A Novel Design of Smart Knee Joint Prosthesis for Above-Knee Amputees

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Amputees suffer greatly from lower limb amputation. A novel smart knee joint prosthesis was constructed in this research to allow the amputee to achieve regular daily movement, such as walking, standing, and ascending/descending stairs. This prosthesis employs sensors, actuators, and a mechanical system to replicate the functioning of a natural limb. As a result of the unique mechanical and electrical components employed herein to boost performance, metabolic energy is lowered. Here, a ball screw is employed, which has been determined to be the most efficient means of achieving linear motion; its precision and efficiency range from 90% to 100%. It is quieter and more efficient than a hydraulic or pneumatic system. An electromechanical linear actuator (servo cylinder) is used with an actuator control system and integrated Phase Index - Field-Oriented Control. It maintains and self-calibrates the needed position with high precision when power or backup power is unavailable. The angle of flexion achieved in this design is 120°. The gait analysis revealed that the current prosthesis could imitate the biomechanics of the normal joint with no difficulty at varied speeds when tested on an amputee (110 kg). Furthermore, it may function efficiently as a passive when power is unavailable, including the capacity to move smoothly throughout the swing phase (high accuracy through deceleration and acceleration). The current active knee joint is lightweight (2869 grams), and the cost has been greatly reduced.

Keywords: *Powered knee joint prosthesis, IMU, wearable sensor, Phase Index, Kalman filter.*

1. INTRODUCTION

Regardless of the place or degree of amputation, amputations are life-changing. Following the traumatic experience of losing a limb, amputees go on the road of rehabilitation and recovery, hoping to return to normal full life [1] finally. Disabled persons have the same health conditions as non-disabled people, allowing them to accomplish everyday activities, including socializing, working, and participating in sports. A person with a handicap caused by lower-limb amputations, particularly, cannot do routine daily activities (e.g., walking, running, standing, sitting, and ascending /descending stairs) without a supporting device.

The linked motion disorder might be congenital or develop over a person's life [2]. Amputees are becoming more common due to war, disease, and injury. Patients with below-the-knee amputation surgery still have a knee joint, making walking with a prosthetic simple [3]. A passive prosthesis, however, causes an abnormal gait in femoral amputees. Various prosthesis forms have been developed to allow these amputees to walk naturally. The manufactured prosthesis may be divided into passive and active prostheses. The framework of the passive prosthesis saves energy and reduces physical strain on the user [4]. However, amputees consume around 60% more energy than others since walking requires the wearer's muscles [5]. A passive prosthesis balances the impedance with a power supply to assist with walking [6–9]. The user of the active prosthesis has less physical stress than with the passive prosthesis while still being able to walk normally. Literature has addressed this issue since it is crucial to provide such prostheses, which have various structural variations and /or can execute difficult walking requirements [10, 14].

This study aims to construct and control a revolutionary smart knee joint for amputees above the knee. Sensors, actuators, mechanical structures, and control algorithms are employed to mimic natural limb functions. The unique smart artificial knee joint prosthesis with high efficiency and perfect match with the human knee joint of the above-knee amputee leads to reduced metabolic energy, allowing the amputee to perform various daily movements, thanks to the mechanical and electronic parts used in the current design.

2. KNEE JOINT DESIGN

Prosthetic feet can meet numerous biomechanical requirements during the stance phase of the gait cycle. Other from toe clearance has no use throughout the swing phase.

The prosthetic knee joint must prevent the amputee from tripping or falling during stance due to unintentional flexion. The prosthetic knee joint must manage the lower limb during the swing phase such that toe

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clearance and subsequent weight acceptance are accomplished when walking at various walking speeds [12]. The consequences of these posture and swing demands result in two entirely distinct kinds of functions:

1. Stance phase = Secure support and flexion control of the knee joint
2. Swing phase = Safe and easy walking, control of acceleration, and deceleration properties.

Various control options are available for knee joint prosthetic technology to prevent accidental bending during heel strike and mid-stance [12]. Figure 1 illustrates the double-pendulum functionality of the prosthesis, which is suspended from the hip joint during the swing phase.

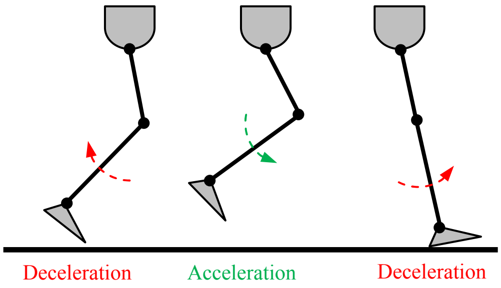

Figure 1. Swing phase control functions

During the swing phase, the thigh is propelled forward by hip flexion and forward advancement. It needs to catch up because of the substantial heft of the foot and the unlocked knee joint. Due to the inertia of the prosthesis during the acceleration of the swing phase, an excessive heel rise occurred, resulting in increased knee flexion. This creates larger-than-normal delays in kinematic results (called first temporal delay). The amputee attempts to compensate for this delay by rapidly decelerating hip flexion, which flicks the part distal about an extended knee forward. Close to the finish of the swing, the knee extends till it meets the extension stop (terminal impact). While the knee joint cannot be extended any farther, the distal section's forward velocity swings the entire leg around the hip like a double pendulum. The momentum of the forward pendulum is interrupted as the heel strikes the ground due to powerful hip extension. As a result, I hit the ground in a down-and-back direction. This kinematic motion is known as the second temporal delay. The time delays increased when this swing was not controlled. In this case, the amputee misses one prosthetic step and hops twice on the sound leg [15].

2.1 Servo Electric Ball Screw Cylinder Actuator vs. Pneumatic and Hydraulic Cylinders Actuators

Actuators are mechanical devices that can convert energy into movement. Actuators operate machinery and allow system components to move. Regardless of the energy source, the commanding signal can be either manually or automatically regulated.

Actuators are often crucial in industrial and manufacturing activities where valves, pumps, motors, and switches are enabled. Actuators often control and steer mechanical motion. This action can be one of the hundreds of activities such as raising, clamping, blocking, and ejecting. Oscillatory, rotatory, or linear movements are possible. In other words, the motion may be in one direction, circular, or back and forth at regular intervals. It would be easier to do with the help of an actuator, regardless of what the ultimate motion of a mechanized machine demands.

Actuators are classified into three types: hydraulic, pneumatic, and electric. Hydraulic actuators employ fluid to create motion, such as pistons moving in a cylinder. Pneumatic actuators create motion by using compressed air or gas, such as a diaphragm moving in a cylinder. Electric actuators create motion using electricity, such as a motor rotating a shaft. They're frequently employed in precise applications like industrial machines or medical equipment. Each type of actuator has advantages and disadvantages, and the choice of the actuator will rely on the specific needs of the application [16, 17-18]. Table 1 summarizes a comparison of different actuators.

2.2 Mechanical Components

Ball Screw: A Ball Screw is a linear mechanical actu–ator that transforms rotational motion into linear motion by utilizing ball bearings as a precision screw on a threaded shaft. With minimal internal friction, ball screws can be withstanding and apply significant thrust loads. They are designed with tight tolerances, making them an excellent choice for high-precision applications.

The primary reason for using a ball screw in a device is the necessity for power. Compared to pneu–matic and/or hydraulic systems, an electrically controlled ball screw is significantly simpler and more accurate. The ability of ball screws to put within micron accuracy magnifies this value. In addition to high accuracy and lengthy strokes of up to 5 meters, ball screws may reach speeds of up to 2 meters per second (Figure 2).

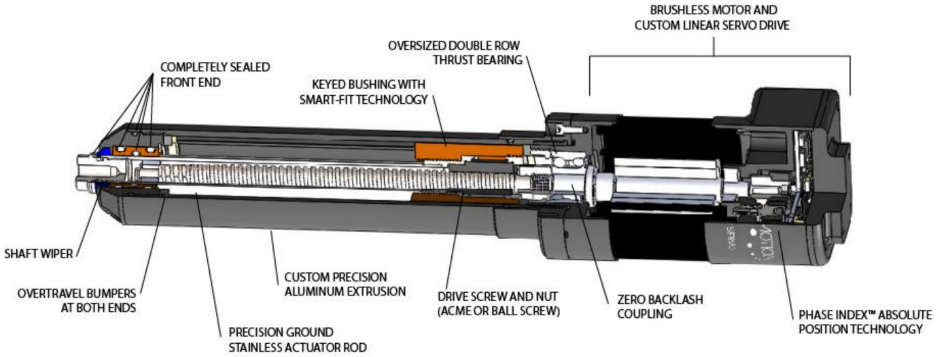

Figure 2. Anatomy of an A1 series Servo Cylinder [19]

Table 1: Servo Electric Ball Screw Cylinder Actuator vs. Pneumatic Cylinder and Hydraulic Cylinder Actuators [13,14]

Specification	Electric Cylinder Ball Screw	Hydraulic Cylinder	Pneumatic Cylinder
Motion Profile Control and Flexibility	Easy and Flexibility of motion control capabilities with electronic controller	Limited or Complex Servo-Hydraulics	Limited or Complex Servo-Pneumatics
Positional Accuracy	High Accuracy	Limited with Complex Servo-Hydraulics	Limited with Complex Servo-Pneumatics
Max Force	Very High	Highest	Medium
Max Speed	Very High	Very High	Very High
Actuator Life / L10	Very High / Calculated	Medium / NA	Medium / NA
Maintenance	Very Minimal	High	High
System Efficiency	~ >90%	~ 40 To 55%	~ 10 To 25%
Energy Consumption	Lowest	High	Very High
Shock Loads	Very High	Very High	Very High
Operational Temperature	Very Tolerant & Efficient	Seal Failure, Sluggish Operation	Seal Failure, Sluggish Operation
Environmental	Very Minimal	Hydraulic Fluid Leaks and Disposal	High Noise Level
Installation	Compatible with Standard Servo Electronic Controls	Complex, Filtering Pumps, Servo-Valves are Required, High-Pressure Plumbing, Linear Positioning, and Sensing	Very Complex, Servo-Valves are required, Filtering, Plumbing, Compressors, Linear Positioning, and Sensing
Utilities	Power Only Option	Pump, Power, Pipes	Compressor, Power, Pipes
Purchase Cost	High Cost	High Cost	Low Cost

As a result, a ball screw was employed to design a powered knee prosthesis with structure and actuation via an Actuator Brushless DC (BLDC) motor and a ball screw, as illustrated in Figure 3. Where X is the length of the actuator, L_1 and L_2 are the distances between the ax–les, α_o is the starting angle when the knee angle is fully extended is 0°, and θ is the knee angle flexion to a 120° angle.

The following explains the relationship between the forces produced by the actuator and the torque of the knee joint [6]:

$$\tau_K = F * \frac{\partial X}{\partial \theta} \tag{1}$$

where τ_K represents the knee joint torque, and F is the actuator force. The actuator's force is represented as follows:

$$F = \frac{2\pi}{L} \tau_m \tag{2}$$

where L is the ball screw lead, and τ_m is the BLDC motor torque. The actuator length may be represented geometrically as follows:

$$X = \sqrt{L_1^2 + L_2^2 - 2L_1 L_2 \cos\left(\alpha_0 + \theta\right)} \tag{3}$$

When equations (2) and (3) are substituted into equation (1), the following result is obtained:

$$X\tau_K = \frac{2\pi}{L} \frac{L_1 L_2 \sin\sin\left(\alpha_0 + L\right)}{\sqrt{L_1^2 + L_2^2 - 2L_1 L_2 \cos\left(\alpha_o + \theta\right)}} \tau_m = A\left(\theta\right) \tau_m \tag{4}$$

where A(θ) represents the function that relates the motor torque and the knee joint torque.

Equation (3) and $\theta_{k,0}$ can be used to obtain the initial actuator length. Equation and the reference knee angle compute the reference actuator length (3). The motor's rotational displacement and the ball screw's lead length are used to compute the length of the current actuator, which is then represented as follows:

$$X = X_0 + L * \theta_m \tag{5}$$

where X_o is the initial actuator length. The reference rotational displacement is calculated by dividing the lead length of the ball screw by the difference between the current actuator length and the reference actuator length and expressed as follows:

$$\theta_{m,ref} = \frac{X_{ref} - X}{L} \tag{6}$$

where x_{ref} is the reference actuator length, and θ_m refers to the DC motor reference rotational displacement. The following equation is used to determine the knee joint angle:

$$\theta_K = \cos^{-1}\left(\frac{L_1^2 + L_2^2 - X^2}{2L_1 L_2}\right) - \alpha_0 \tag{7}$$

2.3 Design of Smart Knee Joint Prosthesis

The main objective of the current paper is to design a low-cost smart knee joint prosthesis that mimics the natural knee performance during normal mobility of the amputee. This prosthesis works effectively with the aid of sensors and electronic circuits. A program was built to control and monitor the smart limb's motion in real time. As a result, the user is no longer required to rotate the prosthesis with the hip by applying a positive force.

Driven prostheses offer stability and propulsion while ascending stairs and hills, distributing forces evenly across the joint and requiring significant energy from the prosthetic knee. Advanced motor systems control these complex movements, and incorporating a kinesthetic control loop can further enhance the prosthetic experience, as depicted in Figures 4 and 5.

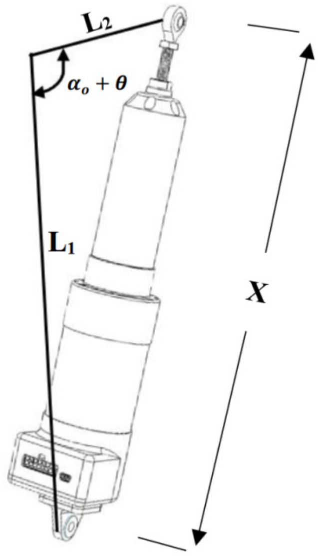

Figure 3. The knee joint configuration with the parameters L_1, L_2, X, and θ.

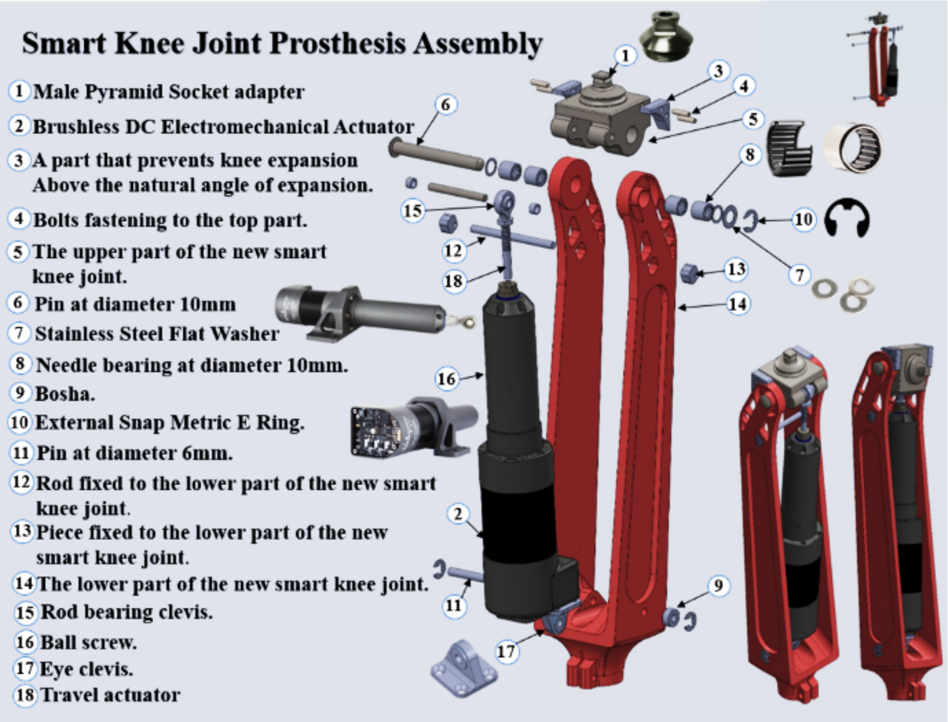

Figure 4.The smart knee joint prosthesis assembly

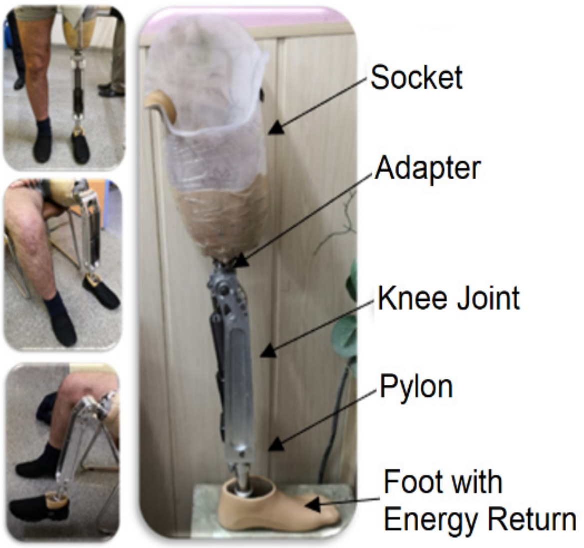

Figure 5.The final design of the smart knee joint prosthesis.

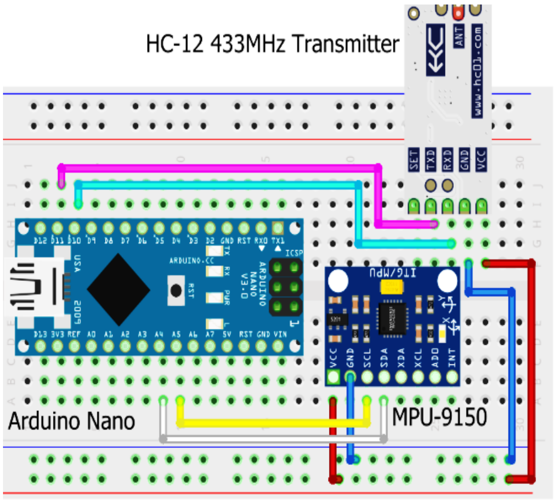

Figure 6. Knee Angle Transmitter Circuit diagram

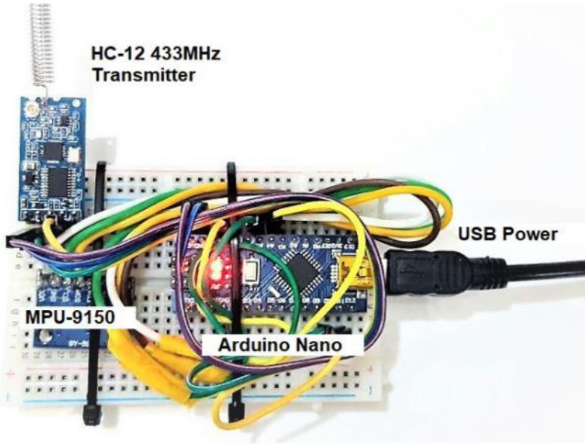

Figure 7. Physical components of Knee Angle Transmitter Circuit

2.4 Electronic Circuit Diagrams

Knee Angle Transmitter Circuit

The knee angle transmitter circuits that provide angle measurement during the gait cycle are illustrated in Figures 6 and 7. These circuits consist of an HC-12 Wireless Transceiver, an Arduino Nano, and an MPU-9150, a multi-axis motion sensor module with a 9-axis motion tracking capability. This module integrates a 3-axis MEMS gyroscope, a 3-axis MEMS accelerometer, a 3-axis MEMS magnetometer, and a Digital Motion Processor (DMP) hardware accelerator engine, making it the world's first of its kind.

In this study, the I2C (Inter-Integrated Circuit) serial communication protocol facilitates communication between the Arduino Nano and the MPU-9150. Specifically, the magnetometer data obtained from the MPU-9150 is transmitted to the Arduino Nano and filtered using a Kalman filter algorithm. The resulting data is wirelessly transmitted to the Servo Motor Controller using the HC-12 wireless communication module. This approach enables effective communication and data transfer between the system's components, supporting the overall design's successful operation.

Servo Motor Controller Circuit

The primary force behind the Ultra Motion Servo Actuator is the Servo Motor Controller Circuit, which can be observed in Figure 8 and Figure 9. This circuit comprises the HC-12 Wireless Transceiver, MPU-9150, and NodeMCU 8266 Microcontroller. The HC-12 receives data wirelessly from the Knee Angle Transmitter and utilizes Pulse-Width Modulated (PWM) signals to steer the servo motor.

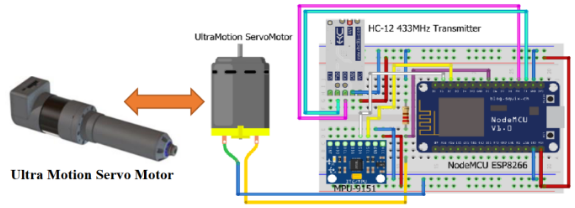

Figure 8. Servo Motor Controller Circuit diagram

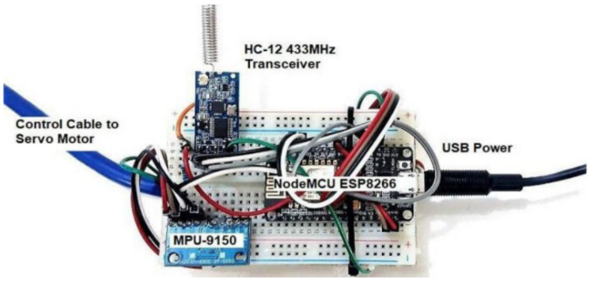

Figure 9. Physical components of the Servo Controller Circuit

The measurement of knee joint angles was achieved using IMUs (Inertial Measurement Units). This intelligent artificial knee joint angle measurement was simulated on a healthy individual to replicate the motion, as shown in Figure 10.

Figure 10. Work environment and testing

The angle transmitter was fixed to the healthy leg to measure the knee angle reading and employed the MPU-9150. Subsequently, the collected data was transmitted to the Servo Controller Circuit via the HC-12, as illustrated in Figure 11. Figure 12 displays a schematic diagram of the overall servo control system implemented in this work. The diagram provides a clear visualization of how the system is structured and controlled.

Figure 11. Smart Knee Joint with Servo Controller Circuit Attached

3. EVALUATION OF THE SMART PROSTHETIC KNEE JOINT WITH THE ABOVE-KNEE AMPUTEE

The smart artificial knee joint was evaluated on an above-knee amputee. The knee joint was designed and manufactured, and the various parts were assembled to form a functional joint. Before the start of the testing, the patient's alignment and mechanical movement were adjusted to ensure the best possible outcome. The patient was a 34-year-old male who weighed 85 kg and had a short amputation level, which was considered the most challenging case. To achieve maximum function and weight-bearing area, the level of amputation should allow for the longest possible residual limb. In this case, the amputation was above the knee, with a distance of approximately 15 cm from the end of the amputation to the middle of the knee, as depicted in Figure 13. However, it's essential to maintain a distance of approximately 12 cm between the end of the stump and the knee to accommodate the prosthetic knee joint.

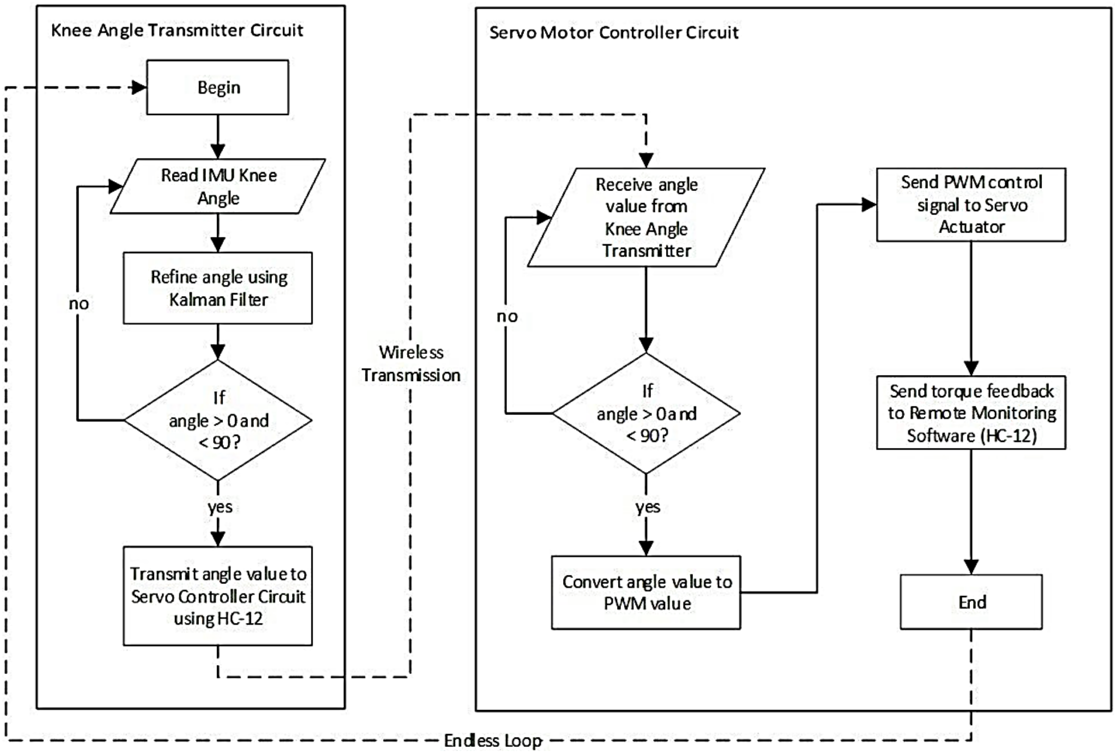

Figure 12.Servo Control Flowchart

Figure 13.Level of above-knee amputation.

Nevertheless, the smart artificial knee joint proved highly efficient in daily activities such as walking, sitting, and performing other movements. Moreover, the joint demonstrated high resilience against power failures at the source, ensuring smooth and uninterrupted movement even during such events.

1. RESULT AND DISCUSSION

4.1 Intelligent Artificial Knee Joint Angle Measurement Test

To evaluate the performance of the knee joint, a single IMU was fixed to the front of the left leg. The person was then asked to stand upright on their right leg while the prosthetic knee joint was in use. The joint's performance was compared to that of a healthy leg, and a close agreement was observed. The healthy leg belonged to a 31-year-old healthy male who weighed 94 kg and was 173 cm tall (as shown in Figure 14). The novel design of the joint allows the leg to be lifted to a reasonable height and achieves good performance during the swing phase.

Through evaluation tests of the knee prosthesis, it was established that the joint could simultaneously stretch and flexion movements during the gait cycle. Figure 15 demonstrates excellent agreement between the actual knee joint angle of the healthy person and the desired angle of the intelligent knee joint. This confirms that the smart knee joint prosthesis can accurately replicate the gait cycle.

The proposed control strategy emphasizes wireless technology based on IMU sensors, which can provide signals even from a smartphone device. This makes adapting low-cost strategies in designing and constructing lower-limb prostheses possible. Another advantage of this strategy is that it does not require prior training, which is preferable for patient rehabilitation.

Figure 14. Joint movement as compared with the healthy leg movement and the Angle Measurement Test.

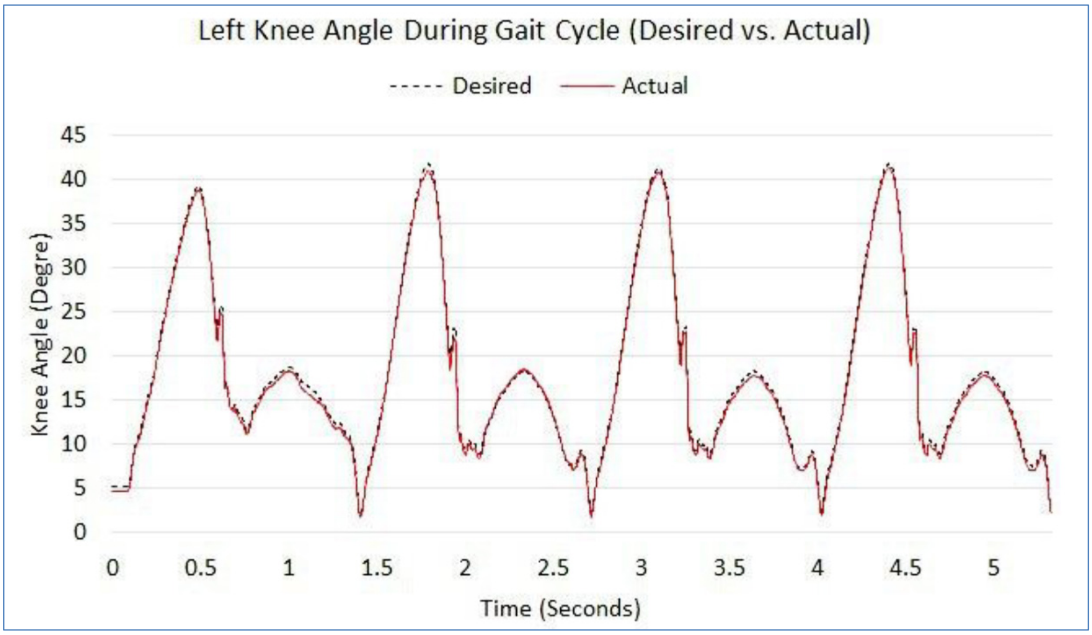

Figure 15. Left Knee Angle during the gait cycle (Desired vs. Actual)

4. RESEARCH ORIGINALITY

The research presented in this study focuses on developing a novel smart prosthetic knee joint that closely emulates the natural knee joint. The primary objective of this design is to minimize the amount of muscular effort required by amputees and alleviate some of the difficulties that above-knee amputees face. By providing positive energy, the prosthetic knee reduces energy expenditure and offers greater comfort to the individual. Additionally, it enables amputees to perform a variety of everyday movements at different speeds, including slow, medium, and high. This innovative design has the potential to greatly enhance the mobility and quality of life of individuals who have experienced limb amputation.

5. CONCLUSIONS

The present work presents a novel smart knee joint prosthesis designed to provide mobility to amputees during daily life activities. The results show that the designed prosthesis successfully mimics the natural knee joint, addressing most of the problems amputees face. The positive energy gained from the active system provides support to the joint and helps in normal walking, sitting, and climbing stairs and slopes that require energy from the knee joint. The novel design enables the amputee to lift the leg to a high height, achieving success in the swing phase and achieving deceleration and acceleration with high accuracy.

The total cost of the prosthesis is significantly reduced compared to available commercial ones. The current design is simple, lightweight, and within the normal limits of the knee joint. An important feature of the current design is its passive functionality in case of power failure. The knee joint also detects movement signals from the residual limb, allowing simulation of the biomechanics of the missing limb.

The proposed control strategy based on wireless technology using the IMU sensor makes the prosthesis adaptable to low-cost strategies in designing and constructing lower-limb prostheses. The strategy does not require prior training, making it preferable for patient rehabilitation.

Overall, the present work offers a promising solution to the challenges faced by amputees. The evaluation tests of the knee prosthesis reveal that it successfully simulates the natural knee joint biomechanics, improving the amputee's quality of life.

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NOMENCLATURE

F	the force generated by the actuator
L	the lead of the ball screw
X_o	the initial actuator length
x_{ref}	the reference actuator length

Greek symbols

θ	is the knee angle flexion
$\theta_{\mathrm{m},\,ref}$	the reference rotational displacement of the DC motor
τ_k	the torque of the knee joint
τ_m	is the BLDC motor torque

НОВИ ДИЗАЈН ПАМЕТНЕ ПРОТЕЗЕ КОЛЕНСКОГ ЗГЛОБА ЗА ОСОБЕ СА АМПУТАЦИЈОМ ИЗНАД КОЛЕНА

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Ампутирани у великој мери пате од ампутације доњих екстремитета. Нова паметна протеза коленског зглоба конструисана је у овом истраживању како би ампутирани корисник могао да постигне редовно свакодневно кретање, као што је ходање, стајање и пењање/спуштање степеницама. Ова протеза користи сензоре, актуаторе и механички систем за реплицирање функционисања природног екстремитета. Као резултат јединствених механичких и електричних компоненти које се овде користе за повећање перформанси, метаболичка енергија је смањена. Овде се користи куглични вијак, за који је утврђено да је најефикасније средство за постизање

линеарног кретања; његова прецизност и ефикасност се крећу од 90% до 100%. Тиши је и ефикаснији од хидрауличног или пнеуматског система. Електромеханички линеарни актуатор (серво цилиндар) се користи са системом управљања актуатором и интегрисаним индексом фаза – управљање оријентисано на поље. Одржава и самостално калибрише потребну позицију са великом прецизношћу када напајање или резервно напајање нису доступни. Угао савијања постигнут у овом дизајну је 120º. Анализа хода је открила да тренутна протеза може да имитира биомеханику нормалног зглоба без потешкоћа при различитим брзинама када се тестира на ампутираном (110 кг). Штавише, може ефикасно да функционише као пасив када је напајање недоступно, укључујући способност да се глатко креће током фазе замаха (висока прецизност кроз успоравање и убрзање). Тренутни активни зглоб колена је лаган (2869 грама), а цена је знатно смањена.