Modeling and Analysis of a Cycling Prosthetic

John Tolentino, Yong Seok Park

***Abstract*—** There are currently many people living with limb loss in the USA. The main causes for amputation can range from vascular disease, to trauma, or cancer. This number is expected increase over the next decade. Many patients have a single prosthetic for the first year but end up getting a second one to accommodate their changing physique. Afterwards, the prosthesis gets replaced every three to five years depending on how often it is used. This could cost the patient up to $500,000 throughout their lifetime. Complications do not end there, however. Due to the absence of nerves, it becomes more difficult to traverse terrain with a prosthetic. Moving on an incline or decline becomes difficult, thus curbs and stairs can be a challenge. Certain physical activities, such as cycling, could be even more strenuous. It will need to be relearned to accommodate for the change in weight, center of gravity, and transfer of energy from the leg to the pedal. The purpose of this research project is to develop a new, alternate below-knee cycling prosthetic using Dieter & Schmidt's design process approach. It will be subjected to fatigue analysis under dynamic loading to observe the limitations as well as the strengths and weaknesses of the prosthetic. Benchmark comparisons will be made between existing prosthetics and the proposed one, examining the benefits and disadvantages. The resulting prosthetic will be 3D printed using acrylonitrile butadiene styrene (ABS) or polycarbonate (PC) plastic.

***Keywords*—**3D printing, cycling, prosthetic design, synthetic design.

I. Introduction

WITH the advancement of additive manufacturing, it has become easier to create complex shapes and structures. A custom-built prosthetic that could take a couple months can be made in just a fraction of that time. This grants amputees more options in selecting a prosthetic and even being able to choose one appropriate for the situation. Although a general prosthetic will suffice for cycling, the amputee may want one specifically for that activity that is more efficient. For competitive uses, a cycling-specific prosthetic provides aerodynamic as well as energy efficient advantages. The objective for this study is to develop a below-knee cycling prosthetic that is available at a lower monetary cost. The design will be bio-inspired and easier to manufacture via 3-D printing.

II. Literature Review

The goal of this project is to model and develop a below-knee cycling prosthetic. It is important to understand the biomechanics of cycling, the processes behind creating a prosthetic, and the design theory involved in this study.

Yong Seok Park is Assist. Prof. Dr. with Department of Mechanical Engineering, California State University, Fullerton. USA. (corresponding author, e-mail: pysilove@gmail.com)

A. Biomechanics of Cycling

The pedal stroke can be separated into four equal and distinct quadrants; top, power, bottom, and recovery. The top of the pedal stroke is from angles 315° to 45°, where 0° is located at top dead center of the bicycle crank. From a portrait view, the crank travels in a clockwise direction. Transitioning from the top to power quadrant, requires an application of force to the pedal in the forward direction.

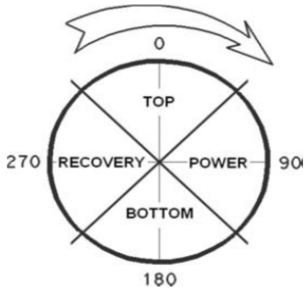

Fig. 1 The Four Quadrants of the Pedal Stroke [6]

The power phase of the cycle is located from 45° to 135° and requires that the body produces enough force to overcome both the resistance at the pedal as well as aid in lifting the opposite leg that is in the recovery phase. The cyclist exerts about 90% of the total power that is applied to the bicycle. The muscles recruited to employ the power mostly come from the gluteus maximus and quadriceps. Similarly, to the top phase, the bottom phase is a transitional point where the leg can stabilize itself and prepare for the recovery phase. It is located from 135° to 225°.

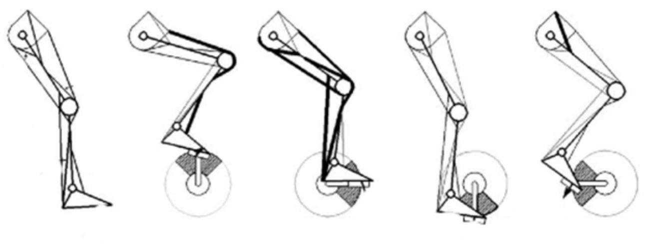

Fig. 2 The Major Limbs Involved during the Pedal Stroke [6]

As the name implies, the recovery phase is when the crank is located from 225° to 315°. During this time, most of the muscles are at rest while the opposite leg is in the power phase. With this approach, most muscles are recruited during the top, power, and bottom phase, where the power phase requires 90% of the total power. However, there is an alternative approach to revolving the crank. This method involves changing the approach to the recovery phase. Instead of allowing the foot to be lifted from the power phase of the opposite foot, the cyclist will pull the foot upwards, reducing the amount of energy needed for the opposite foot to push down in the power phase. Although this method is efficient in mechanical effectiveness, it puts higher strain on metabolic demand, requiring the leg in the recovery phase to increase muscular activity. For amputees, the "pull up" method has a physical restriction in that it will risk ejection of the residual limb from the prosthetic.

B. Calculating Pedal Force

Pedal force is the force that is applied to the pedal to overcome resistive forces and propel the bicycle forward. This number is important because this will be the largest force that the prosthetic is subjected to. This study will explore the stresses that occurs from this force as well as the fatigue life of each prosthetic.

To calculate the pedal force, consider the following.

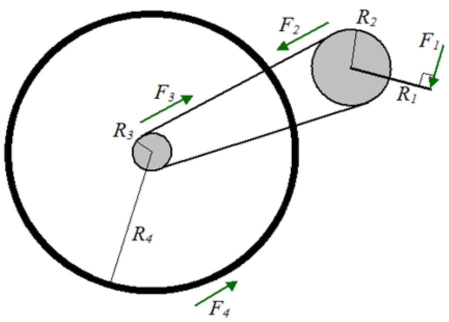

Fig. 3 Pedal Force Calculation Required to Move Bicycle [3]

TABLE I
PEDAL FORCE CALCULATIONS

Variable	Unit	Value	Description
r_1	m	0.12	Length from pedal to center crank
r_2	m	0.10	Radius of main crank (big)
r_3	m	0.07	Radius of rear crank (max)
r_4	m	0.62	Radius of wheel
F_1	N	656.76	Force applied at pedal
F_2	N	736.36	Force occurring at main crank
F_3	N	736.36	Force occurring at rear crank
F_4	N	82.69	Force occurring at surface of tire
C_S	n/a	0.00	Coefficient for sliding friction
C_d	n/a	0.88	Coefficient for aerodynamic drag
A	m^2	0.36	Front area of bike & cyclist
V	m/s	5.36	Velocity of cyclist
ρ	kg/m^3	1.23	air density @ STP
g	m/s^2	9.81	gravity
θ	degrees	0.10	angle of incline
m_1	kg	67.98	mass of cyclist
m_2	kg	7.37	mass of bicycle
m_{total}	kg	75.35	total mass
w	N	739.19	weight

A. Creation and Components of a Prosthetic

The main parts of a below-knee prosthetic are as follows; Liner, socket, pylon, and foot. To ensure a snug fit between the socket and residual limb, a medium is used. The liner can be made of several materials such as silicone, polyurethane, or copolymer. The material can depend on the purpose of the prosthetic as well as the amputee's skin type.

In general, a silicone liner has good adhesion to skin and is used if the limb has a lot of soft tissue. The liner usually features a shuttle lock suspension, meaning that there is a pin at the bottom end of the liner which inserts into a locking mechanism at the bottom of the socket, ensuring a firm connection between the two. Silicone liners are durable, easy to clean and soft. It is used for individuals with low to moderate activity level.

Polyurethane is a softer material that can conform to the contours of the residual limb. This allows for greater distribution of the forces along the limb. This material is the choice for sensitive, bony or scarred residual limbs. It is also recommended for individuals with low to high activity levels.

Lastly, copolymers are soft and highly elastic. It is preferred for amputees with dry skin, as it is lined with oil. Copolymer liners have special characteristics in that they contain antibacterial additives, non-stick treatments, and variable thicknesses to accommodate sensitive skin. It is recommended for individuals with low activity level.

The purpose of the socket is the main interface between the residual limb and prosthetic. Therefore, it is imperative that a snug but comfortable fit is maintained to ensure that the prosthetic is properly used.

The general practice for how a socket is made is that the prosthetist measures the residual limb using a plaster bandage for casting. After the cast is dry, it is separated from the stump and is filled with plaster powder to create a positive mold. The positive mold is then shaved and modified to ensure an optimal socket fit. In some cases, a temporary socket is manufactured before creating the definitive socket. The purpose of this transparent, temporary socket is to check if the residual limb properly fits. The downside to this process is that it is largely time consuming and laborious, usually requiring multiple visits to the prosthetist. Recent technology, however, has provided a faster and efficient alternative to this process.

3D scanning is a process where an object is analyzed using a medium to attain information about the size and color of an object. The data is then used to construct a digital 3D model for use. The characteristics and limitations of a 3D scanner depend largely on the technology being used. In this case, the prosthetist will scan the residual limb of the amputee, creating a digital 3D model of the stump. The 3D model can then be used to create a socket, where it can be tested for optimal fit. After the testing is completed, it can be fabricated using a 3D printer or other manufacturing method. The pylon is the connection between the socket and foot. It is adjusted to accommodate for the amputee's height and gait. The foot is the base at which the amputee uses to traverse.

Fig. 4 Basic Parts of a Prosthetic [4]

III. Design Methodology

A. Problem Definition

The problem definition is that there is a demand for a premium below-knee prosthetic. The objectives for this design are to create a below-knee cycling prosthetic, under certain criteria and constraints. The specific criterion is that the prosthetic must be able to withstand the forces subjected by an average male cyclist.

B. Conceptual Design

The functions, constraints, and criteria were converted into customer requirements and engineering characteristics. Customer requirements may not always be a measurable, tangible requirement. In this instance, the engineer is required to transform the requirements into an engineering characteristic. An engineering characteristic is a measurable requirement that can be controlled and changed through design. This way, there is a defined method to determine if the requirement was met.

To find the most important engineering characteristic, the customer requirements and engineering characteristics were placed into a house of quality (HOQ) chart. The customer requirements are listed as the vertical components, and the engineering characteristics are on the horizontal components. Then, a weighting factor is given to all customer requirements, based on how highly prioritized it needs to be considered. The customer requirements were then compared to the engineering characteristics and were given a value depending on how strongly they affected each other. Afterwards, the engineering characteristics were compared to each other to observe if they were positively or negatively correlated. The value with the highest importance is cost. This helps to determine what engineering characteristics should be considered when designing.

C. Design Parameters

The subject of the study is a male that weighs 68 kilograms, with a height of 177.8 centimeters. The amputation occurs on the right leg, at 15.24 centimeters from the medial joint line, or 25.4 centimeters from the ground. The medial joint line is the point where the femur meets the tibula, at the knee.

The bicycle being used in this study is a 2016 Cervélo S3 Ultegra Black & Red, size 51. It weighs 7.37 kilograms, with a crank radius of 0.1048 meters and rear crank radius of 0.0698 meters. The size of the tires is 700c x 25mm.

To create a model of the residual limb, a 3D scanning software was used. Occipital is a spatial computing company that utilizes the XBOX Kinect's cameras as a 3D scanner through their program called, "Skanect". Although they do have other products and software, this had the cheapest cost as the Kinect was already in possession and Skanect is free.

As mentioned before, 3D scanning can serve as a replacement for the traditional cast, mold, and rectification system for a prosthetic. The subject's full leg was scanned using Skanect cleaned, smoothed, and trimmed using Meshmixer.

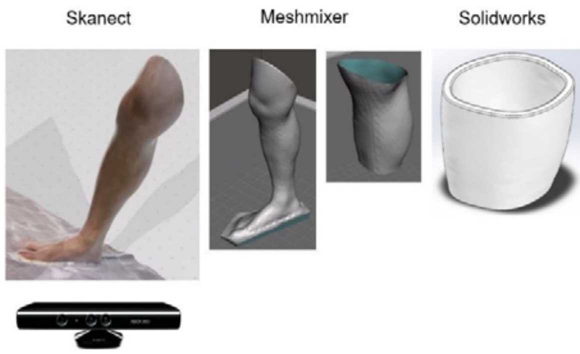

Fig. 5 Scan of Client's Leg and modeling of Unique Socket

Once trimmed, the 3D model of the leg would need to become a residual limb. For below-knee amputations, ideal bone length is between 12cm to 17cm measured from the medial joint line. The medial joint line is the line where the tibia and femur come into contact. Any length below 5cm can compromise the function of a prosthetic. Now that a stump has been created, the fitting for a socket can now be made.

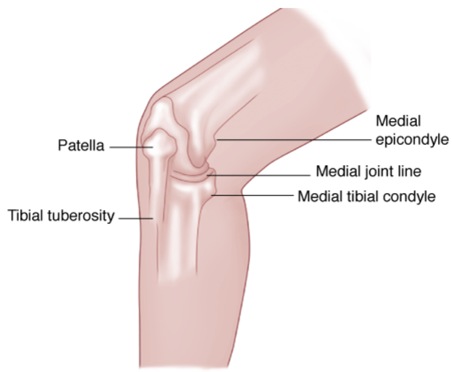

Fig. 6 Medial Joint Line Location [5]

The model of the stump was imported to SolidWorks as a solid body. Measurements of the stump were taken, and the socket was offset 0.2 m to accommodate for the socket liner. The thickness was determined from the average thickness of socket liners that are readily available [2]. It should be noted, however, that the thickness will vary at different areas of the residual limb based on comfort and use. This socket model will be consistent throughout all three designs.

The foot of this design will also be consistent throughout all three designs. The main function of the foot, in this case, is that it needs to be the interface between the pylon and cycling pedal. Since these prosthetics are design specifically for cycling, there will not be a strong emphasis on walking, though the user will still be able to walk. In order to get the most efficient energy transfer between the cyclist and the bicycle, a special type of bike pedal is used.

There are various other designs for clip in pedals, but this specific pedal was chosen due to having a sample of the pedals for measurements. Fig. 7 is a Speedplay pedal, and it is used by road cyclists to have a firm connection with the pedal. To connect the unit, apply a force perpendicular to the pedal using the cleat. While connected, there is very little room for movement between the cleat and pedal. To disconnect the unit, simply twist the cleat towards the bike; for the right foot, counter-clockwise, and clockwise for the left foot.

The size of the foot is designed to completely accommodate the cleat. It also has four cleat fastening screws that ensure a firm attachment between the cycling cleat and the foot. The height of the foot is designed to accept the length of the screw as well.

Fig. 7 Speedplay Pedal Adapter and Cleat

D. Design 1: Biomimicry

The first design is inspired from biomimicry, the production of an artifact based on biological entities or processes. There are two major forces that the cyclist will have to overcome that dictate the design of these prosthesis. The first being the pedal force that the cyclist places the prosthetic under to push the bicycle forward. The second is aerodynamic drag.

The first being the pedal force required to push the bicycle forward. The prosthetic will act as the medium between the pedal and the cyclist. Thus, the prosthetic will be exposed to compressive forces.

There are numerous studies that validate the use of biomimicry for designing. Another example of biomimicry is the Shinkansen bullet train in Japan. It is one of the fastest trains in the world and mimics the biological features of birds.

This conceptual design aims to mimics the features from the fastest land animal in the world, the cheetah. Because of this high pace, the cheetah is subjected to large dynamic forces. Their bodies must be able to withstand these forces regularly.

To design the pylon a cheetah model was obtained, and the hind leg was utilized as the basis. The hind leg, as opposed to the front legs, are responsible for propelling them forward. Similarly, a cyclist's leg shares the same function. After the leg of the cheetah was trimmed to the required height, the standard socket and base were added. To connect the assembly, a boundary boss was used. The result is shown in Fig. 9.

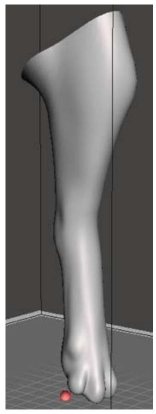

Fig. 8 Trimmed Model of Cheetah leg

Fig. 9 Prosthetic inspired by biomimicry

E. Design 2: Aerodynamic

The second design puts a heavier emphasis on reducing aerodynamic drag. To accomplish this, the design was based on the National Advisory Committee for Aeronautics (NACA) airfoils database [1]. To determine which airfoil would be acceptable for this design, the minimum required area to prevent buckling was found. The minimum area then drove the selection for airfoils. For example, the minimum area for ABS was found for be 0.315cm^2. Consequently, the selected airfoils were chosen to be NACA-0015 and NACA-0024, with a drag coefficient of 0.03 and 0.06, respectively.

The two airfoils were chosen instead of a single airfoil for cosmetic purposes. It would be more aerodynamically efficient, however, if the NACA-0015 was solely used, due to the lower drag coefficient.

Afterwards, the plot was exported as a .dat file and imported into SolidWorks for further design. The dimensions obtained for the airfoil will be used to create the pylon portion of the prosthetic. The socket and base were added into the assembly and were connected to the pylon by utilizing the boundary boss feature. The airfoil concept design is shown in Fig. 11.

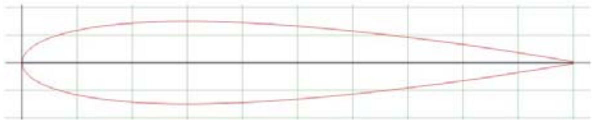

Fig. 10 NACA-0015 Airfoil

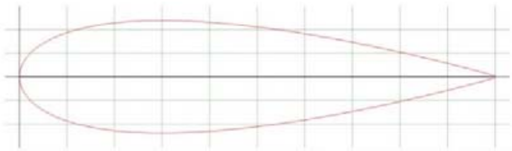

Fig. 11 NACA-0024 Airfoil

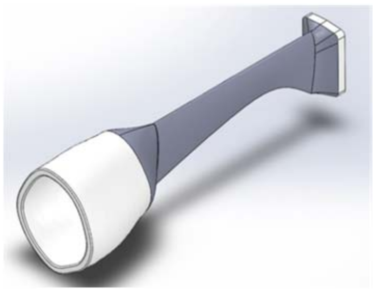

Fig. 12 Prosthetic based on an airfoil

IV. Embodiment Design

Embodiment design is the part of the design process where the design is developed in accordance with the technical and economic criteria. With the two concept designs, the socket and base are customized depending on the measurements of the residual limb and the type of pedal being used, respectively

A. Material Selection

Three materials were selected for this study, ABS, PC, carbon fiber (CF), and titanium. Each material was based on various factors such as availability, cost, weight, material strength, and ability to be 3D printed [7], [8]. All three selected materials are able to be printed, but within certain requirements.

ABS-PC is one of the strongest plastic filaments that is available for 3D printing. It is a mixture of ABS and PC plastics. It is available amongst many suppliers and the material properties may differ depending on the mixture ratio. This study uses a Raise N2 3D printer as well as their PC filament. It costs $49.99 for a 1kg spool and has a melting temperature of 260 °C and high heat resistance. This makes the material a good candidate for the outdoor conditions that the prosthetic will be subjected to while cycling. Compared to the other two materials, PC is more accessible.

The second material, carbon fiber, is used widely in the cycling industry. It is recognized for its high tensile strength and is lightweight. These favorable characteristics come at an expensive price, however. A single spool of carbon fiber infused filament is $450 for a 0.5kg spool. Although there are cheaper spools of carbon fiber filament available, the ratio of polylactic acid (PLA) to carbon fiber is significantly higher. This specific spool is for aerospace grade performance and has an extruder temperature of 360 °C to 390 °C and bed temperature of 120 °C. Additionally, there are supplementary requirements to be able to 3D print with carbon fiber. The printer must have a hardened steel nozzle and the printing speed must be slowed by 30%. This is to prevent the print from failing. The last material, titanium, is used commonly for prosthetics and implants.

B. Loading Conditions

The two designs were subjected to four studies; Static loading, factor of safety analysis, dynamic loading, and fatigue analysis. The static loading condition has a 660N pedal force being applied from the inside of the socket that is normal to the ground. There is also a fixed geometry placed at the bottom of the base to replicate the prosthetic being connected to the pedal, as shown in Fig. 12. This analysis will serve as the basis for the rest of the simulations.

Fig. 13 Loading conditions for prosthesis

The factor of safety can be obtained from the results of the static loading study. It will display a heat map distribution, where it changes color depending on the value. The dynamic loading conditions assume a sinusoidal load in a one second window. The forces applied to a bicycle can be most similar to a sinusoidal load, where the maximum amplitude is located in the power phase of the cycling quadrants. The fatigue analysis is based on the modified Goodman criteria.

V. Developments

Tables II A and B display the results of all the studies. The static stress is uniform across all materials because material does not affect the loading conditions. Factor of safety, however, is heavily affected by material. As expected, the airfoil made in PC has the lowest factor of safety amongst all designs. Although it is low, it is still an acceptable number, and is a good indicator for fatigue life.

The results from dynamic loading are similar to static loading because the prosthetics are subjected to the same load over time. This further validates the background study done to find the pedal force.

Cost analysis was also done to compare the efficiency for both designs as well as materials. The weights of all designs were obtained from the Solidworks properties feature, and the costs of material were derived off of quotes from 3D printing suppliers. The filament required was obtained from Raise 3D's ideamaker software, it is responsible for creating the g-code required to print the prosthetic. The cost of the spools was from several vendors. The PC was obtained from Raise 3D, at $50/kg, while carbon fiber was obtained from 3Dxtech, at $450/ 500g. Although other carbon fiber filament was available, they had a lower mixture ratio of carbon fiber to PLA. Lastly, titanium requires a specialized manufacturer to handle the material. Therefore, a quote was obtained for both designs. Note, the costs reflected are for material costs only, and do not include post processing or initial costs. Therefore, carbon fiber and titanium can be significantly more expensive than what is currently shown.

TABLE II A
DESIGN ANALYSIS RESULTS

	Material	Static (VM Stress)	Factor of Safety	Dynamic Loading
Airfoil	*PC*	Max: 16.8 MPa	4.07	Max: 16.8 MPa
		Min: 166.9 Pa		Min: 166.9 Pa
	CF	Max: 16.8 MPa	70000	Max: 16.8 MPa
		Min: 169.3 Pa		Min: 169.3 Pa
	Titanium	Max: 16.8 MPa	49	Max: 16.8 MPa
		Min: 160.2 Pa		Min: 160.2 Pa
Bio-Inspired	*PC*	Max: 1.8 MPa	37.97	Max: 1.793 Mpa
		Min: 190.2 Pa		Min: 200 Pa
	CF	Max: 1.8 MPa	6.93E+05	Max: 1.793 Mpa
		Min: 169 Pa		Min: 200 Pa
	Titanium	Max: 1.8 MPa	459	Max: 1.793 Mpa
		Min: 154.4 Pa		Min: 200 Pa

TABLE II B
DESIGN FINAL PRODUCT ANALYSIS

	Material	Fatigue Life	Weight	Cost
Airfoil	*PC*	1.00E+06	1.11 lbs	$8.83
	CF	1.00E+06	1.85 lbs	$158.40
	Titanium	4.00E+07	4.61 lbs	$2,000
Bio-Inspired	*PC*	1.00E+06	1.60 lbs	$10.83
	CF	1.00E+06	2.66 lbs	$195.30
	Titanium	4.00E+07	6.62 lbs	$2,100

VI. FUTURE STUDY

There are various studies that can be done for future examinations. One possible study is fluid dynamic analysis for both prostheses. This way, a comparison can be made between how much aerodynamic drag affects both prostheses. It will also determine how effective the airfoil design is when considering drag. Second, optimization methods can be applied to the prosthesis to further reduce the materials required. This reduction in material will be reflected in the cost to manufacture the prosthetic. Finally, the loading conditions can be changed where the cyclist is in different positions. In this study, the cyclist was assumed to be sitting on the seat. However, if the cyclist is standing then the pedal force as well as frontal area for air drag changes as well.

VII. CONCLUSIONS

By utilizing design methods, the cost of producing a prosthetic was reduced. The designs were validated and can withstand a 660N pedal force for at least 1E+06 cycles. Additionally, the design inspired by biomimicry can sustain higher compressive forces, while the airfoil design is more aerodynamic. There can be situations where one prosthetic is favorable over the other, such as when the cyclist is going up a hill at a lower velocity. The choice is left to the cyclist's discretion.

There were three major contributions in this study. The first is a design process that utilizes 3D printing to produce cheaper prostheses. The second is a prosthesis inspired by biomimicry. Finally, the third is an airfoil-based design

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