Prosthetic Exo-Leg: A Functional Robotic Leg Suit to Assist Patients with Transfemoral Amputation

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***Abstract*—The Exoskeleton leg is built to enable amputee patients to walk, ascend stairs, sit, and do fundamental movements. For any basic movements, patients can control the robotic Exo-leg by the movements of their residual limbs concerning the position of lower limb amputation. Prosthetic Exo-leg has been constructed to support patients with transfemoral amputation cost-efficiently. Moreover, the machine consists of multi-functional features under prosthetic exoskeleton legs that will initially support the patients of lower limb amputation, more specifically transfemoral amputation. Enabling the E-leg to a wide range of users and a variety of applications requires the socket to be adaptable through kinematics and actuation. The performance test shows the change of major movement in standing and walking that is expected to improve through further patient training and rehabilitation.**

Keywords— Exoskeleton Leg, Prosthetics, Prosthetics Limb, Gait Detection, Amputation.

I. INTRODUCTION

According to an article posted on the website of La Trobe University, Bangladesh is a lower-middle-income country with a population of over 167 million where around 60% of the population is participating in labor force such as agriculture, and construction incorporating a high chance of workplace injuries [1]. Among the various types of workplace injuries or motor vehicle injuries, the most common is lower limb amputation. Moreover, considering the world population, about 7% to 10% of the world's population have different kinds of limb-related issues where lower limb amputation has been marked as the most common. The National Limb Loss Centre has estimated that only in the United States there are an estimated 1.9 million amputees [2]. This infers the notion that Bangladesh as a developing nation has more patients suffering from Transfemoral Amputation. We can consider an amputation as Transfemoral Amputation when the amputation occurs at any level from the patient's hip to the knee joint. The majority of lower-limb amputations are performed due to several peripheral vascular diseases other than injury-related amputations, and the patients must depend on prosthetics for their movements [3]. Statistically, the yearly count of amputations is around 185,000, It indicates a daily amputation of 300 to 500 and more than 1 million annual limb amputations globally —one every 30 seconds [4]. The cost of a new prosthetic is high to afford as they cost anywhere from \$5,000 to \$50,000. Moreover, the validity to wear and tear the most expensive prosthetic limbs is between three to five years [5]. According to an article of Grand View Research, the global market share for the orthotics segment is quite dominant with around 74% share for its revenue scales concerning the incidences of sports injuries, osteoarthritis, and penetration of orthopedic technology [6].

The project emphasized the construction of a prosthetic leg that supports the ease of design, affordability, and fulfillment of the necessities in high-level amputation considering the patient's safety. The prosthetic exoskeleton enables the patients to do basic movements in a very affordable way. Through several alternations of components and methods, Prosthetic Exo-leg was built and tested on human subjects. Prostheses barely fulfill the necessitates of high-level amputations that are particularly challenging for the amputee and the surgeon due to the usage of Surface EMG as a control source of the legs. While companies in biomedical industries are coming up with control strategies such as neural interfaces, and passive prostheses, this project is designed within the powered limb category. The research begins with a study of several research on this field, then subsequently the methods of the E-leg construction that includes, 3-Dimensional design, and theoretical background on which the hardware setup is made. Methodology subsequently led to the hardware setup and implementation through which a result analysis is made consisting of economic benefit, power analysis., limitation, and solution. Finally, the scope of future work incorporating the project is discovered, which will be taken into account while upgrading the prosthetic exoskeleton leg.

II. LITERATURE REVIEW

Several research studies have been conducted to prevent the issues of post-transfemoral amputation as the amputee always deals with high energy consumption for ambulation, balance, and stability.

The design of a modular lower limb exoskeleton provides the idea of three systems consisting of an active hip support exoskeleton, a fully articulated lower limb exoskeleton for gait support, and a system for treadmill-based gait rehabilitation, through which it was proved that a modular exoskeleton is feasible among the three designs as it can be used for several changing requirements. For this inquiry, only design analysis and requirement analysis have been discussed to produce the result [7]. Research has been carried out on the necessary reduction of limitations using prosthesis by the development of a Neural Interface for Lower Limb Prosthesis. It appears that the user must make extra movements to control the mechanically passive prosthesis. On the other hand, a Microprocessor-controlled prosthesis that uses sensors and a microcomputer to read the data from the body parts or to initiate the movements does not require much body movement. A future work containing a Neural interface instead of EMG-based legs might produce better performance while ensuring user safety [8].

Moreover, inquiring on two different types of prosthesis, passive or quasi-passive exoskeletons, and Powered exoskeletons, a pseudo-anthropomorphic exoskeleton SJTU-EX (Shanghai JiaoTong University Exoskeleton) has been discussed with its performance where typical human motions can help optimizing the joint ranges. This paper is mostly design and performance-orientated orientated that compares how modern technology differentiates between walking, jogging, climbing stairs, and squatting to generate output to the powered knee. Here, another fundamental factor has been discussed to follow human motions and lessen several kinematic constraints, the exoskeleton requires an adequate level of freedom [9]. The exoskeleton named H2 (Technaid S.L., Spain) was developed with an assistive gait control algorithm that was able to generate a force field along a desired trajectory. Eventually, a four-weeklong gait training has been evaluated to find out the usability and the users were post-stroke hemiparetic patients [10]. In comparative research with several microprocessor-controlled prostheses such as C-Leg, Orion, Plié2.0, and Rel-K. I, the functionality of C-leg through technical analysis in comparison to other legs. It includes that the C-leg is controlled based on the joint resistance following the principle of a hydraulic system and the system incorporates two different servo valves. This paper also assures how microprocessor-controlled prosthetics are optimal and safe to use instead of conventional mechanical legs [11].

Through performance and technical analysis, all these constructed prosthetics mostly focus on solving the problem of stroke, lower limb amputation, and development studies concerning several future works. However, none of the work has inquired about their stakeholders. As per the above discussion, amputation and stroke are common in working-class people and lower economic nation, despite knowing that there is a solution to one's amputation or disability, one cannot afford to buy such a high-cost prosthesis that require higher cost not only to buy the prosthesis but also to afford necessary physiotherapy, repair, and testing. Through this project, the prosthetic leg's walking pattern compared to normal walking pattern and non-functional user's walking pattern has been discussed or analyzed. Hence, this research carries extensive analysis of comparative walking patterns to evaluate the machine's performance better.

III. Methodology

The design is customized based on currently developed exoskeleton legs worldwide, namely, the Prosthetic E-leg. The aim is to build a leg cost-efficiently to help the lower economic nations to afford the leg providing them with a fully functional prosthetic.

A. *System Overview*

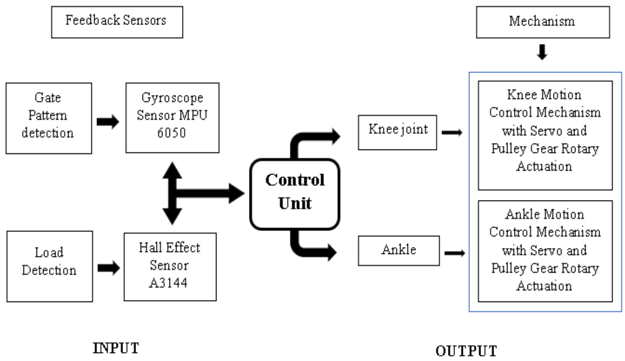

Fig 1: Workflow of Prosthetic Exoskeleton Leg

This system in Fig 1 includes the connection of sensors for gait cycle detection, load detection, and gait assistance control. Gyroscope sensors are used to determine the kinematics of the gait. During the stance phase, hall effect sensors are used to detect the load, while precise motor control in both joints is accelerated by the integration of gyroscope sensors. The hall effect sensor is used for the force feedback control system and the servo motor's position can be maintained and updated based on the force sensor input using hall effect sensor. In case of motor position, it can be adjusted to the corresponding direction when the force is sensed in the ankle joint. Moreover, the use of a hall effect sensor helps stop the toggle switch from unwanted movement in the joints. For the control unit, an esp32 is used for its high clock running speed running. Moreover, it can easily process complex algorithms for prosthetic legs for real-time control. Concerning human movements that require accurate data and fast processing to forecast human movement, ESP32 is a great fit for the design.

B. *Theoretical Background*

The Hall effect sensor is attached to the bottom of the foot, where a customized 3D printed pad with Thermoplastic polyurethane filament is added, which bends when the subject is subjected to a particular weight, and the sensor detects moving load. As a result, the knee joint is locked while the prosthetic leg is in the pre-swing phase position, and the ankle joint moves spontaneously during the limb's loading response. When the leg is in the swing phase and at the terminal stance position, the knee joint actuator engages and moves to the recorded angle while moving forward using the gyroscope sensor inputs as feedback.

One of the signification factors in designing a prosthetic leg is to understand the normal gait pattern of walking in Fig 2. This gait pattern consists of multiple variables starting with step length, stance length, timing, and stance-to-swing ratio. These features determine the pattern and timing of motions when walking, which helps ensure optimal and steady mobility. To record the data about the walking gait, gyro

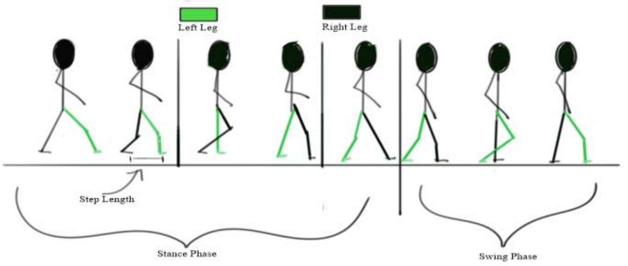

Fig 2: Gait cycle of human walking for stance phase & swing phase

sensors have been mounted on an ordinary leg. When a person is walking, gyro sensors track the direction and movement of the legs by measuring their angular acceleration. This data is further analyzed and processed to derive data on gait patterns that involve joint angles and the timing of various gait phases. The prosthetic leg's gait pattern is then imitated using the data on recorded gait patterns. Through a process of trial and error, the gait pattern is adjusted for the prosthetic leg. Finally, the gait pattern is adjusted until it forecasts the desired movements by continuous iteration to change the code.

The Gyroscope sensor measures the angle of both knee and ankle joints as accelerometer raw data. Through the gyroscope sensor, the angular velocity of the leg's movements is recorded for healthy human movements, movements with poly acrylic leg, and Prosthetic Exo-leg. As per Fig 3, the system axis measured for the experiment were the X-axis, Y-axis, and Z-axis, which specify the rotation of the sensor. The X-axis indicates the acceleration of the longitudinal axis of the human body. Y-axis is the acceleration within the sagittal plane of the subject's leg. However, Z-axis indicates the acceleration within the frontal plan that adds minor value to human walking. Hence, infographics of the gyro sensor's two coordinate system axes are added to determine the performances with respect to healthy human movements and movements with non-functional legs the subject has been using for 6 to 7 years.

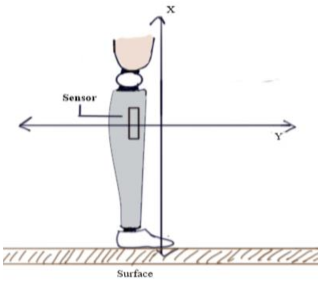

Fig 3: Movement axis of gyroscope sensor (X-axis, Y-axis)

C. 3-D Design

Fig 4: 3-D model of E-leg for the ankle and outer body structure

Concerning all the trial and error, a final 3D design is made to implement the hardware design as Fig 4. The socket of the design is excluded as the socket has been constructed with customized size and width for the subject's leg size, and width.

The 3D design allowed a primary forecast of the result through various simulations regarding the structural stability, material integrity, motion analysis, and load analysis of the project. In Fig 5, the positioning of the MPU6050 Gyroscope is indicated through a 3D design.

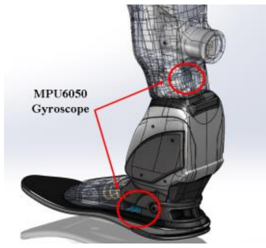

Fig 5: Position of gyroscope & accelerometer (MPU6050 Gyroscope) in E-Leg

Besides, a few functional analysis such as movement, angle, and force measurements were monitored to reach a definite conclusion about the materials and choose an appropriate process to be followed. Hence, during the pre-construction period of the hardware, the following steps were taken to achieve suitable components, size, and width of the prosthetics,

a) Production drawing
b) CNC cutting
c) Bending using a hydraulic bending machine
d) Shaping using a Lathe machine
e) 3D printing using TPU and PLA Filament

IV. HARDWARE SETUP

A. Circuit Layout

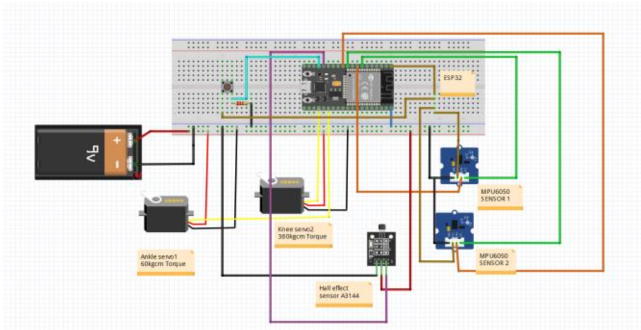

Fig 6: E-leg's hardware connection circuit

Based on Fig 1, a circuit has been designed in Fritzing using the necessary components selected for the project in Fig 6. The circuit consists of a power source, microcontroller, sensors, and servo motors, providing an idea of how the system works while indicating major power source changes needed to acquire.

However, the initial design is not compact and requires a large space for the wiring and placement in the machine leading to a hefty design. Therefore, a voltage distributor board was designed in EasyEDA aiming to compactify the circuit above the ankle. The design in Fig 7 also contributes to a simpler hardware design implementation.

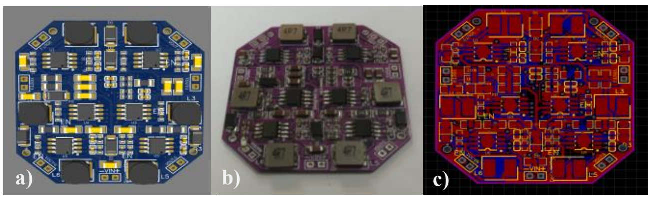

Fig 7: Voltage distribution board of E-Leg, a) 3-D diagram, b) Printed circuit board, c) PCB layout

B. Component Specification

Specifications of fundamental components used for the project are shown in TABLE I.

TABLE I: COMPONENT SPECIFICATIONS

Components	Model	Specifications
ESP-32		Processor: Dual-Core 32-bit Connectivity: Supports Wi-Fi (Up to 150mbps)
Gyroscope Sensor	MPU6050	3-axis sensing, Operation range: -40°C to +85°C Accuracy: ±3°C
Hall-Effect Sensor	A3144	Operating voltage: 3.5mA Temp Range: -40°C to +85°C
High Torque servo motor		1. 60kgcm Size: 4.65 x 4.13 x 1.57 inches Operating Angle: 270 degree Weight: 200Grams Voltage Range: 6v-8.4v 2. 380kgcm Size: 13.21 x 9.91 x 6.86 cm. Weight: 635 Grams Voltage Range: 12V~24V

C. Hardware Implementation

The hardware design has minor changes compared to the 3D design as we have changed its size and width. The leg weighs 2.4 kilograms. For hardware implementation and performance evaluation, experiments have been devised with the human subject. The Subject has been using non-functional prosthetics for 6 to 7 years, and it has also been taken into account during the performance to record mentionable changes in walking patterns. In Fig 8, the performance was evaluated in three separate ways for an average time of 4 minutes as the subject has a medical condition called "Myasthenia Gravis" concerning consequent muscle weakness and fatigabilities.

Fig 8 : Hardware implementation and 3-way data collection: a) With Prosthetic Exo-leg, b) Healthy human walking, & c) With poly acrylic leg

1. Walking pattern of a normal human being
2. Subject with Poly Acrylic Leg (Non-functional),
3. Subjects with Prosthetics Exo-leg (Fully functional)

V. RESULT ANALYSIS

A. Performance Analysis

In Fig 9, for the normal walking pattern, the data suggests are quite uniform as the distribution of three displacements is quite equivalent. The movement of the Poly Acrylic Leg is quite stiff, and the lines suggest that all the movements are inclined towards dragging motion due to its non-functionality where the subject must control it during the movements.

In case of the pattern suggesting walking with a prosthetic Exo-leg, the data confirms similar patterns as healthy human movements in terms of the y-axis. The subject has been using a poly acrylic non-functional leg for years, which is why movements created during the phase are almost equal to a straight line whereas the prosthetic Exo-leg functioned approximately similar to healthy human patterns without any training or physiotherapy in the case of y-axis. However, it is believed that major improvement is possible in the x-axis deviation if the patient is given physiotherapy and training for 3-4 months with the machine.

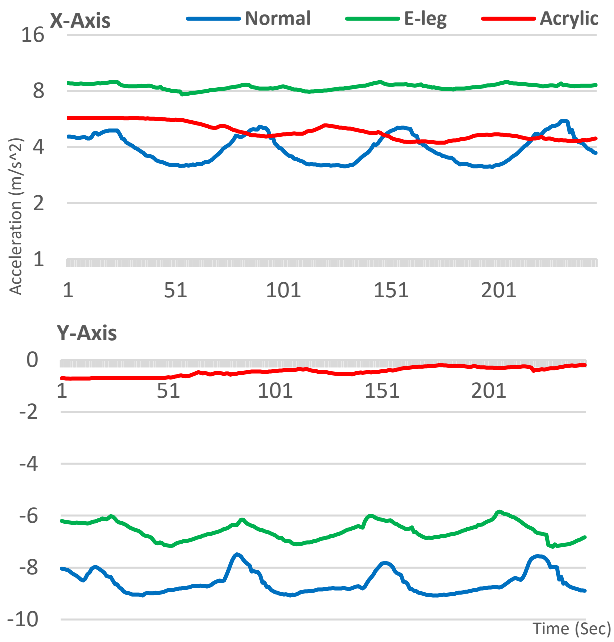

Fig 9: Gyro sensor's X and Y-axis deviation for time vs acceleration

B. Limitations and Solutions

Accelerometers can be noisy in the short run but can offer overall accurate data. Accordingly, the Gyroscope sensor delivers correct information regarding changing orientation, but the necessary integration causes the values to drift over longer time scales. The issue occurred during the experiments as the raw data suggest unwanted spike in peak values indicating unwanted increase in acceleration. By fusing the accelerometer and gyroscope data through the Kalman filtering process, the errors appear to cancel out.

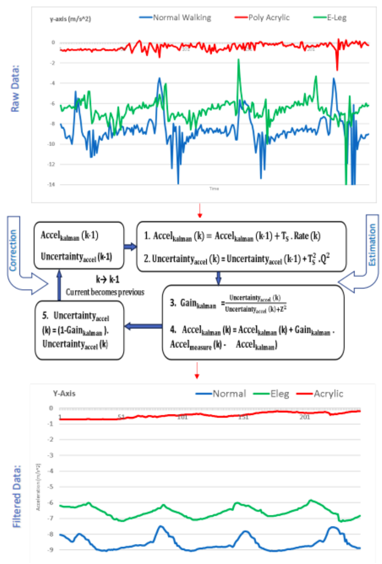

Fig 10: Kalman filtering of Y-axis

In Fig 10, during the fusion, the Kalman filtering method has been adopted to get accurate and smooth sensor values. The sensor's fusion technique improves the accuracy of measurements. Kalman filter is processed by a set of mathematical formulae and used through coding to the system that reduces the average square errors resulting in any drift of value while estimating the state of events effectively and iteratively [12]. Here, T_s represents the time step between consecutive updates, and Rate (k) is the gyroscope rate input at time k. Q indicates the standard deviation of the gyroscope measurement error and Z represents the accelerometer measurement error [13]. The above process shown in Fig 10 predicts acceleration concerning the uncertainties related to gyroscope and accelerometer observations. The Kalman gain ($Gain_{Kalman}$) refines the accuracy and reliability of acceleration over time through an iterative process to balance the prediction and measurement data. Hence, using the Kalman filtering process, the purpose of making assumptions about an event using minimal data is satisfied.

C. Run Time Analysis

Two Li-po batteries with a capacity of 2800mAh each. Here is a theoretical analysis of how long the prosthetic E-leg will be operating [TABLE II].

TABLE II: PROSTHETIC E-LEG RUN-TIME ANALYSIS

Components	**Consumption (mAh)**	**Total Run-Time (hours)**	**Total Run-Time With 90% Efficiency (Hours)**
Servo	410- 510	10.855869-13.541616	9.770282-12.187455
Gyro-Sensor	0.3-0.5		
Hall Effect Sensor	3-5		
ESP-32	0.24-0.35		
Total	413.54-515.85		

Therefore, both batteries with a total capacity of 5600 can be operated for 10.86 to 13.54 hours without 90% efficiency and 9.77- 12.19 hours with 90% efficiency. Practically, the E-Leg's runtime is recorded around 8 Hours and 50 Minutes during its first operation without the subject wearing it. The C-Leg's battery can last for 40-45 hours, and it is not portable [14]. In case of E-Leg, the run time can be varied using portable Lipo-battery as the system is made for portable battery usage. Patient Can be able to carry extra batteries for longer operating time. The battery can also be charged during necessity.

D. Cost Benefit Analysis

Most people in lower and middle-income countries cannot afford to buy a non-functional prosthetic exoskeleton leg let alone the functional legs. The constructed project validates a principal goal of aiding lower and middle-income countries. Besides, the machine can be used as efficiently as C-leg based on different components' alterations, reduced manufacturing costs, working methods, and power management.

The knee joint and ankle joint for the hydraulic actuation system cost respectively 3,700 USD according to India Mart and around 516 USD as per Alibaba [15-16]. According to Bionics for Everyone, the C-legs sell for between 40,000 and 50,000 USD which sells even higher in lower-income countries [17]. Besides, as per a Bangladeshi Limb Center namely Dynamic Limb Center, the selling price of each leg is discussed from 4,592 USD to 5,504 USD and the limbs are built using a hydraulic damping mechanism [18-19]. Moreover, a non-functional leg can be brought for around 412 USD to 21,108 USD as per our Subject's poly acrylic leg cost and the user's review on YouTube.

The prosthetic Exoskeleton leg, on the other hand, is manufactured in a very cost-efficient way. The initial budget plan without manufacturing and miscellaneous costs was 525.74 USD. Afterward, the final budget is set to be 814.84 USD inclusive of the workshop cost adjustment, miscellaneous costs, and current price increment. A huge portion of miscellaneous costs can be reduced during big groups of manufacturing. Comparing the price range of C-leg, and non-functional prosthetic leg, evident that a Prosthetic Exo-leg can be manufactured within 525.74 USD fulfilling the user's demand for performance and cost.

TABLE III: PROSTHETIC E-LEG (APPROX. SELLING PRICE) COMPARED TO C-LEG MARKET PRICE

Limb Type	**Lowest Range in USD**	**Highest Range in USD**
C-leg [17]	40,000	50,000
Prosthetic E-Leg (Approx. Selling Cost)	918	1,378
Cost Difference	39,082	48,622

TABLE IV: PROSTHETIC E-LEG (APPROX. SELLING PRICE) COMPARED TO NON-FUNCTIONAL PROSTHETIC LEG MARKET PRICE

Limb Type	**Lowest Range in USD**	**Highest Range in USD**
Non-functional leg	412	21,108
Prosthetic E-Leg (Approx. Selling Cost)	918	1,378
Cost Difference	-506	19730

Comparison in TABLE III and TABLE IV validate that a fully functional prosthetics Exoskeleton leg is developed that can function similarly to C-leg and can be afforded within the cost range of non-functional legs does not provide the patient any degree of freedom in movements.

E. Summary

Performance analysis and cost-benefit analysis conducted in previous sections validate that Prosthetic Exoskeleton Leg is built to be optimal in both performance and affordability of users. The project is built on available components that are easy to avail and the design being simple, it lessens the repairability cost as well. Moreover, it functioned fully during the experiment and the run-time was 8 hours and 50 minutes with 90% efficiency which was estimated to be 9.77 to 12.19 hours. Whereas the normal non-functional leg appears to be expensive based on quality, this project ensures a fully functional system within a range of non-functional legs. The body is robust and lightweight. Based on an article written in Bionics for Everyone, a C-leg weighs 1.24 kg where the maximum allowable user weight for the knee is 136 kilograms [15]. Prosthetic E-leg weighs 2.4kg which is properly bearable for amputees. The hardware performances during the experiment indicated similarities with healthy human walking patterns in the first day and it can further be improved with training and physiotherapy.

VI. Conclusion

In this paper, a rotary actuation system of the Prosthetic Exoskeleton Leg is built using available components in the market and limb centers to achieve similar performances of a healthy human leg. When the C Leg's affordability is very low due to its high range of prices, Prosthetics Exo-leg is more affordable in both lower and middle-income countries. The constructed design is very innovative contemplating the alteration of components and methods as the hardware is functioning. The development of Prosthetic Exo-leg opens a wider parameter of prosthesis users considering the user's affordability and availability of components. Moreover, its performance seems nearly positive as methods have been used to replicate healthy human movements and data taken during initial hardware implementation indicates probable improvement through patient's physiotherapy and training.

A. Future Work

Few limitations are recorded to adjust in future work. The project is active in finding and developing efficient solutions to amputation, stroke, monoplegia, and injury with powered knee systems. Besides, the design is very flexible and newer solutions can be developed for more amputations such as transtibial amputation, ankle amputation, and upgrading the Prosthetic for stroke and monoplegia patients.

Moreover, the active project is not water resistant. With the use of high-level material such as e-poxy and, Silicon gasket using water-resistant external body, a water-resistant system can be constructed for extended usage. Finally, a mobile application is prospected to be developed once the project is completed for user training and support on any immediate assistance during emergencies and self-training. It is anticipated that numerous amounts of future work can be done on this project as it is easily upgradable and repairable.

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