Design And Manufacturing Knee Joint for Smart Transfemoral Prosthetic

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Abstract. A well-designed lower limb prosthesis is necessary in order to permit an amputee to repeat to healthy locomotion. The aim of this study is to enhance the passive prosthesis to a microcontroller-based transfemoral prosthesis which was unable to reach the designated rotational speed intended for a functional use, and had low cost. The enhancement focuses on designing a new mechanism on the knee joint by using a pre-existed DC motor, a socket, and the foot obtainable from the previous design. This involves mimicking the normal limb function and to improve the range of motion of this knee prosthesis. There are some criteria that required to be achieve at this study such as the new proposed knee joint should be able to flexion up to 90° and has enough strength to bear up the amputee’s body weight. Solid Works software was used to design every single part of the knee joint. Then, each part will be assembled and the mechanism of the knee joint will be simulated for visualize the imagine motion of new model of hinged knee prosthesis. The materials (Aluminium Alloy 6061, Aluminium Alloy 7075 and AISI 4130 Steel) used were chosen by taking the consideration the cost and the properties of that material. By ANSYS computer program (Finite element analysis) was performed and the conclusion were evaluated to discover if the proposed prosthesis can bear certain loads. The results were discussed and evaluated the new model that suggested by this study.

1. Introduction

Patients with lower limb amputations face many physical challenges that compromise their health and mobility [1]. Contemporary prosthesis design goals to restore a natural and efficient gait by means of active and inactive components that are optimized to replicate characteristics of an intact limb [2]. In the past, the only resources available for the people who lost their lower limb were walkers, wheelchairs, wooden pegleg, and crutches. However, nowadays, people with this form of disability can take the advantages of advances in medical scientific discipline and technology by using lower limb motorized prothestic. Leg and knee motion crucial move in the body. Leg contributes to keep the body balanced and supported while standing up. Knee locomotion joins the upper and lower legs together and provides the bending motion that allows us to walk. The few microcontroller based active/semi-active prosthetic knee joints available commercially, such C-Leg, are extremely expensive and do not consider the uncertainties of the input sensory information. Therefore, they are only affordable by a few their high cost, they suffer from sensitivity to input uncertainty which could impact their performance [3].
A good prosthetic knee should mimic the behavior of the biological knee. Nowadays, many types of prosthetic knees are available in the market. They come from simple, purely mechanical devices up to sophisticated microprocessor controlled systems. Typically, a mechanical knee trades increased mobility for decreased stability. This is where a prosthetist plays his role in helping the amputees to find a suitable balance for the individual amputee’s muscular coordination. The types of prosthetic knees are summarized (Single axis knee, Locking knees, Stance control knees, Polycentric knees, Pneumatic/Hydraulic knees and Microprocessor knees) as shown in figure (1) [4].

### Single axis knee
The most basic prosthetic knee which comprises a single pivot between the socket at the thigh and the shank. As long as the leg is straight at heel strike, the knee will not buckle during stance [4].

### Locking knees
Kept straight during walking which incorporates a cable or lever release to allow the knee to bend for sitting. A locking knee is fitted when amputee lacks the hip control to stabilize a bending knee [4]. Stance control knees single axis knee with friction break (self-lock). A load from the amputee’s body weight makes the friction brake engages and preventing the knee from buckling. The brake disengages when loading is removed, which allows the shank swings freely [4].

### Polycentric knees
Consists of four bar mechanism which move in the sagittal plane. Near the straight position of the knee, the effective pivot lies at the posterior of the load path for safe early stance loading. During terminal stance, it buckles easily to initiate the swing [4].

### Pneumatic/Hydraulic knees
Consists of a hydraulic cylinder in a single axis or polycentric knee design. The cylinder contains valves which restrict the fluid flow between the two sides of the cylinder. The adjustable valves allow the prosthetist or amputees to adjust the free swing flexion and extension for comfortable walking speed[4].

### Microprocessor knees
Incorporate angle and load sensors with an on board microprocessor to adapt dynamically to change gait. Flexion/extension is adapted by a servo controlled valve [4].

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**Figure 1.** (a) Single axis knee, (b) Locking knees, (c) Stance control knees, (d) Polycentric knees, (e) Pneumatic knees, (f) Microprocessor knees

Aeyls et al, (1992) [5], developed the first micro-controller based knee joint which comprised of an electromagnetic brake.Hata, N. and Hori, Y, (2002) [6], studied the direct actuation of the joint by an AC servo motor was introduced by Hat. A complex model to simulate human walking gait was developed together with a few different stiffness mechanism to minimize the torque required when the
leg was in a static position. Kapty and Yucenur, (2006) [7], proposed a tethered fully active knee powered by an electro motor and a gear reduction system. They tried to decrease the user’s energy cost by providing a fully powered trans-femoral joint. Fite, K., (2007) [8] describes design and control of a transfemoral prosthesis with an electrically powered knee joint. Details the design described with of the active-knee prototype Martinez et al,(2008) [9],focused on the biomimetic active agonist antagonist structure designed to reproduce both positive and negative work phases of the natural joint while using series elasticity to minimize net energy consumption. N. Murthy Arelekatti and Amos G. Winter, (2017) [10], establishes a framework for designing a potentially low-cost, fully passive prosthetic knee device. Based on a comprehensive set of functional requirements and biomechanical analysis from our past work.

2. Prosthetic knee joint Design
The complete structure of the prosthetic leg of this study is illustrated in Figure (2). The socket, the pylon, and the prosthetic foot are commercial products from the market. This work focuses only in designing the prosthetic knee joint for transfemoral amputees. The prosthetic knee covers the areas of the thigh, and the shank.

![Figure 2. The complete structure of the prosthetic leg](image)

There are two parts in the design prosthetic knee joint, the upper part and the lower part. Their name came from their positions. These two parts are attached by one screw as illustrated in Figure (3).

![Figure 3. Components of Knee joint](image)
The screw hold these two parts together where they can be considered as one rigid body. Meanwhile, Figure (4) illustrates how the two parts play a role as movable the prosthetic knee hinge to create moments at the knee joint. The actuated motor pushes or pull the lower part and creates moments. These moments allow the knee joint to flexion or extension. The actuated motor Fixed to the shank by connection section. The connection part acts as a backbone of the prosthetic knee joint where it supports most of the applied load knee joint during any kind of activities. Finally the microcontroller sends a signal to activate the actuated motor. Then, once the actuated motor is activated, the connected rod toothed interiorly and matched with toothed gear motor to move connected rod upward or downward and making the knee joint rotates and allow the knee joint model to flexion or extension. The flexion of the knee joint for certain degrees is shown in Figure (4).

![Figure 4](image)

**Figure 4.** The flexion of the knee joint for certain degrees

3. Results and Discussion

3.1. The Boundary Condition for Analysis Model of Knee Joint

For analysis model of knee joint and evaluation of Von Miss stress and deformation must apply the boundary condition on the knee joint model. The boundary condition including applied load 1200 N at the tip of upper part of hinged as illustrated position (B) in figure (5) and fixed support at the surface of the lower part of joint position (A) in figure (7). For completing the total results of this model, many of the other important parameters are added, such as Young’s modulus, Yield stress, Ultimate stress, Poisson ratio, and density.
3.2. Finite Element Analysis

Three types of materials are nominated in this project. They are Aluminium Alloy 6061, 7075 and Stainless Steel. In the end of this work, only one material was selected. The simulations using ANSYS 14.5 were conducted to all materials. Two types of analyses were performed. They were the stress Von Mises analysis and the displacement analysis as shown in Figure (5) and Figure (6). The summary of the static stress analysis and the displacement analysis are tabulated in Table (1).

3.3. The Stress Von Mises Analysis

The stress distribution experienced by the prosthetic knee hinge unit ranged from 39.44 Pa to 40.85 Mpa for Aluminium Alloy 6061, 41.6 Pa to 40.86MP for Aluminium Alloy 7075, and 41.79 Pa to 40.88 MPa for AISI 4130 Steel. The colour key refers to the different stress value distributed across the prosthetic knee joint. Low stress distribution is highlighted in blue and light blue, which covered almost every part of the prosthetic knee hinge and high stress distribution (highlighted in red and yellow) is present in the lower part of knee joint as illustrated in Figure (5). Failure might happen to that part if excessive load is applied to the prosthetic knee joint. From the static stress analysis, the AISI 4130 Steel is the best material can be selected because there is a big gap between the values of the maximum stress (41.15 MPa) to the value of yield strength (435 MPa) of that material but at the same time heavier weight than Aluminium Alloys. The yield strength meaning is the value of stress of the material can bear without any permanent deformation.

Figure 5. The knee joint model subjected to Boundary Condition

Figure 6. (a) The stress Von Mises analysis for Aluminum Alloy 6061 (b) The stress Von Mises analysis for Aluminum Alloy 7075 (c) The stress Von Mises analysis for AISI 4130 Steel
3.4. The Displacement Analysis

From Figure (6), the colour ranges refers to the different displacement value distributed across the prosthetic knee joint. As the bottom of the prosthetic knee joint is set to be fixed, there is zero mm displacement on that region. The displacement is high in red/orange colour regions which distributed at top regions for all types of materials. The highest displacements recorded are 0.035 mm for Aluminium Alloy 6061. Then it followed by 0.034 mm Aluminium Alloy 7075, and 0.012mm for AISI 4130 Steel. The displacements for AISI 4130 Steel are very small and preferable. Although the Aluminium Alloy 6061 recorded the highest displacement of 0.035 mm,

![Figure 6](image)

\[ \text{Figure 7. (a) The deformation analysis of Aluminum Alloy 6061} \]
\[ \text{(b) The deformation analysis of Aluminum Alloy 7075} \]
\[ \text{(c) The deformation analysis of AISI 4130 Steel} \]

The estimated total weight is tabulated in Table (1). The estimated weights of each part were calculated by the Solid Works. The estimated total weight of raw materials is the estimation of the total weight of the parts to be fabricated. The estimated total weight of raw materials are vary from Aluminium Alloy 6061 to AISI Steel 4130 Steel. The Aluminium Alloy 6061 is the lightest material compared to the other two materials with weight of 0.192 Kg.

| Materials          | Von Mises stress analysis | Weight (kg) | deformation analysis |
|--------------------|---------------------------|-------------|----------------------|
|                    | Min | Max | Yield stress | Min | Max |
| Aluminium Alloy 6061 |       |     |             |     |     |
| Aluminium Alloy 7075 |       |     |             |     |     |
| AISI 4130 Steel     |       |     |             |     |     |

Table 1. The summary of the Von Mises stress analysis and the deformation analysis.
### 4. Conclusion

1. The Aluminium Alloy 6061 model was selected to be the best to be used in manufacturing the Prosthetic Knee joints which give more stability and comfortable for amputee due to the its low cost, low weight, and acceptable safety.

2. The maximum Von mises stress is recorded when used AISI 4130 Steel with value of 41.6 MPa.

3. The maximum factor of safety is recorded when used Aluminium Alloy 7075 with value of 12.31.

4. The maximum deformation is recorded when used Alloy 6061 with value of 0.035 mm.

5. The minimum weight is recorded when used Alloy 6061 with value of 0.192 Kg.

### 5. References

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