SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Dynamic Model Design and Controller Development of Lower Limb Prosthesis Through Matlab Simscape Multibody Toolbox

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ABSTRACT

Indeed, humans have achieved remarkable feats. Even so, some people lose parts of their bodies due to accidents, disease, or any other reason. Among them, lower limb amputation is the worst. Thus, prosthesis provides an appropriate solution to assist amputees in reintegration into society. Unfortunately, the user of several prostheses feels like a robot when using the prostheses with a traditional controller. Therefore, several efforts have been made to convey the amputee's brain instructions to the prosthesis using electromyography (EMG) sensors attached to the patient's residual muscles. This study aims to derive and realize the model of the lower limb prosthesis using the MATLAB Simscape Multibody library. The simulation model has been created by importing the essential structure from the CAD software. The model simulates the above-knee prosthesis with a single degree of freedom by allowing the knee joint to revolute voluntarily to create flexion and extension movements. A wireless EMG circuit board has been designed and evaluated to collect the amputee's residual muscle electricity. Subsequently, a novel combination between the traditional PID and Adaptive Neuro Fuzzy Inference System (ANFIS) controllers is designed to control, with a high percent of stability, the simulated prosthesis and overcome the oscillation of EMG signals. The movement of the simulated lower limb prosthesis is calibrated to the healthy leg of an 11-year-old child. The evaluation experimental tests have been accomplished by involving a healthy participant to compare his normal leg with the simulated controllable robotic prosthesis. The experimental results proved the functionality of the designed model to track the movement of the healthy lower limb. In addition, the effectiveness of the suggested controller to manipulate the prosthesis knee joint is proven. Fabricating the designed lower limb prosthetic and integrating it with the combination controllers proposed in this work is a continuation of this study in the future.

Keywords:

Robotic prosthetic; Lower limb prosthesis; MATLAB Simscape multibody toolbox; Electromyography (EMG) sensors; PID controller; ANFIS controller; Lower limb amputation

1. Introduction

The prevalence of limb amputations, projected to reach approximately 3.6 million individuals in the United States by 2050, underscores the critical need for advanced prosthetic technologies [1]. However, 1.6 million people had undergone limb amputations in the USA reported in 2005 [1].

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https://doi.org/10.37934/araset.63.1.2736

Lower limb amputations pose significant challenges in terms of energy expenditure, impacting mobility, and overall quality of life [2]. While prosthetic devices play a vital role in restoring functionality, ongoing scientific research is essential to enhance their capabilities and meet the diverse needs of this population [3]. This demand is particularly acute for individuals with knee amputations, as they often experience difficulties with gait symmetry, stability, and energy expenditure during walking.

Robotic prostheses powered by servomotors that mimic the biomechanics of a natural leg offer a promising avenue for improving mobility [4]. Effective control systems are crucial for aligning prosthesis movements with the user's intentions, enabling seamless integration into daily activities. However, traditional control strategies rely on preprogrammed actions for specific activities. For instance, standing or walking through the complexity of real-world scenarios necessitates more adaptable approaches [5]. For example, transitioning from walking to stairs, navigating uneven terrain, or adapting to various walking speeds requires a more nuanced control system that can respond to the consumer's changing needs in real time [6]. Also, a key challenge lies in rapidly and accurately classifying the myriad variations in consumer activity, as misclassifications would lead to unintended prosthesis actions, increasing the risk of falls and injuries [7,8]. Moreover, individualized control systems are fundamental for tailoring the prostheses to the unique needs and preferences of each consumer [9]. This is especially critical for individuals with knee amputations, as their gait patterns and biomechanics can vary significantly [10,11]. Overcoming these challenges is important for the full potential of robotic leg prostheses to be realized.

Current research endeavours are focused on enhancing the control systems of the lower prostatic leg by integrating electromyography (EMG) signals attached to the patient's residual muscles. The EMG-based control offers a new sensor technology with high accuracy compared to systems depending on traditional mechanical sensors, paving the way for more intuitive and responsive robotic knee prostheses [12,13]. Additionally, computer vision technology has been offered to improve traditional sensors' accuracy, though their real-live application is undesired by concerns related to camera location [14] and societal privacy [15]. Despite using the classical sensors, the old algorithms need a long training time with multiple repetitions of each movement, which can be taxing and hazardous without professional supervision [18]. Critically, even with perfect classification, every activity variation has need of a separate controller with manual tuned for adjusting process [16,17].

Alternative controllers based on continuous EMG signal use have been suggested to improve adaptability to real-world variability, as opposed to pre-tuned controllers reliant on mechanical sensors [18]. However, these controllers demand subject- and session-specific training of the machine learning algorithm to translate EMG signals into effective prosthesis commands. Extensive, multi-week, multi-session training is required to achieve performance levels comparable to non-EMG-based controllers [19]. Additionally, a distinct EMG controller is needed for each ambulation mode, such as walking or stair ascent, limiting the practicality of such systems.

In this study, it proposes an alternative control procedure for robotic knee prostheses. The shared neural control method integrates neural signals and robotic control, enabling users to perform various ambulation activities without machine training. Also, continuous volitional control of a robotic knee prosthesis is achieved using EMG signals, allowing users to effortlessly engage in activities such as standing, sitting, squatting, lunging, walking, and transitioning seamlessly between them. Furthermore, the experimental procedures are divided into three phases: EMG signal measurement, lower limb prosthesis design, and real-time evaluation. The EMG signal measurement phase involves developing a sensor to capture and wirelessly transmit muscle electrical signals to a PC. These signals are then used to control the prosthesis. Moreover, the second phase utilizes the MATLAB Simscape Multibody Toolbox to design and simulate a controllable lower limb prosthesis model. The final phase evaluates the effectiveness of interfacing the EMG system with the simulated prosthesis in real time.

2. Methodology

This study presents a combination of experimental and simulation work to investigate the behaviour of the lower limb prosthesis. The primary goal of the study is to design a simple, low-cost, miniature-weight prosthesis for an 11-year-old child who, unfortunately, has an above-knee amputation. Therefore, the prosthesis must be simple and not contain advanced technology because it will be replaced after a short period of time because the child is in a state of continuous growth. A special control system algorithm has been exercised for the designed model of the lower limb prosthesis. The suggested control algorithms involve calculating the desired values for the suggested leg prosthesis, such as the movement and mechanism characteristics, by means of applying the inverse kinematics technique. Firstly, the MATLAB code was used to calculate inverse kinematics parameters before designing the lower limb prosthesis. In general, the methodology of this study is divided into four essential sections to make it easy to understand. The four sections are: designing the simulation model, measuring the EMG signals, designing the controller, and the calibration process.

2.1 Design the Simulation Model

Indeed, this study focuses on designing an effective combination between the amputee residual muscles, EMG sensors, and controller that can manipulate the knee joint and evaluate the inverse kinematics of the suggested lower limb prosthesis. Thus, the MATLAB Simscape multibody toolbox was applied to design a controllable animation lower limb prosthesis that simulates the prosthesis. Simscape Multibody, sometimes called Sim-Mechanics, supplies a multibody simulation environment for 3D mechanical systems. It has the ability to design mechanical parts, joints, actuators, sensors, and torque through blocks. In addition, it formulates and solves the equations of motion for the entire mechanical system.

In general, the Simscape model can be generated using two different methods. The first method is building the mechanical model using the several blocks inside the MATLAB Simscape multibody toolbox, such as body elements, revolute joints, and reference frames. On the other side, the second method provides the ability to import the CAD mechanical model from other CAD design software. Subsequently, the second method was used in this study by drawing the lower limb prosthesis with the SolidWorks program because it significantly decreased the model's creation time and the high percentage of mistakes associated with this process.

The suggested prosthesis is built with two main parts: the thigh and the leg part, as shown in Figure 1. The thigh part represents the upper part of the prosthesis above the knee joint, with a 15 cm height, a 40 cm maximum diameter, and a weight of 0.45 kg. The second part represents the leg under the knee joint with a 40 cm height, a 20 cm foot size, and a 2 kg net weight. Finally, the MATLAB Simscape model is generated from the original CAD assembly model through the Simscape Multibody Link in (.xml) form.

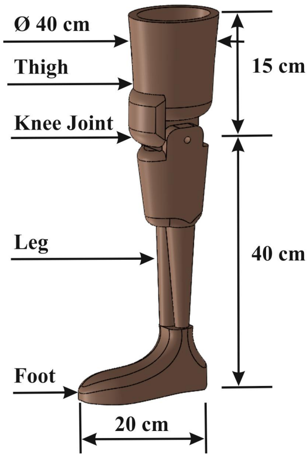

Fig. 1. A lower limb prosthesis schematic

Then, the generated model is imported to MATLAB by using the (Smimport) instruction to transfer it to the final (.slx) form, as represented in the blocks under the dashed red rectangle in Figure 2.

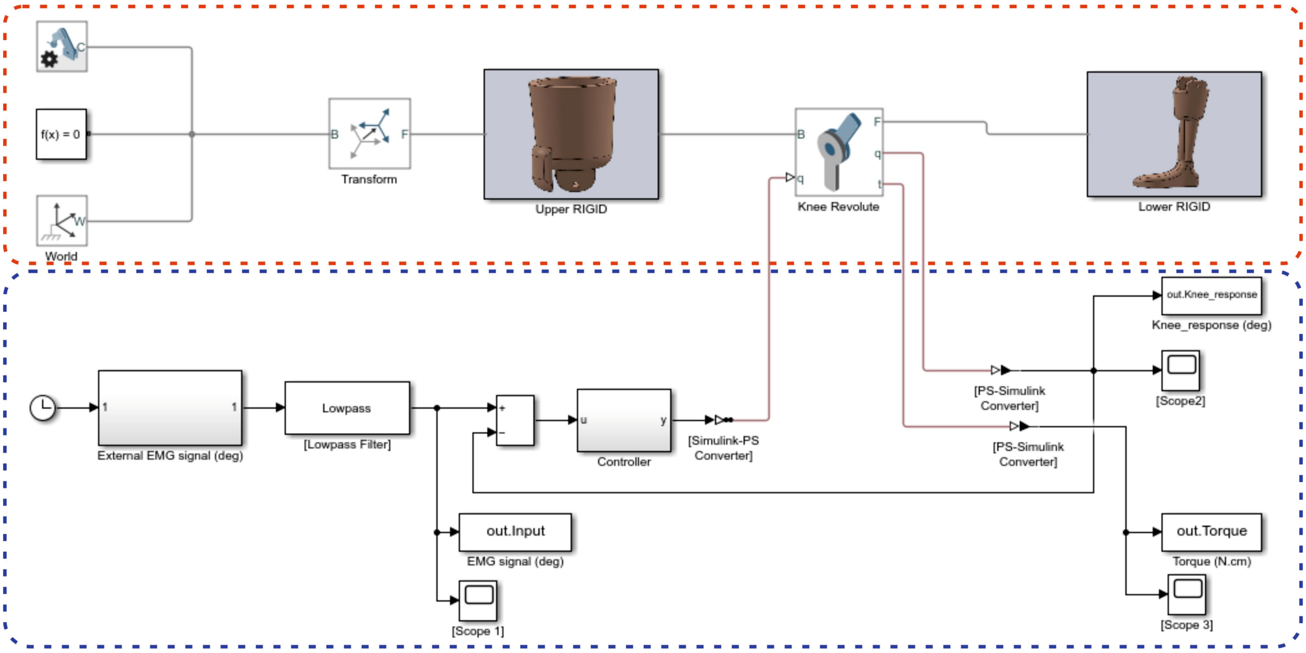

Fig. 2. The suggested simulation model of the lower limb prosthesis

After the preliminary establishment of the lower limb prosthesis Simscape model, the knee actuator should be set. In general, the revolute joint blocks are set as the actuators. The input to it is the desired knee position in the degree unit. The actual knee position and the joint torque are chosen as the output from the revolute joint in degree and N.cm units, respectively. In this case, the controller will be designed to control the knee position, while the joint torque will be computed automatically depending on the excitation time and amplitude. The suggested control system model of the lower limb prosthesis is described in the blocks under the dashed blue rectangle in Figure 2.

2.2 Measuring the EMG signals

The main idea of this section is to measure the EMG signals of the amputees' residual muscles above the knee joint. The main challenge is to measure and filter the EMG signal because it has a high amount of oscillation [20]. However, a combination of microcontrollers, low-pass filters, and other components is designed on one board to overcome this issue. The EMG circuit board has already been designed and evaluated in the previous study [21], as shown in Figure 3.

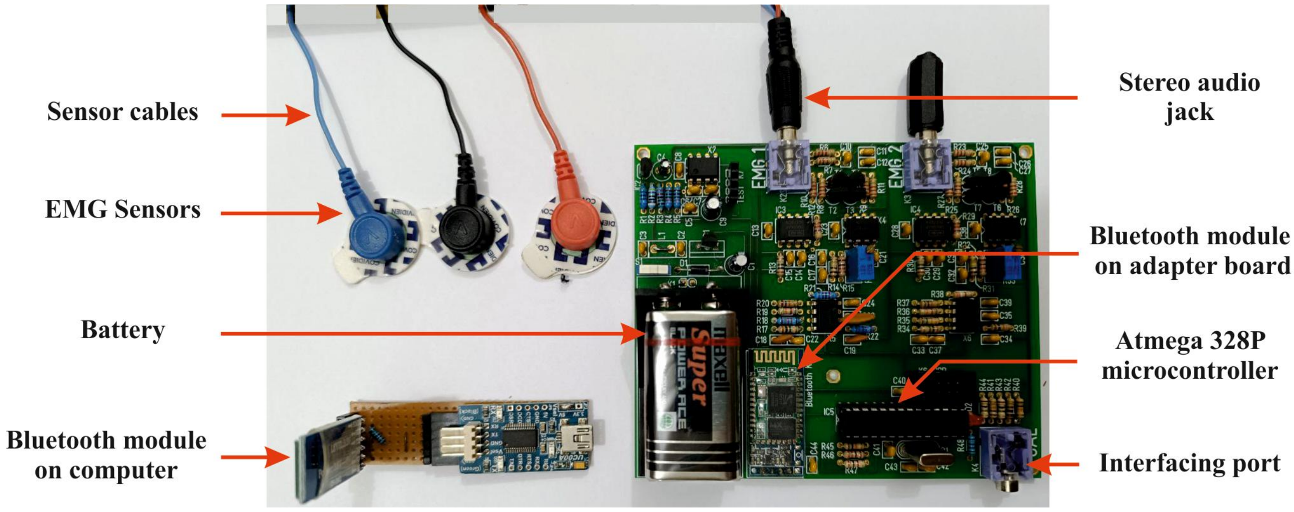

Fig. 3. EMG circuit board

The electromyography sensor is a piece of hardware. It provides two input channels connected by data cables to the electrodes on the main board. Then, the input signals convert to digital signals with a resolution of 10 bits and are conveyed to the essential microcontroller. A wireless Bluetooth device has been used to connect the EMG sensors with the Matlab program on the main computer. The Matlab connector sends commands to the microcontroller. The microcontroller sends measurement data to the Matlab connector.

The MATLAB connector offers a specific and soft interfacing method with EMG sensors. MATLAB scripts that use the EMG sensor can use the MATLAB connector for communication. The script read limit can read a single data set from both input channels. The user can specify the length of the data set in seconds and start the measurement with a button. The script can read data sets from both input channels periodically. The user can specify the period time in seconds and start the measurement with a button. The display is updated periodically after a new data set is recorded.

2.3 Designing the Controller

To effectively control the motion of a leg prosthesis, it is crucial to accurately measure and maintain the precise position and torque of the prosthetic leg. The designed system should respond to inputs with appropriate overshoot, settling time, and minimal steady-state error. Also, in order to streamline control design and analysis, two potential controllers, PID and Adaptive Neuro Fuzzy Inference System (ANFIS), tailored for leg prostheses, are recommended. PID controllers are widely used in various control applications due to their robustness and historical prevalence in engineering [22]. Nevertheless, their performance can suffer from parameter variations and external disturbances. While, the ANFIS controller is one of the best beneficial hybrid technologies for planning intelligent control algorithms [23]. Therefore, combining PID and ANFIS controllers is proposed in this study to potentially enhance control stability and overall performance, particularly in scenarios involving device instability. An ANFIS-based controller is also suggested for regulating the torque of the DC motor in the Active Knee design. The ANFIS controller was designed and adjusted using the ANFIS toolbox in MATLAB [24].

2.4 Calibration Process

A healthy child was involved as a participant in the experimenter's calibration process to calibrate the movement of the simulated lower limb prosthesis. In the first stage, four angles with a vertical line are drawn on a whiteboard using the measuring angle equipment. The four angles are 0°, 45°, 90°, and 110°, where 0° and 110° represent the initial and final positions of the leg. In the second stage, the EMG measuring device was installed on the left leg of the participant. Then, the participant was ordered to move his leg exactly at the angles on the whiteboard. At the final stage, the simulated prosthesis was programmed to move and stay at the angle at which the child's leg was held. The amplitude of the EMG signals provided by the EMG measuring device proportional to the leg positions was reordered. Figure 4 describes the knee position calibration process, where the participant’s leg is on the right side while the simulated prosthesis is on the left side.

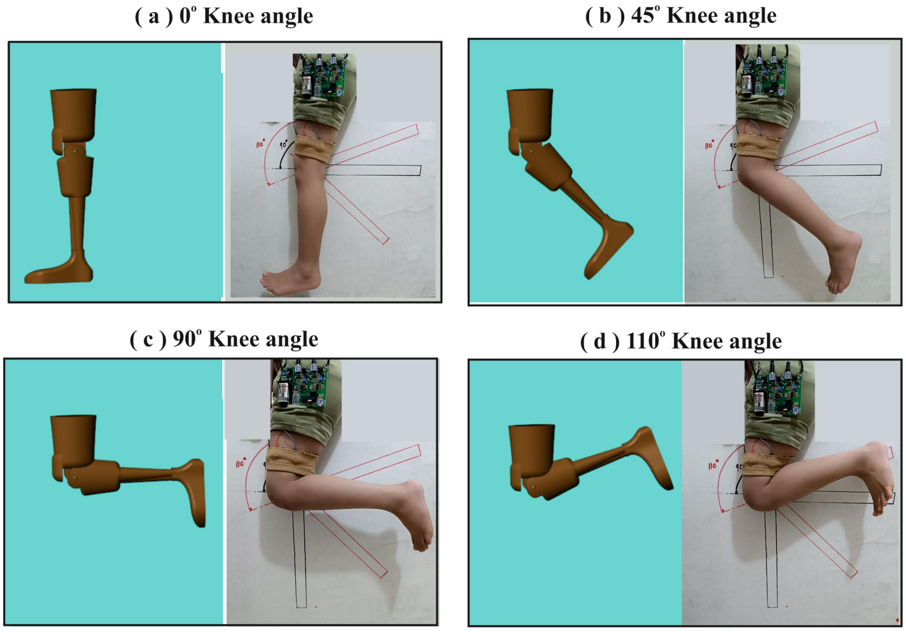

Fig. 4. The knee position calibration process

3. Results and Discussion

The evaluation and experimental results are described briefly in this section. The evaluation process aims to prove the effectiveness of the suggested model in following the internally generated position input signal. In comparison, the target of the experimental process is to verify the ability of the suggested model and its controller to respond to external EMG signals.

3.1 Evaluation Results

The entire evaluation process of the lower limb prosthesis model is described in Figure 5. Where Figure 5(a) represents the input excitation signal to the system, which compensates for the real EMG signal. The pulse generator block is used to generate wave-square pulses as an input source to the Simulink model. Indeed, three waves are generated during the 6-second excitation time. Each wave has 110 final amplitude, 2 seconds of period time, 50% Pulse Width, and 1 second of phase delay. The wave signifies the flexion and extension movement of the knee joint from the rest position at 0° to the fully closed position at 110°. In fact, the wave pulse represents the ramp input excitation with a very slight tilt during the flexion and extension movement.

The response of the simulated lower limb prosthesis due to the excitation of the internal signal is described in Figure 5(b). The results show an acceptable response of the simulated knee joint to the internal input signal during the flexion process. The response takes 1.4 seconds to move the knee from the rest position to its final movement value with, a rising time not exceeding 1.2 seconds without any undesired overshoot. On the other side, the results show the same response of the flexion process as the extension process. In addition, the results show a repeated action during the entire input wave.

Simultaneously, the torque required for the servomotor to achieve the knee movements is calculated and displayed in Figure 5(c). The results show that the servomotor needs to supply 22.62 N.cm maximum torque during the flexion process and 3 N.cm during the extension process. The most likely explanation for this phenomenon is that the process of flexion of the leg works against Earth's gravity, but during the extension of the leg, the force of Earth's gravity is used as a helpful element.

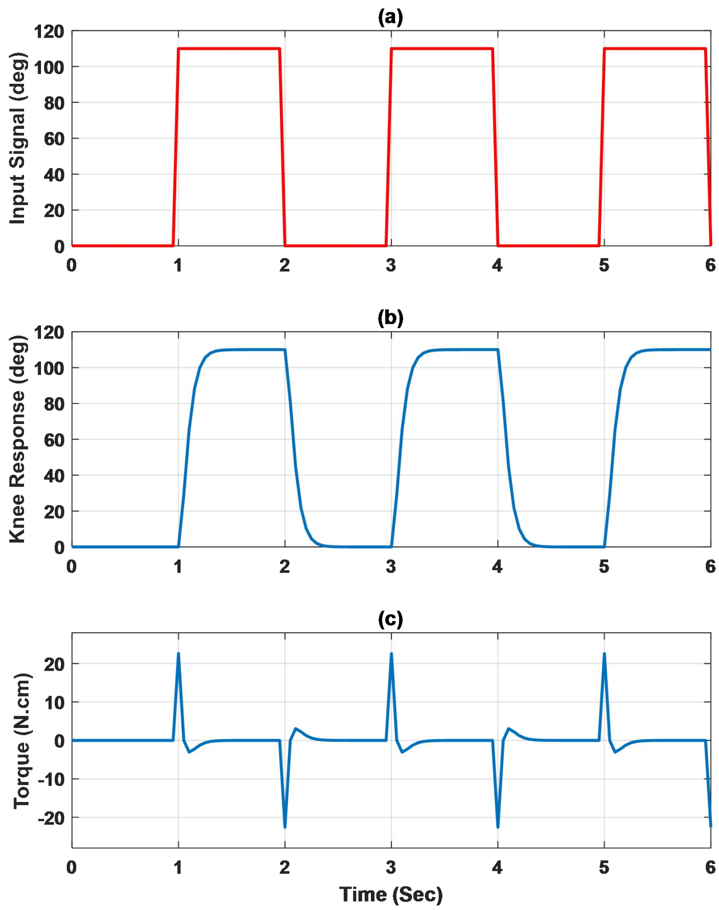

Fig. 5. The suggested simulation model evaluation process (a) internal input signal (deg), (b) the knee position response (deg), and (c) the motor torque (N.cm)

3.2 Experiment Results

The experiment procedure for the real-time experiment was performed by involving a healthy participant. In fact, the researchers thought there was no significant difference between the muscle's physiology and functionality in the residual amputee's thigh muscles and the healthy participant's thigh muscles. In other words, both muscles can provide the same amplitude of EMG signals when the brain provides orders to move the leg.

Therefore, the EMG sensors were attached to the skin above the thigh muscles of the healthy leg, and the sensors were connected to the main EMG circuit board. When the participant orders to move his leg, the EMG system measures the generated electrical currents of the muscles and conveys them wirelessly to the main computer. At the main computer, the provided EMG signals are utilized as the excitation input for the suggested lower limb prosthesis Simscape model. Subsequently, the simulated prosthesis should track the movement of the actual leg.

Effective comparisons between the EMG input signal and simulated knee joint response are accomplished in Figure 6. The red curve represents the EMG-measured signal when the participant was ordered to close his leg and open it three times in six seconds. In comparison, the blue curve signifies the simulated knee joint response. The results proved the functionality of the suggested model to track the movement of the real healthy leg. In addition, the results show that the combination of PID and ANFIS controllers gives an acceptable production to the knee movement and its angles. In other words, the developed controller proves his ability to manipulate the knee joints with a smooth and fast response, leading to overcoming the EMG oscillation and delay.

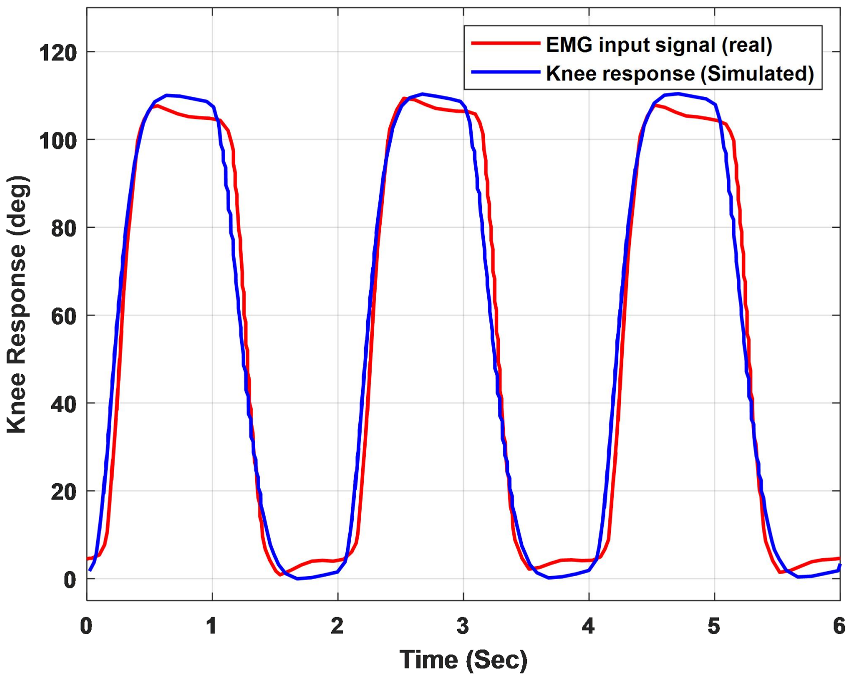

Fig. 6. The real-time experimental results

4. Conclusion

A creative method for the simulation of lower limb prostheses by utilizing the Matlab Simulink and Simscape Multibody toolboxes was presented in this research. The Simscape model was generated by means of importing assembly model files from the Solidwork CAD software to the MATLAB program. The simulated lower limb prosthesis was designed for the child patient with above-knee joint amputation. However, researchers focused on designing a simple, low-cost, miniature-weight prosthesis because the child is in a state of continuous growth and the prosthetic leg is expected to not be used for a long time. Thus, this work is just the first step of research to simulate the prosthesis before the final fabrication process.

The suggested lower limb prosthesis was confirmed using the inverse kinematics method. The movement comments that input to the model was measured using an electronic device of EMG sensors provided with a microcontroller and lowpass filter to eliminate the EMG oscillation. In the Simscape simulated model, a combination of PID and ANFIS controllers was developed to predict and manipulate the knee joint of the prostatic leg and overcome the oscillation issue of the EMG sensors.

The output results show that the combination of PID and ANFIS controllers is more effective than using the traditional PID controller. The designed controller demonstrated a high ability to control and manipulate the knee joints by smoothly tracking the excitation input to the simulated model. Moreover, this study proved that using the Matlab Simscape multibody toolbox gives impressions and visual views that are closer to reality than traditional simulation. Involving a healthy participant instead of the amputee patient is the main weakness of this work. Investigating other types of controllers with the prosthesis and fabrication process is suggested as future work.

Acknowledgement
This research was not funded by any grant.

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