Optimization Design and Parametric Study of Active Transfemoral Prosthesis

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Abstract

This report evaluated clinical demographic and etiology factors connected to prosthesis usage in individuals with lower and upper limb amputation. Whereas this relies on the multitude of issues, that are strongly impacted from the biomechanical act of the prosthesis, the loading imparted to the limb. There have been improvements in numerous prosthetic mechanisms that are made to advance patient mobility and comfort. In this report, a discussion on prosthetic and Vertical Shock-Absorbing Pylon foot ankle structures; particularly, their mechanical impact and properties on amputee posture are presented. A transfemoral prosthesis is an artificial limb which replaces any amputated limb above the knee. This report is about the transfemoral prosthesis for unilateral amputee designed by the team based on a few conditions such as stability, durability, mobility, pressure, energy consumption and cost with SOLIDWORKS. The objective of this assignment is achieved as the team is able to generate a simulation model of the prosthesis and engineering drawings based on the engineering standard. In methodology, the simulation was carried out using SOLIDWORKS to better illustrate the viability of the project. There are numbers of analysis that have been executed by the team which are design study, topology study, static study, estimated cost study and sustainability study. Those studies are carried out to investigate the performance of the proposed design under real-world scenarios. The outcome from the simulation proved to be a success which also underscore the significance of examining components connected to prosthesis usage including the differential influence that these variables might have during the etiology and position continue to be considered.

I. INTRODUCTION

Damaged limb has a great effect on an individual, most especially the lower limb as this is paramount to human locomotion. Every year, people around the world lose their lower limbs due to circulatory and vascular problems, complications of diabetes, cancer or trauma. The effect of mobility loss reduces independence, affecting amputees' quality of life. The exact number of lower limb amputees globally is unpredictable, as many countries do not keep a record of amputees or cause of amputations (Zhen *et al*., 2015). Automobile accidents and diabetes mellitus are considered to be the main causes for these amputations (Wilson *et al*., 2015; Trautner *et al*., 1996). Prostheses above-knee can be classified as intelligent or non-microprocessor, of which a quite number of it are available in the market. Passive or variable-damping knee prostheses are based on a mechanical hinge with speed and ease of swing controlled by the following mechanisms, free swing, manual lock, constant friction, weight-activated friction, geometric locking and hydraulics. External power source is not required for the passive mechanisms and are less adaptive to ground level or gait speed (Wilson *et al.*, 2015).

Amputee rehabilitation is primarily coordinated by a physiatrist as part of an inter-disciplinary team consisting of physiatrists, prosthetists, nurses, physical therapists and occupational therapists (PMRT, 2020).

Transfemoral amputation is a common amputation procedure for the human lower limbs. Active, passive and semi-active, prosthetic devices are generally prescribed to amputees in order to reinstate their quality of life according to their abilities (Carlos *et al.,* 2018).

Due to structural complexity and multifunctional role during gait, the human knee joint is particularly difficult to replicate with a mechanically-passive prosthetic component. Specifically, persons with Transfemoral amputation and without muscles spanning the lower limb must learn to organize the movement of a passive prosthetic knee joint by applying a control strategy that feats the inter-segmental coupling of their residual limb and prosthesis. To date, few studies have systematically explored the nature of these control strategies, particularly during the stance phase of gait when inadequate control may lead to a sudden collapse of the knee joint and an increased risk of falling (Kulkarni *et al*., 1996; Miller *et al*., 2001).

Prostheses can be produced using hand or with Automatic computer aided design (Auto CAD), a software interface that helps creators design and analyze the creation with computer-generated 2-D and 3-D graphics as well as analysis and optimization tools (www.oandplibrary.org).

In order for the stated problem to hit its mark, a definition of optimization design and parametric study would be outlined.

i. Optimization design is an engineering design methodology with the aid of mathematical formulation to provide ease in option selections amongst the other possible alternatives and to achieve the best performance under constraints (Papalambros and Wilde, 2017).

ii. Structural optimization is the process of determining the best design shape of the structural part. The shape of the model resulted after applying some optimization criteria such as: maximum strength, maximum rigidity, minimal displacement, minimal cost, minimum weight, etc. (Iacob-Liviu *et al.*, 2016).

The beginning of the optimizations was founded by Pythagoras of Samos (569 BC to 475 BC). It was a Greek philosopher with many contributions in mathematics, astronomy and the music theory, after developing the computational system, the mathematical algorithm of optimization was programmed (Iacob-Liviu *et al.*, 2016).

Therefore, optimization design is an engineering design methodology with the aid of mathematical formulation to provide ease in option selections amongst the other possible alternatives and to achieve the best performance under constraints (Papalambros and Wilde, 2017). In this case, the already existing transfemoral prosthesis are dominated by the passive version as it is more affordable when compared with the active version.

To ensure the research is concise, the objectives that accompany this research are as follows:

The aim of study of this study is to optimize and study active Transfemoral prosthesis using mathematical and 3D modelling software.

1. To study the ideal composite material that will be used in the construction of an active Transfemoral prosthesis based on cost-effectiveness.

2. To develop or provide a self-powered actuation design using pneumatic principle to increase stability.

3. To develop a model that withstands stress, enhances fatigue life, and increases stability, strong materials and proper architecture are used.

II. LITERATURE REVIEW

A. *Prosthesis (History of Prosthesis).*

An artificial limb designed to mimic the natural function, structure and aesthetics of the limb being replaced is known as prosthetic. A prosthetic device that starts between the hip and the knee is known as Transfemoral Prosthesis (Kathryn Chan and Astrik Golendukhin, 2011).

Prosthetics is an artificial device (artificial arms and legs) that substitutes a lost body part, which may be lost through disease, trauma or a condition present at birth. Artificial body parts (arms and legs) are estimated to restore a degree of normal function to amputees. These Automated devices that allow amputees to walk again and continue to make the use their two hands and legs have been in existence since ancient times, the most common one being the simple is leg. Since then, the progress of artificial limbs has improved hurriedly. Plastics and some materials, including carbon fiber have made artificial limbs to become stronger and lighter, regulating the amount of additional energy necessary to operate the limb. Extra materials have allowed artificial limbs to be much more realistic (Finch, 2011).

B. *Researches Done on the Prosthetic Leg*

There are two main types of artificial lower limbs which are transtibial and transfemoral prostheses. A transfemoral prosthesis is an artificial limb replacing a leg that is missing above the knee while a transtibial prosthesis is an artificial limb replacing a leg missing below the knee.

There are two types of prosthetic legs which are exoskeletal prosthesis and endoskeleton prosthesis.

According to Hanger (2020), an exoskeletal prosthesis has a wood or urethane foam prosthesis with a rigid outer plastic shell. It is cosmetically pleasing and has better strength by having the outer lamination. However, it is heavier and has a limited range of components used. It is suitable for an amputee that uses the same prosthesis for several years. On the other hand, endoskeleton prosthesis has an internal support pylon and it is made of lighter materials like titanium or aluminium (Hanger 2020). This design has modular connectors and other components such as feet and knee. It also tends to be lighter and offer more component choices to obtain better adjustability. This type of prosthesis is usually more appropriate for amputees with an active lifestyle.

C. *Transfemoral Prosthetics*

Transfemoral prosthetics are prosthetics for interfemoral amputees. Interfemoral amputations are lower limb amputations and specifically those of the region above the knee. A prosthetic device that starts between the hip and the knee is known as Transfemoral Prosthesis (Kathryn Chan and Astrik Golendukhin, 2011).

They can be carried out fora variety of reasons from trauma to infection and most commonly dysvascularity (these are diseases of the peripheral vascular area). Like most amputations a transfemoral prosthetic is necessary to compensate for the lost body part so as to allow for mobility, normal activity, potential professional career and maintain or increase the quality of life for the patient. Transfemoral amputations are particularly associated with increased morbidity. They are considerably more detrimental on the patient when compared to other forms of amputation such as below-knee amputations (transtibial) due to the fact that prosthesis for above-knee amputations is more difficult to fit and patients usually find it quite hard to adapt to the prosthesis after which they eventually opt to using a wheelchair instead. (Samir, 2013).

D. Active Prostheses

Due to the limitations of semi-active and passive prostheses, active (i.e., powered) lower limb prostheses have been developed over the years (Joseph, 2018).

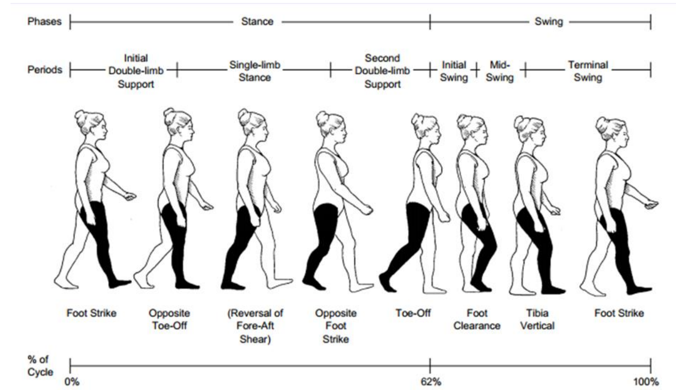
Regardless of these differences, all prostheses are aimed at repairing the weakened functional performance of the amputee. In contrast to their passive and semi-active counterparts, these active prostheses are capable of providing net progressive work and thus act on their own. Therefore, a control scheme that ensures a dependable interaction with the amputee and enables intended motion from user commands is required. (Varol *et al*., 2008; Wu *et al*., 2011).

E. Gait

Gait is a behavioural biometric and is defined as the manner of walking. It includes both the body appearance and dynamics of human walking motion (Ashutosh *et al*., 2011).

F. Gait Cycle

The movement from one foot strike to the successive foot strike on the same side is known as a complete gait cycle in Fig. 1. The beginning of the foot strike and ends with toe-off is known as the stance phase, which usually lasts for about 62% of the cycle; the swing phase, begins with toe-off and ends with foot strike also usually lasts for the final 38%. During each cycle, a regular sequence of events occurs. Expressing each event as a percentage of the whole normalizes the gait cycle. Initial foot strike, or initial contact is designated as 0%, the successive foot strike of the same limb is designated as 100%. The events of the gait cycle, which define the functional periods and phases of the cycle, are foot strike, opposite toe-off, reversal of fore shear to aft shear, opposite foot strike, toe-off, foot clearance, tibia vertical, and successive foot strike. The older terms heel strike and foot flat should not be used because these events may be absent in subjects with pathologic gait. The stance phase is divided into three major periods: initial double-limb support or loading response; single-limb stance; and second double-limb support, or preswing (Henry and David, 2002).



reported in centimetres per second (cms^{-1}) or meters per minute (m/min) mean normal for a 7-year-old child, 114 cm/s and cadence, or number of steps per minute, mean normal for a 7-year-old child, 143 steps/min. Average velocity for adults more than 40 years of age is 123 cm/s, average cadence is 114 steps/min. Step length is the distance from the foot strike of one foot to the foot strike of the contralateral foot. The distance from one foot strike to the next foot strike by the same foot is Stride length. Therefore, each stride length is comprised of one right and one left step length (Henry and David, 2002).

H. Gait Control Strategy

The recently portrayed prosthesis is a completely controlled two level of opportunity robot, equipped for critical joint force and force, which is inflexibly connected to a client. In that capacity, the prosthesis requires a solid control system to produce the necessary joint forces while guaranteeing steady and composed communication with the client and the climate.

The all-encompassing methodology in all earlier work has been to produce an ideal joint position direction, which by its inclination, uses the prosthesis as a position source. Such a methodology represents a few issues for the control of fueled transfemoral prosthesis. To start with the ideal position directions are regularly registered dependent on an estimation of the sound-side leg direction, which confines the way to deal with one-sided amputees, requires instrumentation of the sound-side leg, and mostly creates a much number of steps, which can introduce an issue when the client wants an odd number of steps. (Sitaramanjaneya *et al.,* 2019).

I. Gait Force

Gait is an interchanged between loss of balance and recovery of balance, with the center of mass of the body shifting continuously. As the person pushes forward on the weight-bearing limb, the center of mass of the body shifts forward causing the body to fall forward. The non-weight-bearing limb fall is stopped, which swings into its new position just in time. The forces that act on and modify the human body in forward motion are gravity, pathway of the centre of mass of the body is a smooth, regular curve that moves up and down in the vertical plane with an average rise and fall of about 4 cm. The low point is reached at double limb support, when both feet are on the ground; the high point occurs at midstance. The centre of mass is also displaced laterally in the horizontal plane during locomotion, with a total side to side distance travelled of about 5 cm. The motion is toward the weight-bearing limb and reaches its lateral limits in midstance. The combined vertical and horizontal motions of the center of mass of the body describe a double sinusoidal curve (Henry and David, 2002).

J. Topology Optimization

Compared to numerical modelling, topology optimization brings upon convenience in design iterations whereby changes are not made on existing schematics but rely on parametric constraints. By definitive, topology optimization is an alternative method to standard optimization methods whereby the generation of an improved design is based on pre-set constraints and distribution of materials (Hale 2017).

Preliminary conditions of conducting topology optimization would require data relays from a finite element meshing produced by external pre-processors (Gould 2015).

K. Energy Transfer Mechanism

It can be said that the proposed biomimetic-controlled transfemoral knee prosthesis based on a polycentric mechanism and an echo control scheme is able to reproduce the biomechanical performance of a natural knee. However, more work is needed in order to enhance the prosthesis design in terms of topology optimization, portability, aesthetics, and its evaluation on a real amputee.

L. Prosthesis Mechanism System

The ESCON drivers, running a tuned ebb and flow, deal with low-level control of the arrangement of the prosthesis and speed input circle. The speed signals utilized through the ESCON continue to be produced under the FPGA of the b RIO running a control circle at 1,000 Hz. Location orders remains determined through the constant framework for 100 Hz and took care of for the FPGA. Position orders that are followed by the constant framework are determined by the Top-Level Control.

M. Actuation Systems

The actuation system is a combination of multiple sub-assemblies/parts, used to operate a device by applying physics, chemistry or biology principles. In a transfemoral prosthesis, an actuator is used to mimic the flexion and extension of the knee, and the dorsiflexion and plantar flexion of the ankle joint. Contrary to public belief, actuators are not only used in active and semi-active prostheses but in passive prostheses as well. In fact, a semi-active prosthesis uses the same actuation system as a passive prosthesis, but it has microprocessors to enhance its performance (Dehghani et al. 2012).

N. Actuation Option

Hydraulic and Pneumatic Actuators apply the same fluid dynamics concept, which is Pascal’s Principle. These actuators consist of a hydraulic or pneumatic cylinder, which is made up of a chamber containing a liquid medium (typically silicone oil) or compressed air respectively, a piston, variety of valves, and sometimes a spring is placed under the piston to further enhance the functionality (Physiopedia 2020). During flexion or dorsiflexion of a prosthetic joint, the fluid and the spring in the cylinder is compressed by the piston to store energy in term of pressure, while valves are used to control the flexion rate of the joint by determining the amount and rate of fluid flow. The energy from the compressed fluid and springs will then be used to assist the extension or the plantar flexion of the joint. For prostheses with passive knee system, the valves’ openings are adjusted manually, while its semi-active counterpart harnesses the microprocessors-controlled valves’ ability, also known as servo valves, to alter the size of valves’ opening, to provide the amputee with more effective locomotion (Bellmann et al. 2014). Even though prostheses with Hydraulic Knee System are heavier and more expensive than those with Pneumatic Knee System, the Hydraulic Knee System has a higher power density compared to Pneumatic Knee System (Dupes 2020, Heney 2016). Therefore, hydraulic actuated prostheses are more suitable for active adult or teenager while its lightweight pneumatic counterpart will be more preferred by senior citizens. The hydraulic knee is even more superior to the conventional knee. This is proven by Ülger, Topuz & Bayramlar (2009), where their study has found that the energy cost of walking is reduced by an average of 56% by using a hydraulic knee, provided more natural gait and increased speed as well.

O. Knowledge Gap

This work presented the conception, design and development of an intelligent, low-cost prosthesis for one-sided transfemoral amputees.

Several simulations and tests were performed, including mechanical strength analysis to select materials for the structural components through the Finite Element Method, electromechanical tests for the calibration of the sensors and actuators and tests of the electronic circuits for verification of data acquisition, signal conditioning and data transfer to the knee prosthesis.

The experimental tests for the activation of the knee prosthesis, in terms of the dynamic response during flexion and extension during a slow walk, showed results consistent with the required features of the prosthesis. In this study the researcher tries to work on the materials cost, so as to produce something good and with a low price and to develop a model that withstands stress, enhances fatigue life, and increases stability.

III. METHODOLOGY

The study of active Transfemoral prosthesis requires a research methodology of quantitative approach. The study of previous literatures concerning active Transfemoral prosthesis to understand the relevant theory and also experimentally determine the optimized design, torque, weight efficiency and involved forces.

A. Quantitative Experimental Methods

i. Modelling of active Transfemoral prosthetics based on suitable size, and efficiency to reduce energy consumption.

ii. Simulation of active Transfemoral prosthetics.

iii. Evaluation and analysis of results of the active transfemoral prosthetics model.

iv. Presenting and Conclusion and recommendation.

B. Design Study

The researcher estimated that the prosthesis designed has an estimated height of 926mm. In the team's opinion of an average human being, it is too long relative to the intact leg of an amputee who weighs around 90kg. Thus, the researcher decided to carry out the design study to optimize the height of the prosthesis. The subject would be assumed to be an adult weighing 90kg and the prosthetic limb to be designed will be based of the testing loading levels P3-P8 in which the loading level P4 was developed for the structural test surrounding lower limb prosthetics in the range of the weights 0kg-90kg as the ISO 10328:2016(E) standards states. The active prosthetic to be designed later on will be powered through motors that will promise efficiency as the supporting knee mechanism will be made of Aluminum alloy 6061-T6, the pins of the mechanism will be made of low carbon steel, plastic for the inner parts and carbon fiber for lamination. Still using the ISO 10328:2016(E) standards, parameters such as the test force, ankle bending moment, knee bending moment, axial force and twisting moment would be used to determine the external and internal forces that eventually prove the selected dimensions of each part that later make up the prosthetic lower limb and ensure it is in a suitable state when being modelled in Solidworks.

Control methodologies for the Beta-Prosthesis utilized a changed Intention Detection structure and Wearable Sensory Apparatus controller with a restricted state machine. Here the state machine has been changed in accordance with fuse the new Weight Acceptance (WA) part positions similarly as the KD request positions. The state machine of the Wearable Sensory Apparatus (WSA) contained different levels, the first including a quiet standing, step initiation, and walk end stages. From the progression commencement stage, the essential walking state machine was entered. The walking state was broken into four particular sub-states named, from the viewpoint of the prosthesis, the Early Stance (State 1), Late Stance (State 2), Swing (State 3), and Late Swing (State 4) times of the walk cycle as found in a mix of the WSA jaunty speed sensors similarly as signs set off these states from pressure insoles. All of these states were proposed to get a specific step event, heel strike, heel off, toe off, or terminal swing stage.

The final design after many calculations to determine suitable sizes will be run through MATLAB Simulink multibody in multiple external conditions, presuming the patient would be in mountainous regions for example high rocky land, steep sides and pointed or rounded top and if the simulations return a failed result showing both instability and high-power consumption, the process will be redone again until a more suitable model is gotten which is finally optimized. This will be called a cyclic test in most part of the report.

The data analyzed for the gait result was the product of three iterations of the subsequent tests performed on: right foot walking, left foot walking, right foot running, left foot running, jumping, and standing. The tests with the left and right foot were separated by simply conducting a test that specializes on either foot at a time. These tests were repeated for three case studies (CS 1, CS 2, and CS 3) with the participants having the ability to repeat iterations of the procedure if they thought that they were conducting the walk, run, or jump abnormally. All tests were analyzed using excel from data extracted from the HR Mat software.

The subjects were 24±2.1 years of age. They weighed 85.3± 16.4 kg and had heights of 176.3 ± 8.3 cm. The three subjects were healthy at the time of the study, though one had a history of back issues. Foot types of the subjects: CS 1 has a normal arch, CS 2 has a high arch, and CS 3 has a flat foot.

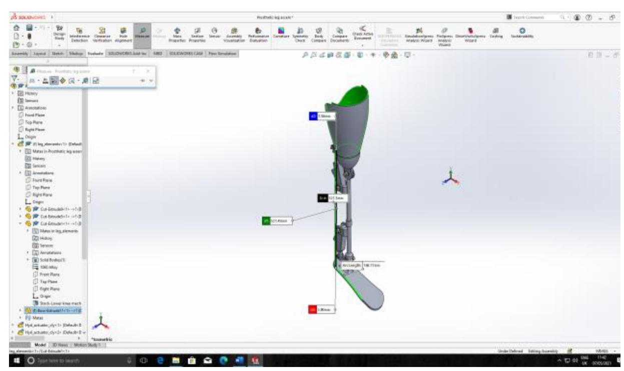


Figure 1: Shows the Simulation Model of the Transfemoral Prosthesis

IV. RESULTS

The experimental tests for the activation of the knee prosthesis, in terms of the dynamic response during flexion and extension during a slow walk, showed results consistent with the required features of the prosthesis. In this study the researcher tries to work on the materials cost, so as to produce something good with a low price and to develop a model that withstands stress, enhances fatigue life, and increases stability. The researcher did some research to determine the materials to use that will produce a quality product with a low cost of production and will still sell at a cheaper price, the materials have to be in a good and standard quality so that the patients will not suffer from any side effect or discomfort when using it, a model that will not be affected by stress or fatigue of usage.

Virtual Reality (VR) is in a position to simulate or virtualize an environment, allowing people to immerse in it. In Solidworks Visualise Professional software, it's a platform where engineers can share their mighty ideas by presenting their e-drawing product with the visual environment as background.

It lowers the physical prototyping cost and improves designs by offering a spread of virtual environments thus helping in making important decisions during the event phase. It can also display the prototype in 360 degrees. aside from that, drawings are mainly how to speak the design or concept and it's important as they permit engineers to construct 3D geometry from the 2D drawings. With SOLIDWORKS, it's easier to form a drawing from a neighborhood or assembly file and also generate immersive images and animations. This chapter will display the rendered images of the model.

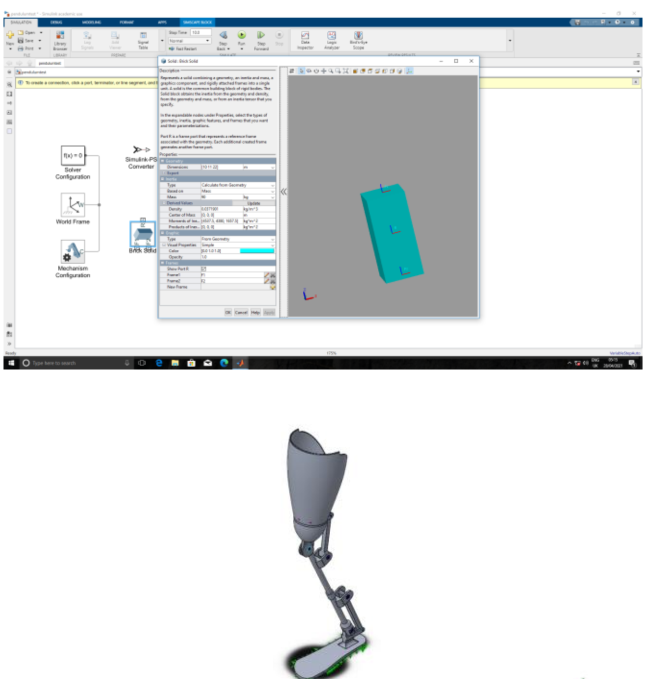


Figure 2: Simulation of Brick Solid and Assembled Model of Prosthetic Leg.

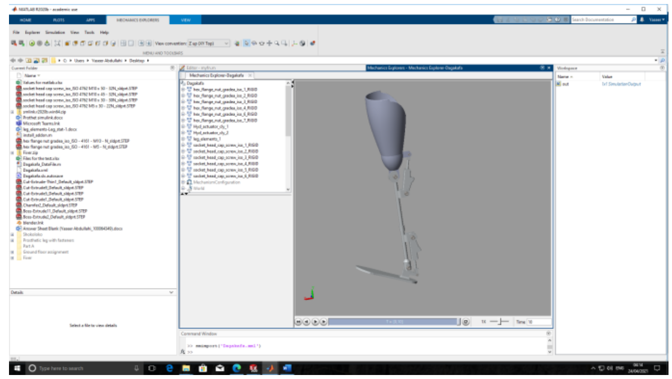


Figure 3: Prosthesis Simulation

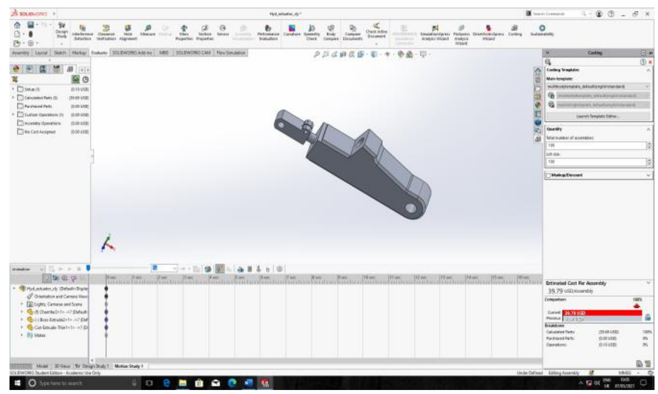


Figure 4: Shows cost of the actuator being reasonable.

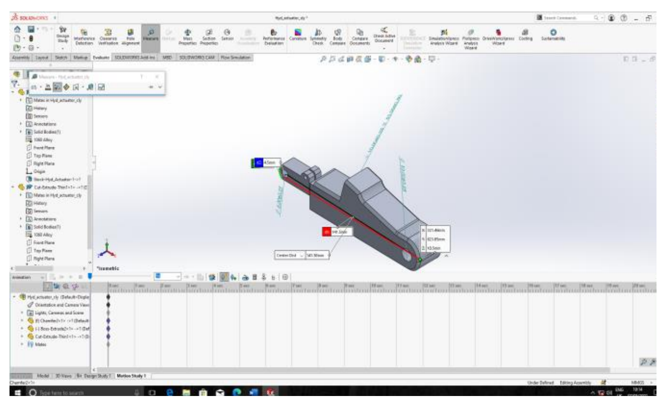


Figure 5: Shows the Dimensioning of actuator.

V. DISCUSSION

This work presented the conception, design and development of an intelligent, low-cost prosthesis for one-sided transfemoral amputees.

Several simulations and tests were performed, including mechanical strength analysis to select materials for the structural components through the Finite Element Method, electromechanical tests for the calibration of the sensors and actuators and tests of the electronic circuits for verification of data acquisition, signal conditioning and data transfer to the knee prosthesis.

The experimental tests for the activation of the knee prosthesis, in terms of the dynamic response during flexion and extension during a slow walk, showed results consistent with the required features of the prosthesis. Of these features, the prosthesis achieved a good correlation between angular position of the prosthetic knee joint and the foot sole contact pressure of the preserved leg. In the present study, only two contact areas of the sole were considered for the activation of the flexion and extension of the knee prosthesis. This approach to monitoring the sound leg ground reaction, also referred to as “echo control”, as a control signal for the above-knee prosthesis was first reported by Flowers and Mann (1977), Grimes et al. (1977) and Bar et al. (1983). More recently, Joshi et al. (2010) and Vallery et al. (2011) used a similar system. The “Power Knee”, which is commercialized by the Ossur Company, uses a similar echo control approach in which sensors on the sound leg are used to optimize the patient’s gait.

Nevertheless, using only the preserved leg to control the above-knee flexion and extension is a simple system and has some limitations, including a lack of precise and smooth gait control for any self-selected walking speed. Most of the recent developments in gait control for above-knee prosthesis are based on instrumented shoes coupled to the prosthesis, as reported by Bar et al. (1983), Herr and Wilkenfeld (2003) and Kapti and Yucenur (2006). Compared to our approach, which is based on the echo control, when the load sensors are installed on the prosthesis foot, there are limitations for cyclic and symmetric patterns and the use for only unilateral amputees.

Even though the prosthesis proposed in the present work is based on a simple control mechanism, it can be classified as an intelligent powered above-knee prosthesis that be controlled by only one embedded DC motor. This is in contrast to current prosthetic controllers that are highly complex and intelligent through the use of sophisticated rules, which in turn make them more costly.

Compared to passive above-knee prostheses, the powered prostheses require a battery and associated weight and power consumption. In the present design, the power supply and the DC motor are installed inside of the prosthesis, allowing for a reduced size, as suggested by Bar et al. (1983) in the group’s early work. We have also used only one DC motor, a microcontrolled micromotor, which is a more compact solution compared to other designs proposed, such as that of Kapti and Yucenur (2006) or Martinez-Villalpando and Herr (2009).

We have developed a microprocessor-powered knee prosthesis for unilateral transfemoral amputees. The prosthesis was designed to be compact and inexpensive and is based on an echo control for the preserved leg.

It was found that only two load sensors installed in an instrumented sole for the preserved leg were required to easily and smoothly activate the flexion and extension of the prosthetic knee. The electronic circuitry, including the load cells used to control the prosthesis activation and the micromotor drive, could easily be adjusted for different walking speeds and knee joint angles, thereby ensuring the safety of the transfemoral amputees.

Further research is needed to improve the system characteristics and verify if this adopted electromechanical concept could allow a reduction in the estimated manufacturing cost of the prosthesis, compared to commercially available microprocessor active prostheses. In addition, it is necessary to test the system in humans to confirm the results of the prototypes.

VI. CONCLUSION

To conclude this project, the researcher has designed a semi-active transfemoral prosthesis simulation. Each sub-assembly was carefully designed to meet the solve the common problems with a conventional prosthesis. For example, a more comfortable socket simulation is designed according to the pressure-sensitive area in the residual limb, multi-axial foot to provide better stability, single-axis knee with better flexibility, and hydraulic actuation system to reduce energy consumption. Meanwhile, less costly materials are used, and to improve the durability, fillets are implemented whenever possible to reduce the effect of stress concentration.

Besides, Finite Element Analysis (FEA) is carried out to validate the viability of the prosthesis. Topology study was conducted to reduce the unnecessary mass of the prosthesis, thus reducing the energy consumption of the amputee. Even though not all of the suggested alteration was implemented, 8% of the total mass was removed from the whole assembly by just performing the topology study on one specific part. Future works might be needed to take the parts in weighty subassembly for topology study, such as the foot. Note that should there be any instability, the foot’s mass should not be reduced as it would lift the centre of gravity unless modifications in the design are made to compensate for this loss.

Design study was performed to reduce the excessive height, thus fewer modifications are needed when the prosthesis is custom-made for the amputee. The total height reduction was 24mm, which yields a final height of 886mm. Note that excessive height is not a problem in a conventional prosthesis, but the researcher decided to optimize it as it would affect the overall usability of the prosthesis.

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