as the load each beam experiences to obtain the von mises stress plot and deformation (U) contour plot. The result was based on the steady-state solution because time was not a variable in the analysis.

From the von mises stress plot, the range of shear stress the beam experiences at different points can be identified (Figures 1, 3, 5). Through the deformation plot, the amount the beam deforms in a particular area is showcased (Figure 2, 4, 6). Each model experiences its range of shear stress and deformation in the same areas along the beam as expected. Although the results of greatest shear stress and deformation between each material were similar, it was found that the aluminum beam experienced the most shear stress and the stainless steel beam deformed the most.

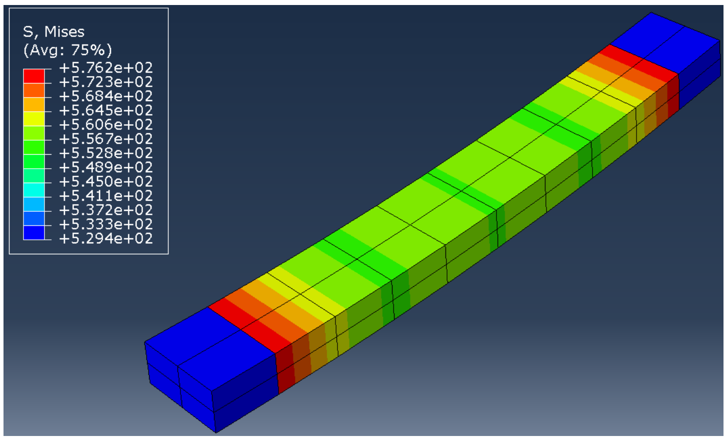

Figure 1: Von mises plot of 7075 Aluminum

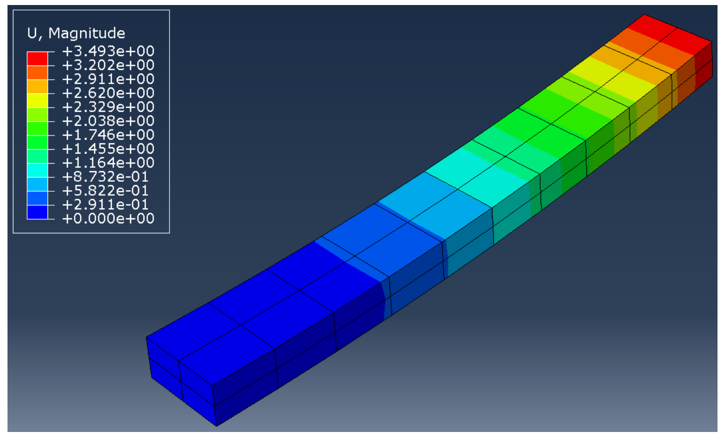

Figure 2: (U) Deformation plot of 7075 Aluminum

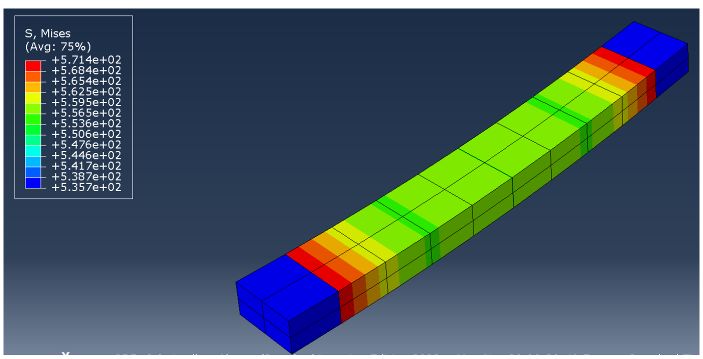

Figure 3: Von mises plot of 361 Stainless Steel

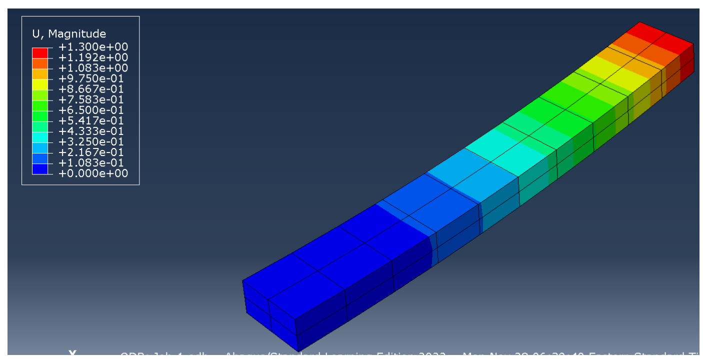

Figure 4: (U) Deformation plot of 361 Stainless Steel

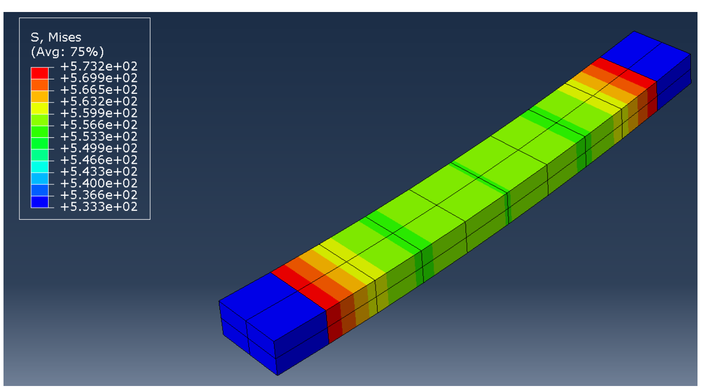

Figure 5: Von mises plot of T800 Carbon Fiber

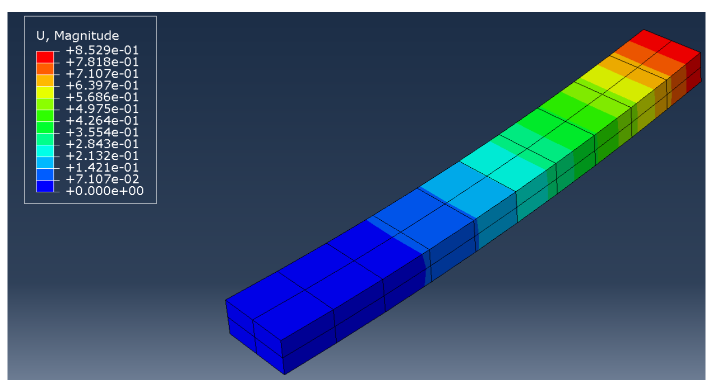

Figure 6: (U) Deformation plot of T800 Carbon Fiber

Table 1: Decision matrix of the requirements fulfilled by each material with the points denoted in brackets (#).

Weight	Requirement	7075 Aluminum	316 Stainless Steel	T800 Carbon Fiber
4	Weight (g/cm^3 of material)	2.81 (2)	7.99 (1)	1.8 (3)
3	Cost (USD/lb)	0.37 (3)	1.16 (2)	7.00 (1)
2	Shear Modulus (GPA)	26.9 (2)	78 (3)	5 (1)
1	Greatest Shear Stress Experienced (N/cm^2)	5.762 (1)	5.714 (3)	5.732 (2)
5	Greatest Deformation Experienced (cm)	3.493 (2)	1.300 (1)	8.529x10^-1 (3)
Total Score		32	24	34

The cost of 7075 Aluminum was obtained from [8]. The cost of 316 Stainless Steel was obtained from [9]. The cost of T800 Carbon Fiber was obtained from [10]. The Shear Modulus of 7075 Aluminum was obtained from [11]. The Shear Modulus of 316 Stainless Steel was obtained from [12]. The Shear Modulus of T800 Carbon Fiber was obtained from [13].

Creating a decision matrix is a systematic way to decide on the best elements of a product during the design process. In this case of deciding materials for the beam of a knee brace, a decision matrix was used to evaluate the “fitness of purpose” of the beam (Table 1). Specifically, the evaluation was done through measuring the fulfillment of the requirements of weight, cost and shear modulus set at the beginning of the project. Each requirement was allotted points on a scale of 1 to 3, 3 being the highest score for that category. The requirements of weight, cost and shear modulus were found through secondary research. Weight measured in grams represents pounds per centimeter cubed of the material. The lower the weight, the higher it scored on a scale of 1 to 3. The cost of each material is written in USD per pound. The greater the cost, the lower the points it received. The shear modulus is the measure of elastic shear stiffness. The higher this constant is, the more the material is able to resist transverse deformation. Hence, the higher the shear modulus constant is of the material, the more points it received. Through the FEA analysis of the beam made from different materials, the highest shear stress the material experiences can be measured. The legend on the left of each von mises stress plot (Figure 1, 3, 5) can be used to obtain the greatest shear stress from the value in red (Table 1). The material that has a higher greatest shear stress, scored lower for this category because it experienced more shear stress compared to the other materials with the same torque applied. The values of the (U) deformation plot were also used (Figure 2, 4, 6) to evaluate how much the material deforms from equilibrium when the same torque is applied to each material option. The greater the maximum deformation value is, the lower the score it received.

Each category was also allocated a weight depending on its importance relative to one another. This way, the scores for the more important requirements would be weighed heavier in the final decision. The greatest deformation the material experiences was set to the most important to prioritize durability. Weight and cost were second and third respectively because comfort is slightly more important than the cost. The shear modulus was fourth because it relates to the deformation the material experiences which was accounted for already. The greatest shear stress the material experiences is last because its results among each material were very similar. The material with the greatest total score can be concluded to be the best choice according to the requirements of weight, cost, shear modulus and ability to withstand the highest shear stress. From the total score on the decision matrix, T800 carbon fiber was established to be the best choice since it received the highest score.

III. Conclusion

The best material for the design of the beam for the knee brace is T800 carbon fiber. It scored the highest in the decision matrix considering the requirements of weight, cost and shear modulus, as well as from the conclusions regarding the greatest shear stress and deformation gathered from the numerical analysis on Abaqus. Looking at it subjectively, carbon fiber is still the best fit. Although it is the most expensive, it experienced the least deformation and is the most lightweight, which correlates with providing more comfort and being better for frequent use. The price is a one time investment while the comfort and durability are not compromised which are more important, especially for an application related to health.

The software used for the analyses shown above was Abaqus. Abaqus was an adequate software to use for this analysis. It did not have any limitations in regards to the necessary functionality for this assignment and can be used for a deeper numerical analysis in the future. An aspect to be mindful of was the units of the values being inputted, as Abaqus does not display the standard units it uses. For instance, it was not known that Abaqus used millimeters when creating a part, hence instead of the generated shear stress being in the standard unit of megapascals (N/mm^2), it was rather in N/cm^2. However, it is noted that although the final unit was not in the expected megapascals, it did not result in unreliable data because the values were being compared hence they just needed to be accurate in terms of being relative to one another.

For future analysis, modifications can be made to the beams analyzed. Instead of only analyzing the lower beam, both the upper and lower beams of the knee brace should be analyzed. This is because each beam would experience different forces due to the three different directions the knee can move in. In the analysis, specific factors such as heat retention can also be considered. Heat retention is an important factor in choosing a material for knee braces due to being able to promote healing and reducing both swelling and pain [14]. A transient state analysis would also be an extension for further analysis to understand how the different beams deform overtime. This analysis can help measure material properties such as fatigue. Setting more material properties as requirements also allows for better analysis in choosing the best material for the beam. Another future consideration is to analyze options of combined materials. Choosing materials made up of different compounds allows for more flexibility and options with cost, strength and durability that can potentially lead to better fulfillment of the chosen requirements, and ultimately a better design.

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Appendix I

Table With Material Properties Used In The Numerical Analysis

Material	**Density (g/cm^3)**	**Young's Modulus (GPA)**	**Poisson's Ratio**
7075 Aluminum	2.81	71.7	0.33
316L Stainless Steel	7.99	193	0.25
T800 Carbon Fiber	1.8	294	0.26

The material properties for 7075 Aluminum were obtained from [11]. The material properties for 316L Stainless Steel were obtained from [15]. The material properties for T800 Carbon Fiber were obtained from [16] and [17].

Appendix II

Free Body Diagram of Lower Beam Under Twisting of Knee