Design and Control of an Electrically Powered Knee Prosthesis by Taking Feedback from a Fully Functional Leg

K.B.M. Sharif Mahmood, A.M. Imrul Hasan, Shahrin Iqbal, Sourav Pal and Md Ishfak Tahmid
Department of Electrical and Electronic Engineering
Shahjalal University of Science and Technology (SUST), Sylhet-3114, Bangladesh
kb28@student.sust.edu ,imrulhassn7@gmail.com ,shahrin19emma@gmail.com,
adittyapaul007@gmail.com , ishfaktahmid@gmail.com

Abstract

In this work, a prototype of a trans-femoral prosthesis with an electrically powered knee joint have designed and implemented. As automated (without feedback) prosthetic legs independently control different joints and time periods of the gait cycle (resulting in control parameters and switching rules that can be difficult to tune), the paper has included the provision for real-time control by taking feedback from a fully functional leg by utilizing a flex sensor and a rotating encoder. A dynamic model of the below-knee prosthesis of a complete gait cycle is developed through computer-aided 3D design prior to implementation. The model is based on a two-dimensional multi-body mechanical system and includes a DC motor with worm gear and Arduino based control system for the knee. Thus, the model will provide an enhanced human-prosthesis interaction and motion capabilities for the impaired.

Keywords

Prosthetic leg, Gait cycle, Feedback control, flex sensor, 3D computer-aided design (CAD).

1. Introduction

Physical disability is a hindrance for those suffering from it, as these people, in general, have to depend on others for their everyday activities. Every year numerous people fall victim to road accidents, which is one of the prime causes of physical disabilities. Additionally, due to various diseases, the number of limb amputees is on the rise [1]. For being unable to move according to own-willingness, these people consider themselves a burden to others in the present competitive world. However, Physical disability is no longer a curse. Today the scenario has changed a lot due to the blessings of knee prosthesis. Significant improvement in the design (for providing greater comfort and reliability) of the knee prosthesis is the primary focus of engineers in recent decades.

A variety of technologies, like Neuroprosthesis, Thought Controlled Prosthesis, 3D Printed Prosthesis, are already in existence. But these prostheses with highly advanced technologies are often so costly to implement that a general person can't afford these. Moreover, the heavyweight of some advanced prosthesis inhibits the free movement of the person bearing them. For this reason, light and easily operable knee prosthesis can be a preferred choice for limb amputees. Sensory systems can be considered one of the most essential parts of such a prosthesis, which ensures reliability through feedback. Sensors take information from the operating body parts and regulate the prosthesis according to the generated data [2].

1.1 **Objectives**

This research is relates to the design of a prosthesis for a limb amputee who has lost his knee or a portion of the thigh and femur above the knee. Our key aim is to operate the prosthetic easily and to design a lightweight prosthesis accordingly at an affordable cost. By taking feedback from the functional leg using a flex sensor, the knee prosthesis will be controlled. Depending on the amount of bending in the knee section, the phases of the gait cycle will be controlled as the flex sensor senses the bending. The research also includes a knee housing where a drive motor is mounted, and it rotates in one direction to bend the knee. Whenever the rotation of the drive motor is reversed, the knee is straightened. Thus the model is promising to be implemented for an enhanced human-prosthesis interaction.

2. Literature Review

Some researchers have suggested that the total number of transfemoral amputees (TFA) worldwide is approximately 7 million [3]. Artificially powered legs could significantly improve mobility and quality of life for millions of lower limb amputees. But control challenges currently limit the clinical viability of these devices [4]. A proportional-integral-derivative (PID) conventional control with feedback linearization is developed to make a robotic prosthetic leg following a desired walking pattern [5]. Despite significant technological advances over the past decade (such as the introduction of microcomputer-modulated damping during the swing), commercial transfemoral prostheses remain limited to energetically passive devices [6].

3.Methodology

3.1Gait Control Strategy

Human gait is the pattern of the movement of limbs during locomotion over a solid substrate. There can be a variety of gaits of humans. For example, walking, flouncing, staggering, pacing, rolling, skipping, waddling, and so on [7]. To have proper regulation of the knee prosthesis from the functional leg, we need to analyze the basic walking gait cycle of the human body. In short, the gait cycle can be sectorized into two halves: one is the stance, and the other is the swing.

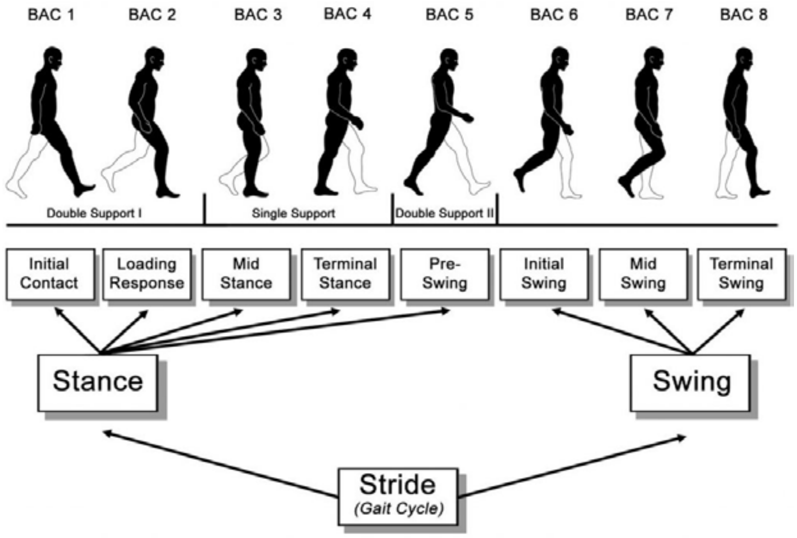

Fig 1: Phases of Gait Cycle [8].

From Fig 1it is seen that one full stride is consists of stance and swing. Where the first phase of stance includes initial contact to the ground by both legs. The next phase involves taking the load of the body. In this phase, the body starts to take some extra load than the previous phase of stance. The next phase is called the mid-phase of stance in which the front leg bears the maximum load of the body while the other leg prepares to go forward by lifting it in the air. At the terminal stance, the back leg creates a strong action force on the surface, and with the help of the reaction force from the surface human body goes to the next pre-swing mode. At this point, the body position is similar to the initial stance. But the position of the front and back leg is interchanged. In the initial swing phase, the knee joint of the front leg starts to bend. And in the mid-swing phase, the front leg finds a fully vertical position bearing the maximum load of the body like the mid-stance phase. Afterward, the swing ends with a pushing forward of the body and striking the front leg into the ground. Thus the complete phase of a gait cycle of human walking is completed [8].

3.2 Proposed Structure

Considering the position of the phases of the gait cycle, a prosthetic leg has been designed that will take the feedback from the functional leg. This prosthesis requires a reliable control framework for generating required joint torques while ensuring stable and coordinated interaction with the user. In this paper, a flex sensor with a rotary encoder has been used which is installed on the fully functional leg, positioned at the knee joint. These sensors will generate data for gait control mechanism by changing the resistance as the knee bends. Depending on the amount of bending of the knee joint, the resistance will be changed thereby. Later this data will be sent to the Arduino for analysis. A suitable algorithm has been designed that provides the output data for the next stride. This data will actuate the DC motor; thus, it makes a complete stride. A block diagram describing the process is presented in Fig 3.

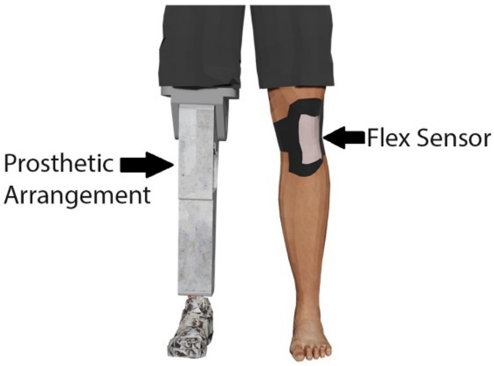

Fig. 2: Arrangement of Prosthetic.

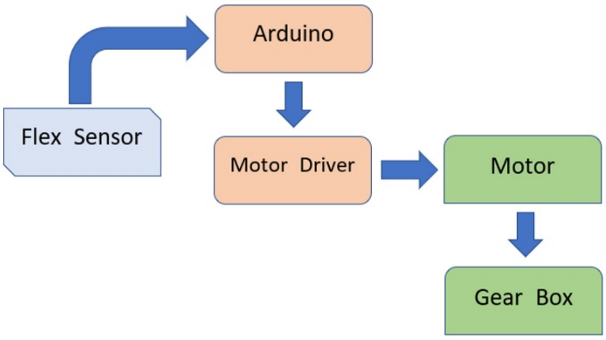

Fig 2: Block diagram of the operation of the prosthesis.

In the model, the gait control strategy requires less complexity than the previous methods as the data required for a complete stride is obtained from only the flex sensor (fig. 2) and a simple rotary encoder. And for each stride, the data obtained may or may not be the same as the previous stride. Thereby users can have easy control over their steps.

4. Prosthetic Modeling

A 3D design of the prosthetic leg is depicted in Fig. 4. The device incorporates a 12V brushed DC motor with 18 kg-cm stall torque. A worm gear is mounted on the rotatable shaft of the drive motor. The worm gear has a pinion with 20 teeth. A 3d model of the gearbox is shown in Fig. 4. The pinion of the gear was made of Copper and the worm was of Steel. The other structures were formed of the Aluminum sheet.

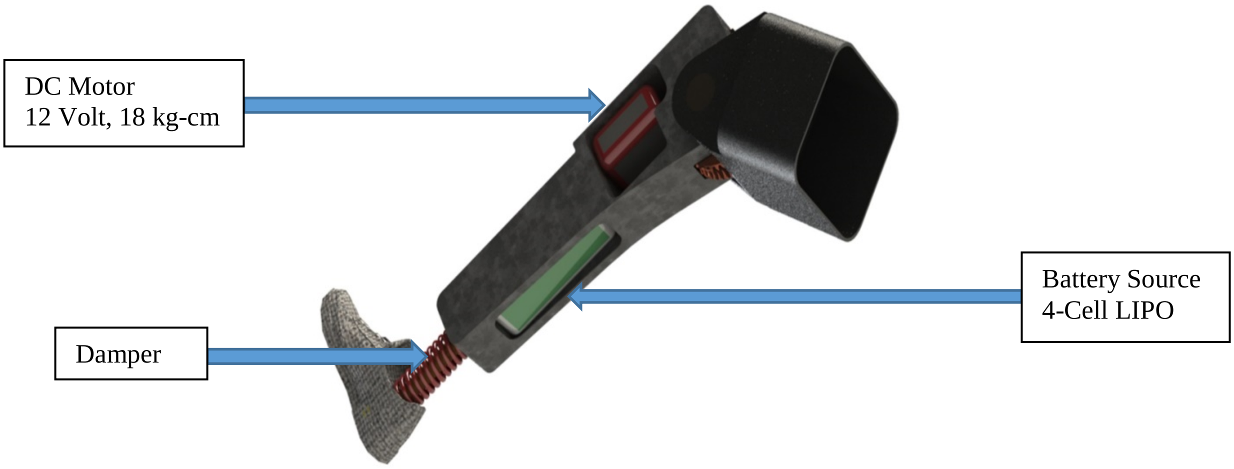

Fig.4: Computer-aided 3d design of the prosthetic leg.

Worm gear was chosen because of its ability to provide high reduction ratios and correspondingly high torque multiplication. As the reduction ratio is dependent on the number of gear teeth alone, this gear is more compact than other types of gears. Like fine-pitch lead screws, worm gears are typically self-locking, which is essential for a robotic knee to be positioned at any co-ordinates. So it can be effectively used for stair climbing. This gear has an additional advantage of carrying the weight of a human loading in a locked position. Moreover, this gear requires less space. Also, by using this gear, it is possible to place the motor parallel to the leg.

Fig. 5: Computer-aided 3D design of the gear box (Developed by CAD software).

The active prosthesis was designed to fit a broad range of different sized persons, ranging from two standard deviations below the female norm in length, up to two standard deviations above the male norm in length. The tibial length is varied by changing the whole single structural (tibia) component.

5. Results and Discussion

5.1 Implementation Results

The model has been implemented based on prosthetic modeling. The assembled design is shown in Fig. 6 below.

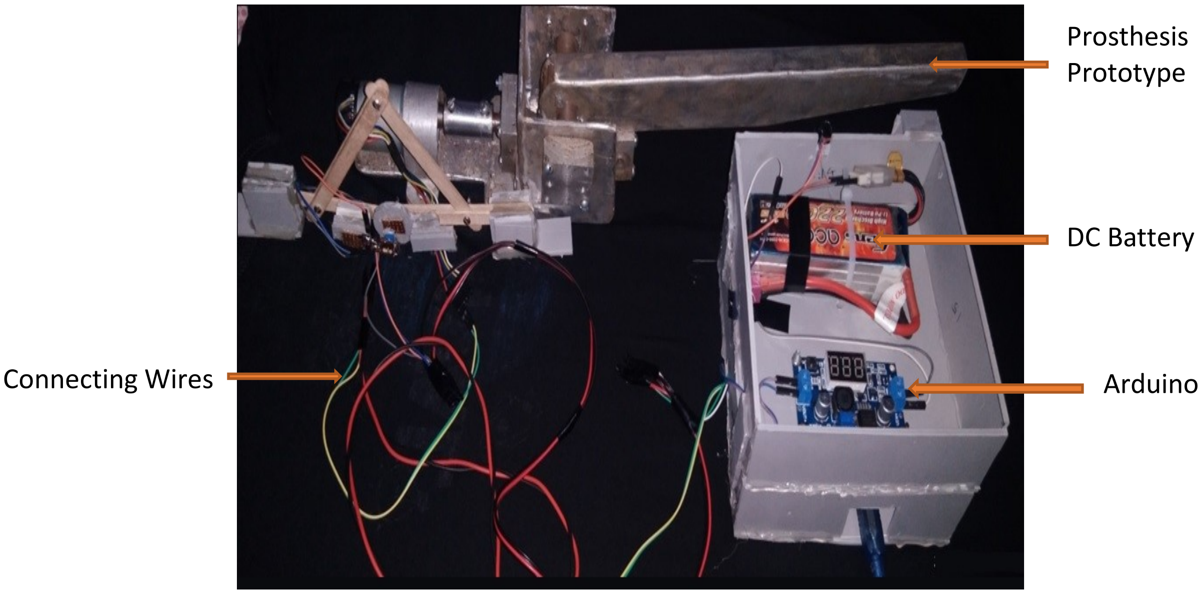

Fig 6: Assembled Prototype.

The assembled prototype consist of flex sensor, DC battery, Prosthesis prototype, drive motor and Arduino. The total weight of the tethered transfemoral prosthesis, excluding the foot and control box, is approximately 2.5 kg (5.512 lbs), which is within the normal and acceptable range for transfemoral prostheses [9]. The drive motor is powered by a battery pack (4-cell LIPO) and controlled by an Arduino AtMega 2560 Module.

5.2 Validation

The researchers did not explicitly design an ankle push-off period into the control strategy, but this is to be implemented in the future work. In this paper, an Arduino AtMega micro-controller was used which has a limited processing efficiency. A micro-controller with high-speed data processing may solve this issue. For a longer period of power supply, the researchers plan to utilize alternative power sources (such as hydrocarbon fuel based electric generators) in the future models. The design of the prosthesis could be made more compact, and future work with this device will entail structural development. Suitable flex sensors for collecting data from the active knee joint are not manufactured commercially. However, if these are made available, a more interactive control parameter tuning process can be studied for future progress and greatly improve the patient experience by adapting to varying walking conditions encountered in daily life. The overall mechanical structures could be made of lighter materials so that the structure can afford to store the battery weights as well as spaces for future addons.

6. Conclusion

In this work, a complete model of an electrically powered prosthesis with an active knee joint was developed. Computer-aided 3D design was used to develop a dynamic prototype of the design. Taking feedback from the fully functional leg, enhanced human-prosthesis interaction is ensured. The design of the prosthesis was detailed and a control methodology has been developed for a complete gait cycle. Finally, a prototype of the model is implemented. The developed model holds promise for providing the impaired an efficient human-prosthesis interaction capabilities at an affordable cost which is BDT 10,000.00 (Ten Thousand Taka Only). Cost of Mechanical parts is BDT 5,500.00 (Five thousand five hundred) and the cost of electrical parts is 4,500.00 (four thousand five hundred only). If the above mentioned prototype is produced in mass number, then the cost will be less.

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Biographies

K. B. M. Sharif Mahmood is an undergraduate student of the Department of Electrical and Electronics Engineering at Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh. His research interests include Photonics, Spectroscopy and Robotics. At present, K.B.M. Sharif Mahmood is involved in a research project with Md. Ishfak Tahmid, Department of Electrical and Electronics Engineering at Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh.

A.M. Imrul Hasan is an undergraduate student of the Department of Electrical and Electronics Engineering at Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh. His research interests include Property of 2D materials, Devices based on 2D Materials, Nanophotonics and Robotics. At present, A.M. Imrul Hasan is involved in a research project with Md. Ishfak Tahmid, Department of Electrical and Electronics Engineering at Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh

Shahrin Iqbal is an undergraduate student of the Department of Electrical and Electronics Engineering at Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh. Her research interests include Optical properties of semiconductor, Photonics, Robotics and Biomedical Engineering. At present, Shahrin Iqbal is involved in a research project with Md. Ishfak Tahmid, Department of Electrical and Electronics Engineering at Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh.

Sourav Pal is an undergraduate student of the Department of Electrical and Electronics Engineering at Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh. His research interests include Robotics, Grid-power quality improvement, Micro grid challenges, Photovoltaic Solar energy, and Wind energy. At present, Sourav pal is involved in a research project with Md. Ishfak Tahmid, Department of Electrical and Electronics Engineering at Shahjalal University of Science and Technology, Sylhet-3114, Bangladesh.

Md Ishfak Tahmid received his B.Sc. Eng. degree in Electrical and Electronic Engineering (EEE) from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh, in 2018. He is currently in the Department of Electrical and Electronic Engineering at Shahjalal University of Science and Technology (SUST), working as a lecturer. He is also pursuing M.Sc. in Electrical and Electronic Engineering in BUET. His research interests include photonics, optical properties of semiconductor, carbon nanotechnology, Nanophotonic Inverse Design, and photonic crystal fiber.