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Material Selection of Below-knee Leg Prosthetics

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Abstract. *The effort to select the best pylon material, part of below-knee leg prosthetic, has been performed. It begins with function analysis to generate design requirement, which concludes that the objective is to select material that gives proper mechanical properties with lowest weigth and cost. Constraint requirements eliminate unsuitable material. Material indices, a scoring function, are derived from objective with respect to a function, and used for ranking material candidates. Ranking from material indices gives top material candidates of woods. Al alloy, Mg alloy, and ferrous alloy. Further seek of documentation is undertaken by failure analysis, value analysis, fabrication, and environmental impact. The final decision is PLA carbon fibre is the best material for pylon of below knee in respect to performance to weigth and cost.* **Keyword:** *Failure Analysis, Leg Prosthetic, Material Index, Material Selection, Value Analysis.*

INTRODUCTION

Amputation not only lowers the capability of physique but also gives mental demotivation or even depression. There are several reasons to undertake amputation, but essentially the aim is to save a life. Technology has delivered a solution for an amputee to aid them in "regain" their missing body part by prosthetic. As replacement of body parts, e.g., limb and leg, prosthetic will experience mechanical load during its application. Thus, the engineer must design and select appropriate materials for the prosthetic.

Below knee amputation, also known as transtibial amputation, is one more minor, severe type of amputation because, in most cases, the amputees are still capable of moving the knee, e.g., rotating and hinging. Nevertheless, the below-knee prosthetic still encounters various mechanical loads. Various types of material have been studied and used for below-knee prosthetics by several trial-error and research [1], [2]. In the previous studies, the material selection usually compares several selected types of material by the mechanical properties to mass ratio [3], [4], and many based on availability and cost due to economical purpose [1], [3], [5], [6].

As an engineer, a generic method of material selection is important, even though each application might already have its own method for selecting material. The reason is generic method can include all potential material and exclude material without a reasonable argument [7]. Michael F. Ashby, in his book "Material Selection in Mechanical Design" [8], has developed generic material selection method for mechanical design, which will be utilized in this study.

Material selection method is undertaken by four steps: translation, screening, ranking, and documentation. By defining function of an application, we can translate it into design requirement of function, constraint, objective, and free variable. Constraints dictate exclusion of incapable material; thus, screening can be done. Objective and free variable can be derived to material index, comparison parameter to rank material. By ranking, we take best three or four candidates to further consideration. Last, we deeply explore the documentation of each candidate, e.g., history, superiority, failure report, etc., before the final material candidate is selected.

In this study, a generic method of material selection is utilized to select the proper material for below-knee leg prosthetics. To limit the scope of this study, pylon, one component of the prosthetic leg, is chosen to be discussed for this article. Several problem-solving analyses, including failure analysis and value engineering, were conducted for additional consideration for the documentation step. The fabrication process is also a consideration for cost purposes. Last, Environmental issues regarding the process and material were discussed.

FUCTION ANALYSIS

Defining Fuction for Application

The purpose of prosthetics is to restore the lost ability of people who undergo amputation. Depend on the body part replace, different types of prosthetics will have different functions. Below the knee, the prosthetic will function as shin and foot, thus bearing load usually carried by shin and foot. Even though a human has two-leg, one leg does not merely bear the load of half-person weight. There is a condition that one leg needs to hold whole body weight, such as walking. When walking, one leg will move forward while the other is behind and stay in the ground; hence, whole body weight will support one leg. In more active movement, e.g., running and jumping, the load can be twice as much. As assurance in some scenarios, a safety factor of two is used. Those considerations yield the specification that a single leg prosthetic must be at least able to take the load of four times the amputee body weight [5].

Bearing load is the primary function of leg prosthetics, and there could be a secondary function that is derived from a specific application. For instance, leg prosthetics for Paralympic athletes need to deliver better force transmission for faster running; thus, affect the design. Aesthetic and ergonomic functions are also considered secondary functions [7].

The below-knee prosthetic is essentially composed of three components, i.e., socket, pylon, and foot (fig. 1a). All parts need to be assembled to fulfill the prosthetic leg function, but each part serves its own distinct function. The socket is part that is directly in touch with the human body, so ergonomic function is dominant in this part, including comfortability and biocompatibility. The foot part directly touches the ground. It delivers the weight force to the ground while delivering normal force in the reverse direction.

Pylon, also known as shin or shank, connects socket and foot (fig. 1b). It delivers forces from two sides, i.e., weight from socket to foot and normal force from foot to socket, so that force resultant of the y-axis is zero. While accomplished, the pylon itself undergoes internal compressive stress. Another function of the pylon is to adjust the length of the whole product because it is one part that can be single-handedly altered in size.

Deriving Critical Criteria

As mentioned in previous subsection, this study will focus on a material selection of one part in the below-knee prosthetic leg, i.e., the pylon, which primary function is to support the compressive load. The length of the pylon will determine the length of the whole product; thus, the pylon's length is restricted to the height of the amputees and the length of the leg lost. The shape of the pylon is dictated as cylindrical, so there will be no sharp edge for safety reasons. It also must not deform, buckle, and break. The aim is to get suitable material with the lowest possible mass and cost. The diameter is free to change. Critical criteria of pylon derived from its requirement summarize in table 1.

SCREENING AND RANKING

Screening Unsuitable Material for Constrain

It has been defined that the compressive load undergoes by pylon is four times the human weight. The average weight in Indonesia is 62,8 kg [9], [10], and the gravitational value of 9,81 m/s2 will be used for weight calculation. Although cross-section area has been stated as a free variable, for initial screening, pylon dimension designed by Murphy, et al. [5], 25 mm diameter, will be used for cross-section calculation. Calculation (1) show a compressive load of 5,02 MPa is expected to be withstood by pylon material. The value may vary since human body weight and cross-section are also various.

$$P = \frac{F}{A} = \frac{4 \times mg}{\pi r^2} = \frac{4(62 \times 9{,}81)}{\pi(12{,}5 \times 10^{-3})^2} = 4{,}956.22 \ \approx \ 5\ MPa \tag{1}$$

To exclude incapable material, the constraint minimum strength of 5 MPa is plot in Fracture toughness - strength diagram (fig. 2). Additional filter of minimum fracture toughness of 5 MPa.m$^{1/2}$ is added since pylon must not break due to rapid crack propagation. It shows that foams, polymers, elastomer, technical and non-technical ceramics are excluded

Defining Material Index to rank Material Ccandidates

Material index is optimization criteria to maximise performance based on combination of material properties [8]. The objective is to minimise mass and cost of pylon. The sample is cylindrical with cross section A, radius of r, and length of L must carry maximum load of F^*. Mass m can be formulated as eq. (2) with ρ is density of material

$$m = A\rho = \pi r^2 L\rho \tag{2}$$

As free variable, radius r is defined from eqution (2) gives:

$$r = \left(\frac{m}{\pi L\rho}\right)^{\frac{1}{2}} \tag{3}$$

Subject to constrain is pylon must not buckle when supporting a load. Equation (4) is second moment is of the cylinder, and the equation (5) is elastic buckling load F_{crit} of the cylinder.

$$I = \frac{\pi r^4}{4} \tag{4}$$

$$F_{crit} = \frac{\pi^2 EI}{L^2} \tag{5}$$

Substituting (4) to (5) will give formula of elastic buckling load with variable of young modulus E, radius, and length in equation (6)

$$F_{crit} = \frac{\pi^3 E r^4}{4L^2} \tag{6}$$

Elastic buckling load must be at least F^*:

$$F_{crit} = \frac{\pi^3 E r^4}{4L^2} \geq F^* \tag{7}$$

Substituting r from (3) to (7) gives:

$$\frac{\pi^3 E\left(\left(\frac{m}{\pi L\rho}\right)^{\frac{1}{2}}\right)^4}{4L^2} \geq F^* \tag{8}$$

Solving (8) to define minimum mass:

$$m \geq \left(\frac{4F^*}{\pi}\right)^{\frac{1}{2}} (L^2) \left[\frac{\rho}{E^{\frac{1}{2}}}\right] \quad (9)$$

At the right side of equation (9) first bracket defines the specified load, the second bracket defines specified geometry, and the last (square) bracket is material properties. Since the objective is to minimize mass, the material property is inverted, thus give a material index (10). Subscript 1 means first material index.

$$M_1 = \frac{E^{\frac{1}{2}}}{\rho} \quad (10)$$

The second objective is to minimise cost C. Formula of cost material:

$$C = m\, C_m = AL\rho\, C_m \quad (11)$$

where C_m is cost-per-kg material. by solving C definition from equation (11) to equation (9) gives:

$$C \geq \left(\frac{4F^*}{\pi}\right)^{\frac{1}{2}} (L^2) \left[\frac{\rho C_m}{E^{\frac{1}{2}}}\right] \quad (12)$$

Like equation (9), bracket at the right side of equation is specified load, specified geometry, and material properties, respectively. To obtain minimum cost, the material property is inverted to be the second material index equation (13).

$$M_2 = \frac{E^{\frac{1}{2}}}{\rho C_m} \quad (13)$$

Both material indices, $M_1$and M_2, are used to rank material candidates. Young's modulus to density ($E - \rho$) chart is needed for the first material index and Young's modulus to material cost is needed for the second material index. In the $E - \rho$ chart, a guideline with slope of 2 is replotted to the left side (with the same slope) to the value of $M_1 = 2\ GPa^{\frac{1}{2}}/(Mg/m^3)$. Note that the unit is Mega gram (Mg) instead of kilogram (Kg) for a simpler number. Materials in the area of top-left side indicate $M_1 > 2$, hence are in the search region (fig. 3a), while the darkened area is area of excluded materials. Similar work was also performed for $M_2$to Young's modulus to cost-per-volume ($E - C_{v,R}$) chart. Even though C_m is the one that present in M_2, utilization of $E - C_{v,R}$ chart makes no difference. Guideline replotted to the value of $M_2 = 2\ GPa^{\frac{1}{2}}$. The search region indicates $M_2 > 2$ while the darkened region is for excluded materials.

Materials that included in search region of both $E - \rho$ chart (fig. 3a) and $E - C_{v,R}$ chart (fig. 3b) are listed in table 2 from highest M_1 to smallest. Some materials may show in search region in $E - \rho$ chart, but not in $E - C_{v,R}$ chart, and vice versa. It means that those materials only satisfied one of two material indices, thus eliminated from the selection. For instance, composite family of material has excellent modulus to mass ratio to satisfied M_1. But the modulus to price ratio does not satisfy M_2, thus composite family eliminated from selection. Identical but inverted case also happen to zinc alloy. Some materials of foam and ceramic family achieve both M_1 and M_2, but still eliminated because do not meet the constraint criteria (fig. 2).

Wood // grain has highest value of both material indices, suggesting that it is the best material for the minimum weight and cost ratio to the performance. Ferrous metals are great in price-performance ratio, but poor in weight-performance ratio; except stainless steel, which poor in both material indices. The rank dictated by material indices will not lead straight to the final decision. The next step is deeply seeking documentation for consideration.

RELATED PROBLEM SOLVING ANALYSIS

Failure Analysis

The type of failure that occurs in applying pylon is commonly mechanical failure since the utilization of leg prosthetic in ordinary living environment, i.e., not in extreme temperature or chemical exposed condition. Even though some amputees might have the extreme application of prosthetics, e.g., athlete, rock climber, they use a unique design of prosthetic, which cannot be bound to cost limit. Whereas the prosthetic we discuss in this study is one that utilizes for regular daily life activity.

Pylon of leg prosthetic does not experience stress continuously, even like any other structural tube. Because when human walk, the load will consecutively move from one leg to the other, which generate cyclic load. To these factors, high cycle fatigue fracture tends to occur to the pylon [11], [12].

Stress that is experienced by pylon is un-uniform. Even in one leg itself, the load is not evenly distributed because the leg orientation is not perpendicular to the ground when walking (fig. 4), thus generate stress concentration [2].

The solution for this problem is design adjustment instead of material shift. Lee & Zhang [11] report that a foot bolt adaptor to connect pylon to the foot part affects the fatigue strength of the product significantly. By the addition of distal flange to elliptical foot bolt adaptor, the product fatigue life improved from failure before reaching 20.000 cycles to withstand 500.000 cycles without visual necking.

Value Analysis

Value analysis is helpful to assess the value of a product by referencing the cheapest and/or viable product with the same capability to do the function. Selecting cheaper materials is not always the answer; more expensive material can be cheaper if the material needed is less [13]. Both objectives of the design, reducing mass and reducing cost, are in line with value improvement as less weight of material needed means less material cost. We analyze pylon design to achieve less mass and cost. Re-designing effort can be a breakthrough to generate lower costs while maintaining the function. We redesign the solid cylindrical pylon into a hollow tubular shape (fig.5).

From cross-section area (14) and second moment of area (15) of the hollow tube, radius r can be defined as (16). With r as outter radius and t as thickness.

$$A = 2\pi r t \tag{14}$$

$$I = \pi r^3 t \tag{15}$$

$$r = \left(\frac{2I}{A}\right)^{\frac{1}{2}} \tag{16}$$

Plot of r in four quadrant diagram, which consists of: a modulus-density, modulus-second moment of area, section area-density, and section area-second moment of area, shows that slimness and weight are interchangeably [8]. By using a hollow design, will yield less weight, but it requires a bigger radius to withstand the load, thus resulting in a less slim size. As slimness is no object that is concerned in this study, the redesign of pylon will be used to minimize mass and cost.

Materials based polymer has unique combination of low processing temperature and great mechanical properties especially when a fiber was added [14], [15]. PLA carbon fiber is lightweight and cheap material with excellent mechanical properties. A recent study reported by Tahir & Kadhim [16] shows that PLA carbon fiber can be material for prosthetic leg pylon, concluded from several tests, including tensile test, fatigue test, and finite element analysis. Not only reduce the weight of the final product, but utilization of PLA carbon fiber also significantly reduces the total cost of the pylon (table 3). PLA carbon fiber will be included in material candidates for the pylon.

FABRICATION PROCESS

The hollow tube is a square shape that many processes can be fabricated depending on the base material. Each material may have a different method of fabrication. Casting, powder metallurgy, and molding are standard practices to fabricate hollow 3D dimensions for the candidate of metals family, i.e., Mg, Al, and ferrous alloys [13]. Each method can deliver different properties even though the material composition is the same. Unique characteristics of powder metallurgy are controlled porosity of the product, and they can deliver net shape product. Hence no machining is needed. While in casting, machining is commonly performed for finishing, and the property of the product depends highly on the solidification process [17].

In contrast to metal, the only way to shape woods is by machining, i.e., cutting, drilling, grinding, etc., which is cheaper since it does not require energy for heating. However, due to shaping by carving, the loss of material is most severe in wood shaping. Wood dust is common to waste in fabricating wood. In the fabrication of wood, one must carefully pay attention to the direction of the grain. Wood strength is maximum in parallel to grain direction and minimum in perpendicular direction. Wood types and age also affect properties significantly. The skill requirement of a woodworker is high, especially the design of wood shaping restricted by mechanical properties. These factors cause wood to be less favorable and slowly abandoned for commercial pylon use. Conventional woodworkers still can be found, but the number is decreasing along the period.

For shaping PLA carbon fiber, additive manufacturing of 3D printing has been used. 3D printing can obtain a net shape product with the desired dimension accurately, even for complex shapes. It also can obtain high-quality and straightforward manufacturing at a low cost compared to the other methods of pylon fabrication [16].

ENVIRONMENTAL ISSUE

Leg prosthetic is a nonpower-consuming class of product, which mean that the application of (conventional) leg prosthetic does not require energy, except human effort. Energy consumption is defined as a measure of input needed and waste generated from material, manufacture, transportation, and use of a product [8]. Energy consumption of leg prosthetics lies in the material production and product manufacturing phase. Thus, those phases are the targets to achieve significant differences for environmental objectives.

In the material production phase, energy consumed to make one kilogram of material (embodied energy) and side product of gas associated with one kilogram of material production (undesired gas emission) are variable for comparison. Table 4 shows embodied energy and CO_2 emission of each material candidate of the pylon.

Mg and Al alloys are on the top of the list due to high embodied energy and CO_2 emission. Ferrous alloy is significantly lower. As a natural material, Wood is renewable material which demand little energy for production. Wood is also easy to recycle [13]. PLA carbon fibre initially has high embodied energy and CO_2 emission of up to 200Mj/kg and 25 kg/kg for virgin carbon fibre fabrication. Recent development of carbon fibre can reduce embodied energy to 0,3-2 Mj/kg and CO_2 emission to 4,4 kg/kg [18].

Material processing energy can be estimated from the processing method. Metal family can be processed by casting, powder metallurgy, and moulding to create pylon. Those method required high energy for melting and deforming. Wood is the least energy consume of processing. Only require energy for machining that even human can do independently. PLA carbon fibre utilize 3D printing additive manufacturing. This method requires less energy and cost [16].

CONCLUSION

Generic method for material selection is basic material selection process throughout systematic and coherent steps of function translation, screening, ranking, and documentation. By this method, all types of material will initially include in the selection. Hence no potential material is missed. This study has performed material selection to select the best material for the knee below leg prosthetic part, pylon. The main objective of the selection is to select materials whose mechanical properties are suitable for the application with the lowest possible weight and cost. The result is that PLA carbon fiber, manufactured by 3D printing, is the best candidate for the job; this will be the material recommendation for pylon of leg prosthetic.

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