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Development of Powered Semi-Active Ankle-Foot Prosthetic with Fuzzy Logic-PI Controller

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Abstract
One of the most difficult issues in the design of power ankle-foot prosthetics is to create a control system that can simulate biological ankle-foot behavior in various operating conditions. The mechanical design of a novel PSAAP is studied. The powered semi-active ankle-foot prosthetic is a complex nonlinear system with high coupling. For powered ankle prostheses, a fuzzy logic- proportional-integral (FLC-PI) controller is presented. In the initial stage of control, two proportional-integral (PI) controllers are designed to regulate motor speed and current, respectively. In the next stage of control, two FLC-PI controllers are designed. The PI controller's gains are intended to be adjusted online by the fuzzy logic controller. FLC-PI controllers are used to control the designated model under these external disturbances during a typical walking gait cycle. The performance of PI controllers and FLC-PI controllers are compared during the walking gait cycle. The results reveal that a powered semi-active ankle-foot prosthetic with a fuzzy logic-PI controller method outperforms a PI controller alone.

1. **Introduction**

Worldwide, the number of traffic and industrial accidents, as well as injuries from everyday sporting activities, is increasing the number of transtibial amputees [1]. Ankle amputations are the most frequent kind of amputations. This fact has spurred the development of prosthetic devices, which are vital for those who have undergone lower limb amputations to achieve everyday mobility and a better quality of life [2]. A wide range of ankle prosthetics have been developed to help amputees below the ankle regain or improve their walking. Passive ankle prostheses are inexpensive; however their lack of ankle angle mobility may lead to aberrant walking patterns among users. Although challenging in unstable terrains like stony or rocky terrain, Chang et al.'s [1] fuzzy logic-based terrain identification technique is implemented in the detected terrain environment during walking.

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Ge Li et al. study [3] used a robotic prosthesis with two Inertial Measurement Units (IMUs) and a load-cell to use a cascaded classification technique to discern human locomotor intents. As a fuzzy-logic controller FLC based terrain detection method, the use of the foot-pressure sensor and two IMU sensors, each placed to the surface of the shank and base of the foot, was also suggested [4]. Semi-active prosthetics can only adjust joint stiffness during the stance phase, but they use microprocessors to support the amputee throughout the gait cycle [5]. While many scholars concentrated on the mechanical design of these devices, another area of study is how these devices can be managed. The central question that still needs to be addressed is what challenges these powered devices have when developing a control strategy. The primary design goal is to create controllers that take into account the user, device's, and environment's physical interactions. Controllers developed in perfect lab environments seem ineffective and unable to handle obstacles and difficulties like disruptions, uneven surfaces, and different gait modes in everyday human gait. Researchers have spent the last few decades developing controllers that mimic how a person would interact with their surroundings while wearing a healthy limb [2].

The ankle joint's major job is to provide enough energy support for the body to move forward [6]. The control's purpose is to steer the powered ankle prosthesis to the specified ankle angle. To adjust the progression deviation, the general control algorism is to apply mechanical torque to a controlled ankle prosthetic. The control problem consists of two parts: establishing the dynamics model of the powered ankle prosthesis and determining the control strategy. There have been studies on a variety of control approaches, which can be categorized into five categories: neural control, robust control, adaptive control, nonlinear control, and FLC [7]. For position control, Vallery et al. [7] used impedance controller algorism. Yang et al. [8] suggested a fuzzy neural algorism controller for controlling the lower limbs prosthetics and assisting humans in walking. Since Zadeh et al. [9, 10] introduced fuzzy theory, the fuzzy sets have progressed significantly. Control engineering, pattern recognition, signal processing, machine intelligence, motors, and robotics are just a few of the applications [11]. FLC more closely likes the way the human brain thinks and makes decisions. In fact, FLC has been effectively used to nonanalytic systems as well as time-varying nonlinear systems [12]. Human factors, particularly the creation of fuzzy rules, have an impact on FLC. Acquiring a precise control effect is really challenging.

In this paper, the Powered Semi-Active Ankle Prosthetic PSAAP has been designed and developed using CAD-CAM program. Mechanical design of model can simulate the motion of non-amputee but not exactly because there is no control system. The PSAAP prototype is imported into ADAMS [13] for dynamic analysis. The model of the PSAAP in ADAMS is then imported into MATLAB/Simulink for control system design. A DC electric motor DC MOTORS is used to regulate the performance of Experimental results PSAAP model. The speed and current of DC MOTORS are regulated using two PI controller algorithm PI CONTROLLER. In this paper the fuzzy logic is used to tune the gains of the PI controller. However most of the research on fuzzy logic control design use PI-like FLC. The results from simulation and practical display show that the FLC-PI is better than PI CONTROLLER when the system is nonlinear. The paper is arranged as follows: section two displays the mechanical design of the PSAAP model. Section three includes the design of PI CONTROLLER and FLC-PI controller. Experimental results are given in section four. Final section shows conclusions of this paper.

2. Mechanical Setup of the powered semi-active Ankle Prosthesis

During the stance stage of walking, the PSAAP model's active and passive parts cooperate to produce total positive power at the PSAAP joint [14]. The system that was developed with the aid of a CAD-CAM application is shown in Figure 1 [15]. The PSAAP prototype features an actuator, parallel springs with a cam profile mechanism, a carbon fibre foot, and leaf series springs. The purpose of the carbon fibre foot is to reduce shock when striking with the heel. The primary parts of the actuator are screw bolts, belts, pulleys, and DC motors. The PSAAP is actuated by a DC MOTORS in response to the actuator's requests for torque, speed, and peak power. A pair of custom pulleys and a belt are used to transfer spin from the DC MOTORS's output to the screw bolt. The DC MOTORS's velocity is reduced by using the pulley-belt transmission. The pulley-belt transmission dissipates shock and vibrations from the outside world. Ankle joints require the highest level of precision and sensitivity, and a screw bolt nut is used to make sure the prosthetic limbs keep moving properly. Pulley drives used in rigid transmissions are always effective in terms of operation stability, dependability, and transmission efficiency [16]. In addition, the bolt nut transfers rotational to move in line.

When the transmission fails to meet bandwidth requirements, the leaf series springs are used to increase the level of series elasticity, preventing the transmission from being destroyed during heel striking [17, 18]. The nonlinear parallel springs system consists of a cam, follower, and spring element. The nonlinear parallel springs mechanism was created to simulate human ankle dorsiflexion stiffness, and the cam profile was designed in [17]. A specially designed ramp piece in the cam shape allows the ankle to be sufficiently twisted in the plantarflexion direction to unload the springs. A conventional pyramid adapter sits atop the device, which is used to attach it to a patient's prosthetic socket. PSAAP model development is underway. After using the series and parallel springs and cam, the model functions like an ankle that isn't amputee. The velocity of the PSAAP is more similar to the velocity of non-amputee [19] as displayed in figure 2. The angle-torque of the PSAAP is more similar to the angle-torque of non-amputee [20] as displayed in figure 3. The stages of the ankle at heel hit, flat foot, maximum dorsiflexion, and toe off are represented, respectively, by the points (1), (2), (3), and (4). The ankle torque-angle behaviours during the controlled plantar flexion, controlled dorsiflexion, powered plantar flexion, and swing phases of gait are represented by the segments (1)-(2), (2)-(3), (3)-(4), and (4)-(1), respectively. The human ankle joint exhibits distinct spring behaviors during controlled plantar flexion and controlled dorsiflexion, as demonstrated in segments (1)–(2) and (2)–(3), respectively. There is a reduction in the amount of energy used. The PSAAP model [21] meets the design requirements and intended angle-torque.

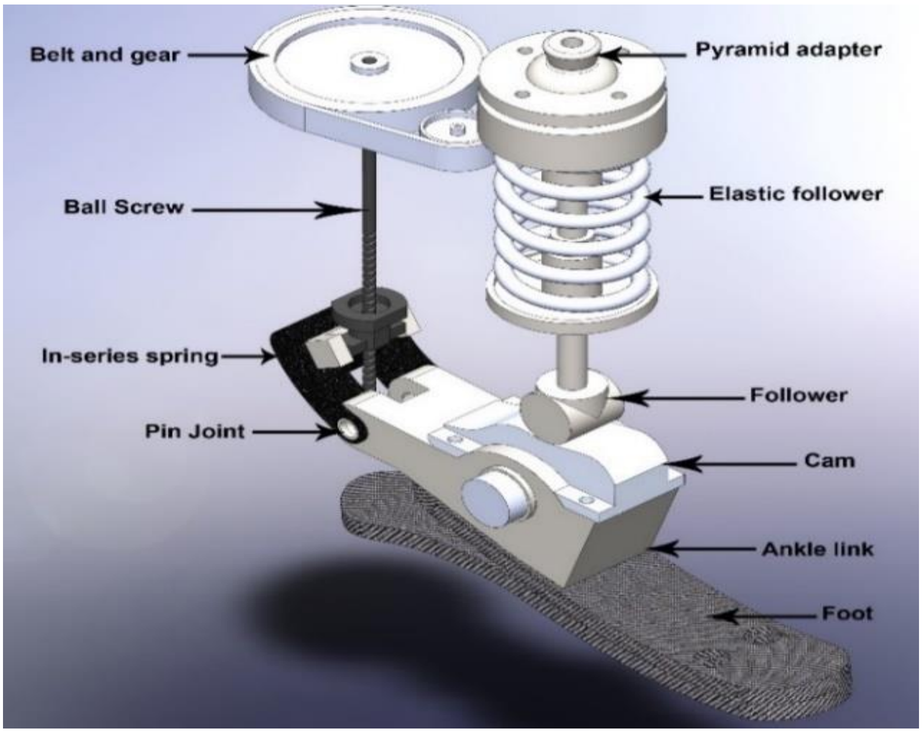

Fig. 1: The PSAAP model in CAD/CAM.

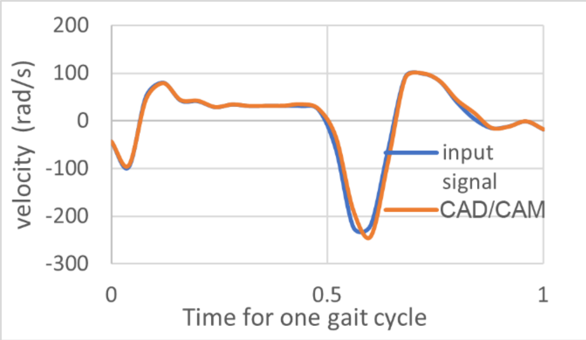

Fig. 2: The input signal and the velocity of motor from CAD/CAM.

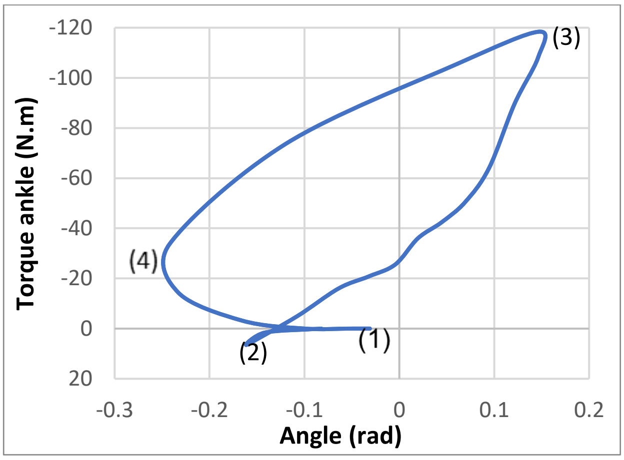

Fig. 3: The angle–torque of the CSAAP for one gait period from CAD/CAM.

The powered semi-active ankle prosthetic is modeled. The DC MOTORS, leaf series springs, and parallel springs make up the powered semi-active ankle prosthesis model. When the bandwidth requirements are not met, the leaf series springs are used to raise the series stiffness to a level that sufficiently shields the gearbox from damage during heel strike. The parallel springs are used to reduce torque and power requirements.

The control system for the PSAAP was designed and implemented using MATLAB/SIMULINK and a DC MOTORS. After the PSAAP has been modelled using CAD-CAM, it must be regulated. A dynamic analysis must be done prior to control. Figure 4 depicts how the PSAAP prototype is put into ADAMS for dynamic analysis. The most typical prototypes imported into ADAMS are ground, components, joints, and other prototypes. The prototype of the PSAAP in ADAMS is imported into MATLAB/Simulink. The control simulation system's block diagrams are produced using the PI CONTROLLER technique first [22], and then the FLC-PI control algorithm second, as shown in figure 5. By connecting it to additional control modules in MATLAB and Simulink, the control simulation system block diagram is produced [23]. The DC MOTORS that is used in the PSAAP model, can be modeled by using the following equation [24]:

$$V_{ac} = Ri + L\frac{di}{dt} + E \tag{1}$$

where

V_{ac} is voltage applied to DC L is armature inductance.

R is armature Resistance. E is back emf of the DC MOTORS.

$$T_e = J\frac{d\omega}{dt} + B\omega + T_L \tag{2}$$

where : T_e is Electromagnetic torque in Nm. J is Moment of inertia.

$\frac{d\omega}{dt}$ is Angular speed for motor. B is Friction coefficient. T_L is Load torque.

3. Controller design

In the following two sections, PI CONTROLLER and FLC-PI controllers are designed to regulate DC MOTORS speed and current to simulate the motion of non-amputee.

3.1 PI-Controller design

The primary role PI CONTROLLER design method is to set a suitable proportional gain (K_P) and integral gain (K_i) for optimal control performance using signal constraint by Matlab/Simulink toolbox. The signal constraint block GUI is adjusted during optimization progress so that the optimization method can be showed. Optimization reiterations are achieved on variable ranges of Kp, Ki, and N (filter coefficient) parameters. These parameters can be estimated using different methods. In this case, signal constraint method was applied [23, 25].

Two cascade PI CONTROLLER [21] will be designed to regulate DC MOTORS speed and current, respectively. First PI CONTROLLER is designed in outer loop to regulate the DC MOTORS speed as displayed in equations (3, 4). The reference speed $S_r(t)$ is the begin point for the PSAAP's control mechanism. The DC MOTORS speed $S_m(t)$ is compared to the reference speed. The input of first PI CONTROLLER is the difference between the reference and feedback speeds $e(t)$. This PI CONTROLLER output is reference current.

$$u_r(t) = k_{pv}e(t) + k_{iv}\int e(t)\,dt \tag{3}$$

$$e(t) = S_r(t) - S_m(t) \tag{4}$$

Where k_{pv} , k_{iv} are proportional gain and integral gain for speed loop respectively. Second PI CONTROLLER equations (5, 6) in the inner loop are designed to regulate DC MOTORS current. DC MOTORS feedback current $u_m(t)$ is compared to the reference current $u_r(t)$. The difference in current $ec(t)$ between reference and feedback is incorporated into the second PI CONTROLLER. The voltage $V(t)$ is the output and is applied to the DC MOTORS. The DC MOTORS parameters can be found in [26]. Figure 6 shows the control system of the virtual PSAAP prototype produced in MATLAB/Simulink using the PI CONTROLLER approach.

$$V(t) = k_{pi}ec(t) + k_{ii}\int ec(t)\,dt \tag{5}$$

$$ec(t) = u_r(t) - u_m(t) \tag{6}$$

Where k_{pi} , k_{ii} are proportional gain and integral gain for current loop respectively.

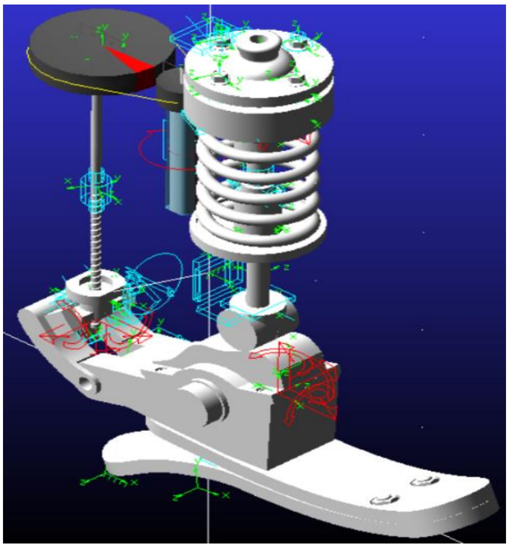

Fig. 4: The model of the semi-active ankle prosthesis in the ADAMS program.

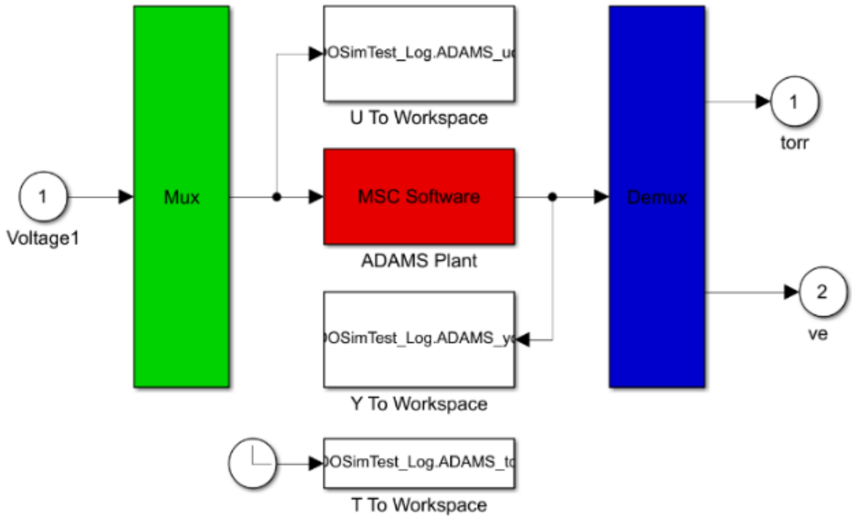

Fig. 5: Control plant generated by ADAMS.

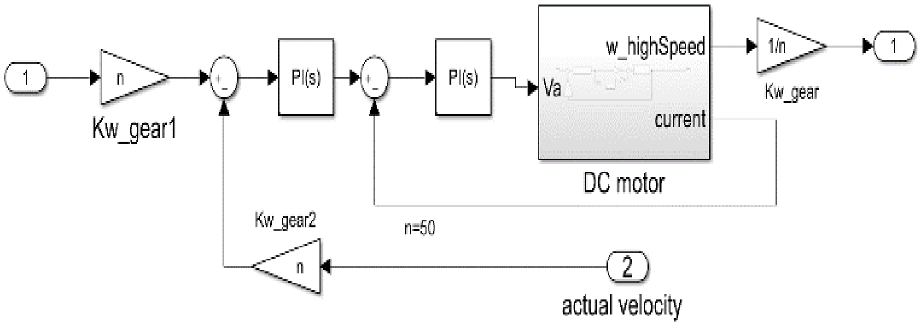

Fig. 6: The control system using PI CONTROLLER.

3.2 Fuzzy Logic-PI Controller

FLC is a type of logic that employs human knowledge to implement a system. It's typically used in systems that don't have any mathematical equations to deal with. The norms of common sense, human reasoning, and judgement are all a bit hazy. It aids engineers in the resolution of nonlinear control issues. For intelligent control systems and sophisticated applications, it mathematically simulates human knowledge. When compared to other types of controllers, FLC has various advantages, such as ease of control, low cost, and the ability to build without knowing the equation of the model [24, 27-28].

Figure 7 displays a MATLAB/Simulink of the FLC-PI control. Two FLC-PI controllers are used in the control system. The variable inputs of the first FLC are the error (e) and the change of the error (Δe) of the speed. The first FLC's variable output tunes the speed PI CONTROLLER's parameters, after which the PI CONTROLLER determines the reference DC MOTORS current. Input memberships are given in Figures 8 and 9. Five memberships functions are selected for each input. There are two outputs as displayed in Figures 10 and 11, proportional and integral gains each of them had five memberships. The memberships of the inputs and outputs are Negative big (NB), negative small (NS), Zero (Z), positive small (PS) and positive big (PB). Since there are five fuzzy memberships for each input; therefore, the fuzzy rules used are 25 rules. These rules can be seen in Tables 1 and 2.

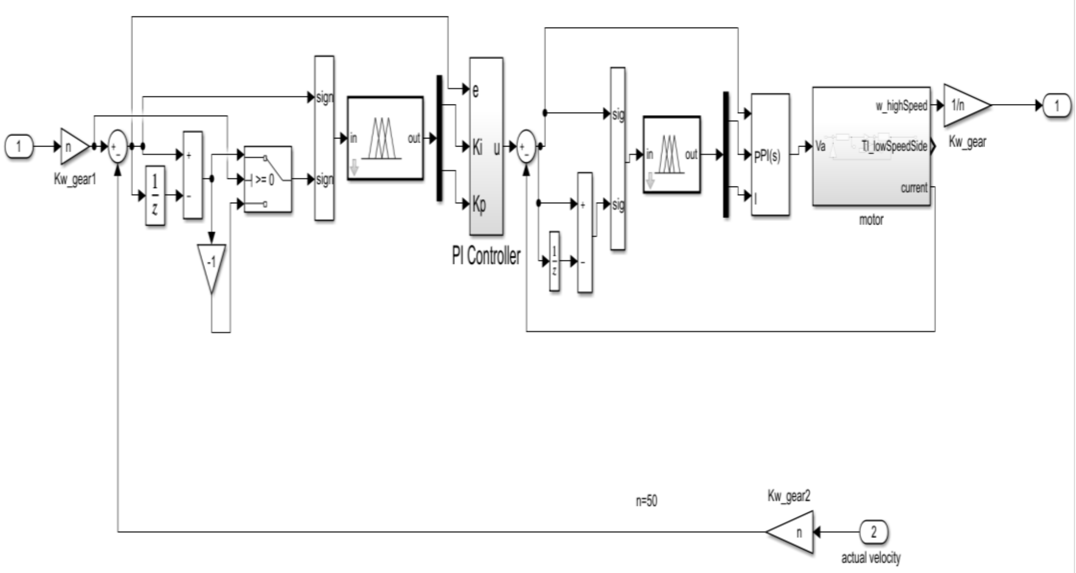

Fig. 7: The Simulink diagram of the FLC-PI control.

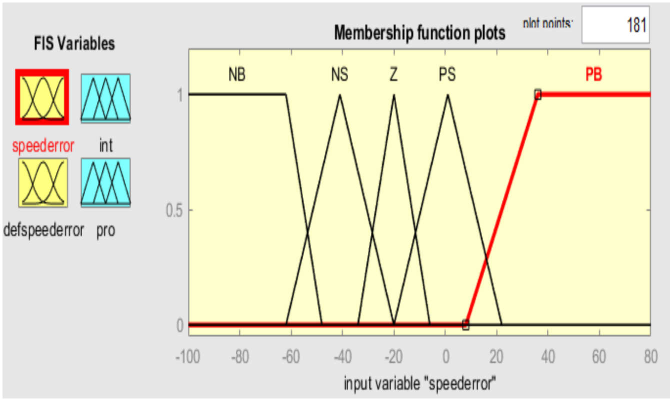

Fig. 8: Membership function of the speed error.

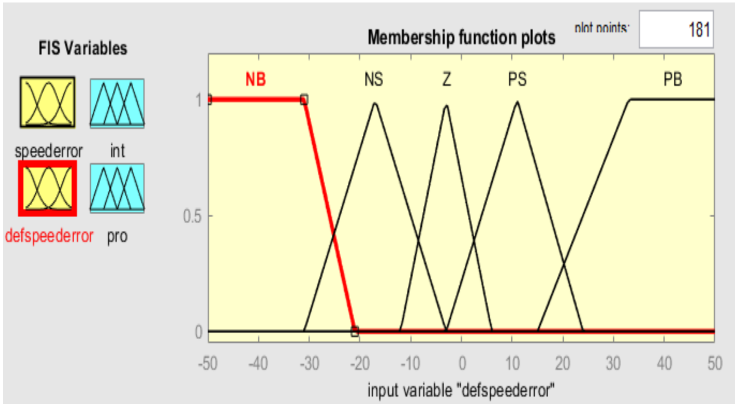

Fig. 9: Membership function of the change in the speed error.

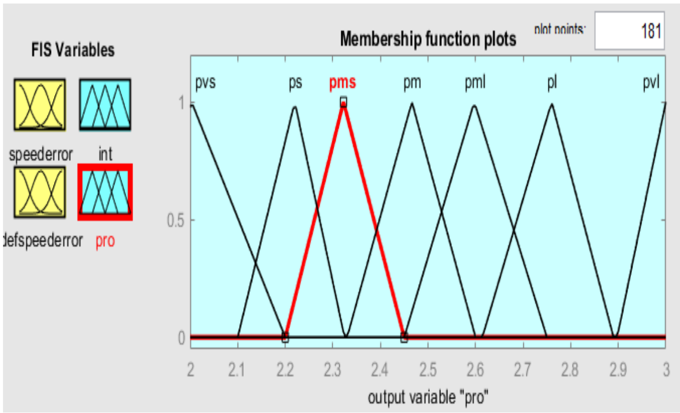

Fig. 10: Membership function of Kp for PI CONTROLLER - speed controller.

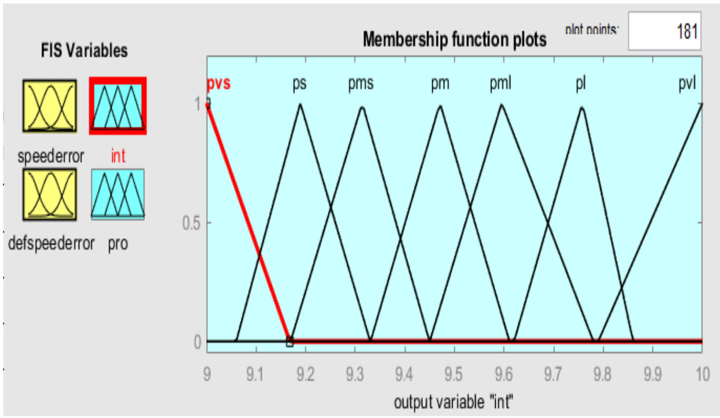

Fig. 11: Membership function of Ki for PI CONTROLLER -speed control.

Table 1: The rules applied in the first PI CONTROLLER for k_{pv}.

	NB	NS	Z	PS	PB
NB	PVL	PVL	PVL	PVL	PVL
NS	PML	PML	PML	PL	PVL
Z	PVS	PVS	PS	PMS	PMS
PS	PML	PML	PML	PL	PVL
PB	PVL	PVL	PVL	PVL	PVL

Table 2: The rules applied in the first PI CONTROLLER for k_{iv}.

	NB	NS	Z	PS	PB
NB	PM	PM	PM	PM	PM
NS	PMS	PMS	PMS	PMS	PMS
Z	PS	PS	PVS	PS	PS
PS	PMS	PMS	PMS	PMS	PMS
PB	PM	PM	PM	PM	PM

The DC MOTORS current error and its change are the inputs of the second FLC. The input variables memberships are shown in Figures 12 and 13. The output variable memberships are shown in Figures 14 and 15. Since there are five fuzzy memberships for each input; therefore, the fuzzy rules used are 25 rules. These rules can be seen in Table 3 and 4.

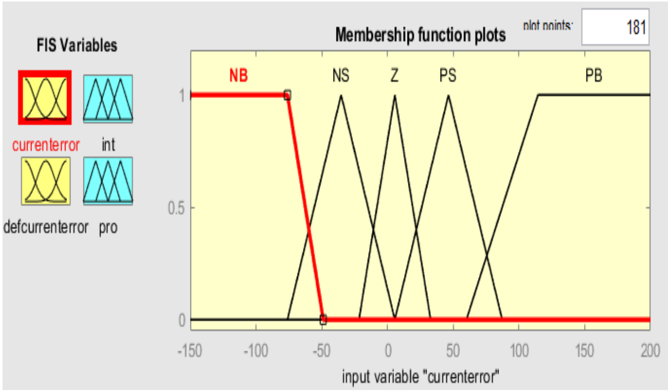

Fig. 12: Membership function of the error of current input.

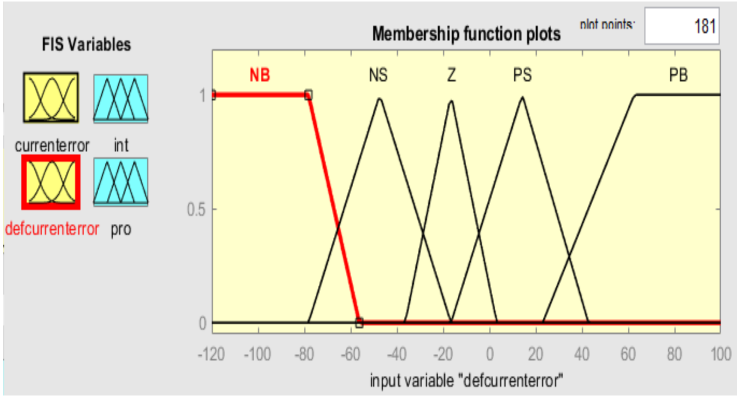

Fig. 13: Membership function of the change in the error of current input.

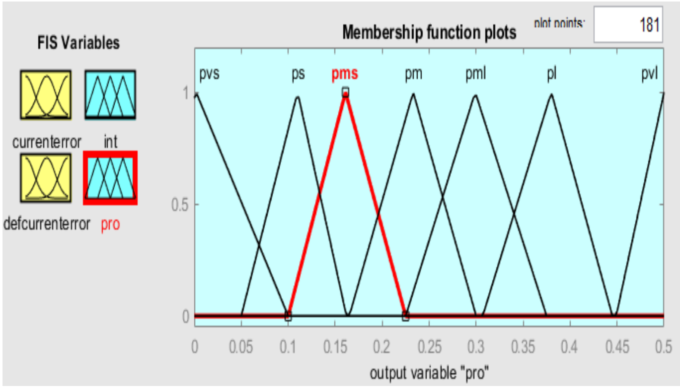

Fig. 14: Membership function of Kp output for the second loop of current control.

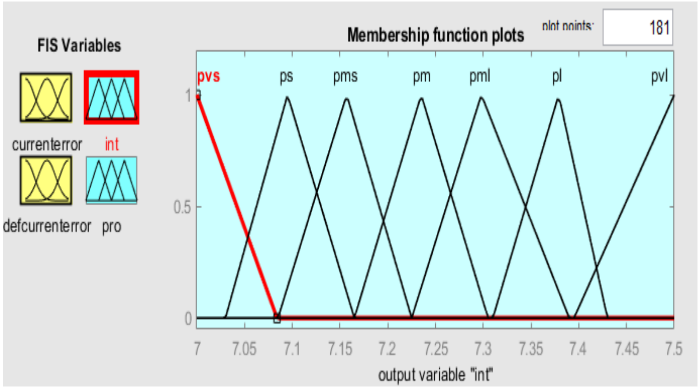

Fig. 15: Membership function of Ki output for the second loop of current control.

Table 3: The rules applied in the second PI CONTROLLER for k_{pi}.

	NB	NS	Z	PS	PB
NB	PVL	PVL	PVL	PVL	PVL
NS	PML	PML	PML	PL	PVL
Z	PVS	PVS	PS	PMS	PMS
PS	PML	PML	PML	PL	PVL
PB	PVL	PVL	PVL	PVL	PVL

Table 4: The rules applied in the second PI CONTROLLER for k_{ii}.

	NB	NS	Z	PS	PB
NB	PM	PM	PM	PM	PM
NS	PMS	PMS	PMS	PMS	PMS
Z	PS	PS	PVS	PS	PS
PS	PMS	PMS	PMS	PMS	PMS
PB	PM	PM	PM	PM	PM

4 Results

4.1 Simulation results

In this section, the performance of PI CONTROLLER and FLC-PI controllers are compared. Figure 16 shows the reference speed (black), the output speed of the DC MOTORS using PI CONTROLLER (red) with fixed gains, and the output speed of the DC MOTORS when FLC-PI controller algorism (blue). The response system in FLC-PI is nearer to the reference than in PI CONTROLLER only. Figure 17 shows the reference of the current using PI CONTROLLER (black), the output current of the DC MOTORS using PI CONTROLLER (red) with fixed gains, the reference of the current using FLC-PI (green), and the output current of the DC MOTORS when FLC-PI controller algorism (blue). Negative motor current occurred during regenerative mode where electric power returns from motor to the battery. The continuous current of DC motor is 30 Ampere, 100 ampere for lees than 0.1 sec (10% of cycle time) is not dangerous on motor winding. The results show that FLC-PI controller algorism is better a little than the only PI CONTROLLER algorism.

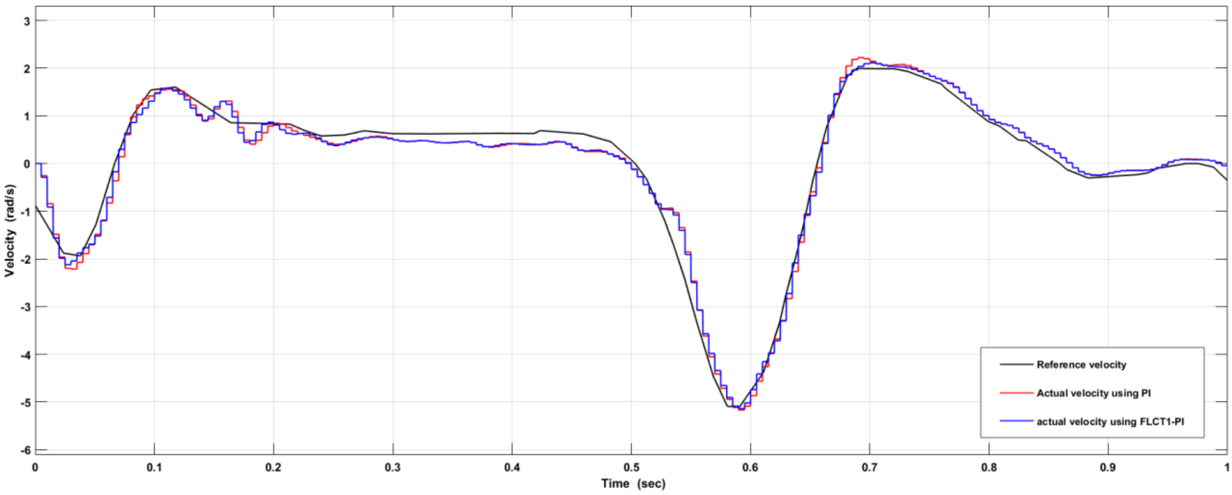

Fig. 16: System response using PI CONTROLLER and FLC-PI controller algorithm.

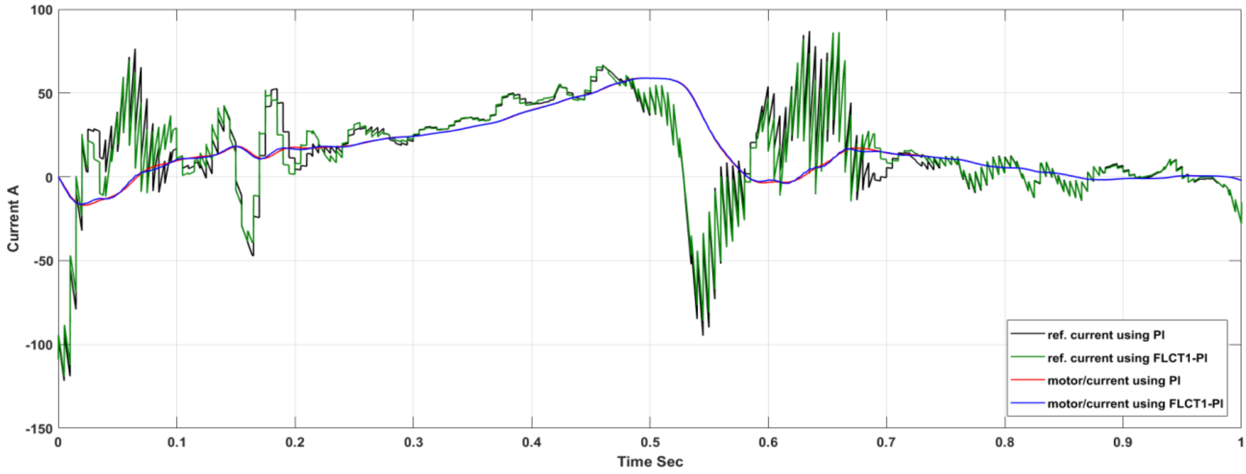

Fig. 17: Current of DC MOTORS response using PI CONTROLLER and FLC-PI controller algorism.

The PSAAP system is not still constant. The weight of amputee may be increased, or the amputee carries anything so the load may be increased. The parameters of the DC MOTORS also may be increased. In practical, the resistance and inductance of DC MOTORS may be increased with increasing the temperature. In simulation, the load and the parameters of DC MOTORS are increased with 20% and 50%. Figure 18 shows the reference speed (black), the output speed of the DC MOTORS using PI CONTROLLER (red) with fixed gains, and the output speed of the DC MOTORS when FLC-PI controller algorism (blue) when the load and the parameters of DC MOTORS are increased by 20%. Figure 19 shows the reference of the current using PI CONTROLLER (black), the output current of the DC MOTORS using PI CONTROLLER (red) with fixed gains, the reference of the current using FLC-PI (green), and the output current of the DC MOTORS when FLC-PI controller algorism (blue) when the load and the parameters of DC MOTORS are increased with 20%. Figure 20 shows the reference speed (black), the output speed of the DC MOTORS using PI CONTROLLER (red) with fixed gains, and the output speed of the DC MOTORS when FLC-PI controller algorism (blue) when the load and the parameters of DC MOTORS are increased with 50%. Figure 21 shows the reference of the current using PI CONTROLLER (black), the output current of the DC MOTORS using PI CONTROLLER (red) with fixed gains, the reference of the current using FLC-PI (green), and the output current of the DC MOTORS when FLC-PI controller algorism (blue) when the load and the parameters of DC MOTORS are increased with 50%. The results show that FLC-PI controller algorism can be adjusted the system when the load and the parameters of DC MOTORS are increased with 20% and 50%.

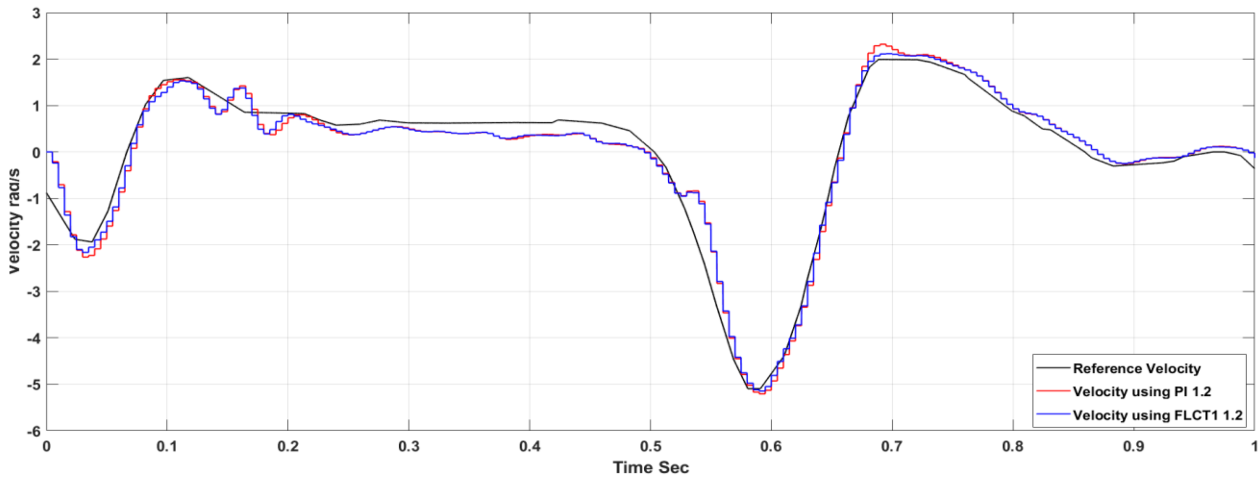

Fig. 18: System response using PI CONTROLLER and FLC-PI controller algorism when the parameters increase with 20%.

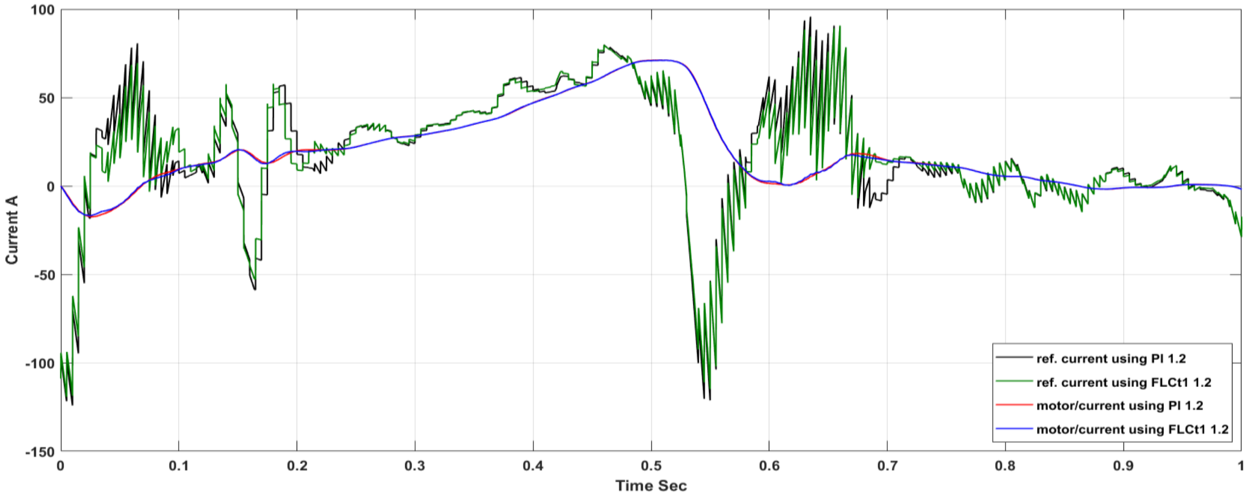

Fig. 19: Current of DC MOTORS response using PI CONTROLLER and FLC-PI controller algorism when the parameters increase by 20%.

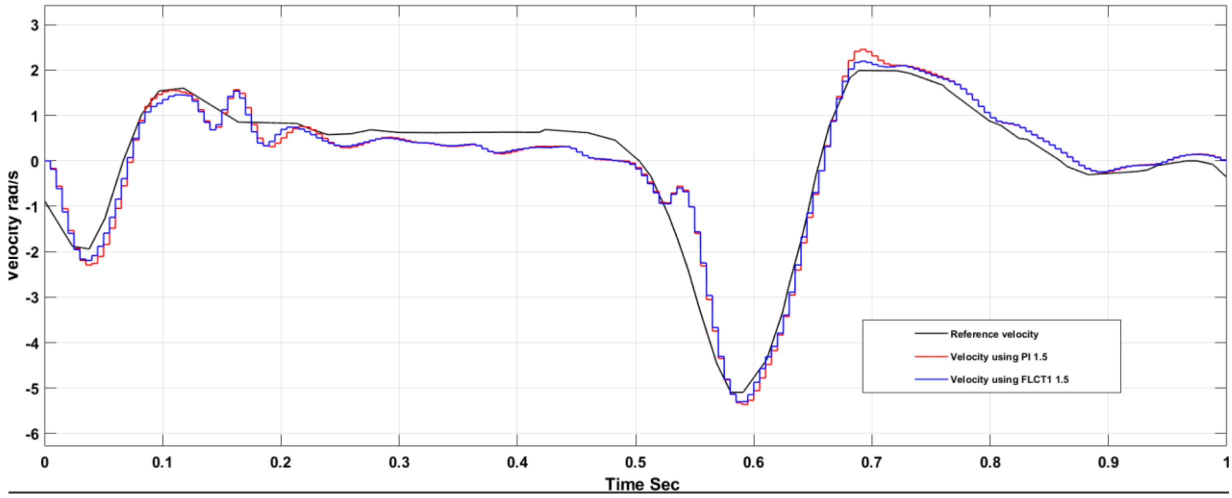

Fig. 20: System response using PI CONTROLLER and FLC-PI controller algorism when the parameters increase by 50%.

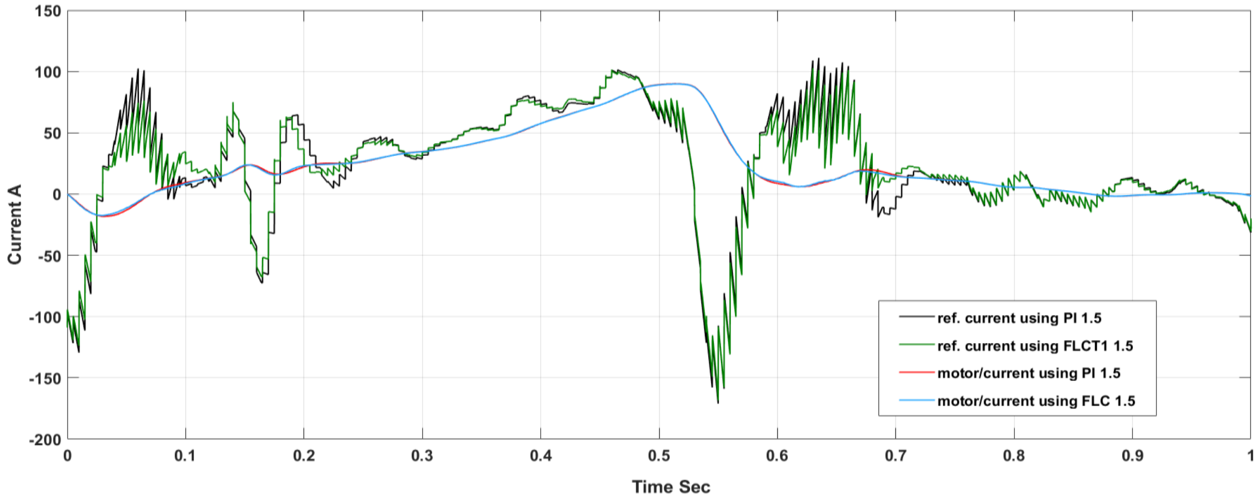

Fig. 21: Current of DC MOTORS response using PI CONTROLLER and FLC-PI controller algorism when the parameters increase by 50%.

4.2 Experimental results

In this section, the assembled and controlled practical model of the proposed PSAAP model is presented. The outcome demonstrates that the PSAAP's motion with the FLC-PI controller performs better than with just a PI CONTROLLER.

To demonstrate that amputees can benefit from the PSAAP model simulation, the practical PSAAP model is crucial. Every part's material is selected based on what is suitable for the model and what is available in Egypt. A CNC machine is used in the manufacturing of mechanical parts. Every component is made using the materials listed in Table 5. The assembly of the PSAAP is depicted in figure 22. Figure 1 illustrates the PSAAP model as the practical model.

Table 3: the materials for each part.

Part	Material
Foot base	PFR
The cam and follower mechanism	AL alloy
Ankle link	AL alloy
Series leaf springs	PFR
Screw and nut	Stainless Steel
Cover	PLA

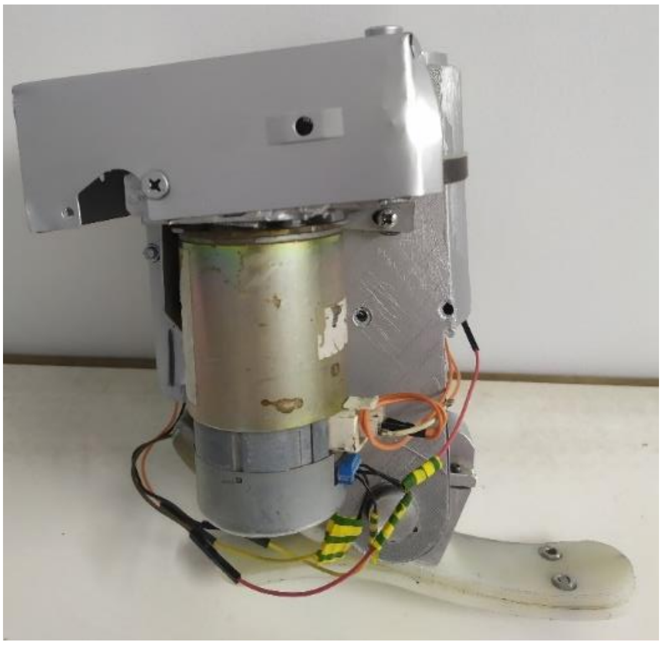

Fig. 22: the semi-active ankle prosthesis.

The PSAAP model is controlled by means of the FLC-PI control algorithm. The Arduino MAGE is used to carry out this control. The 150-watt DC MOTORS used to power the PSAAP model. The 150-watt brushless DC motor from Maxon is a good choice due to its lightweight and high power. The DC motors are too expensive to be used. Since personal weight is not used in the experiment, 150-watt DC MOTORS are not required. Therefore, small personal weights can be used with small DC MOTORS. the encoder used to determine the speed of DC motors. H-bridge is used to derive DC motor current, and current sensors are used to measure DC motor current.
The reference speed is the first step in the control system. The DC MOTORS speed is compared with reference speed. For speed control and current control, two loop FLC-PI controllers have been constructed. The error and change in this error are entered to the first FLC then the parameter of this PI CONTROLLER -speed controller is adjusted by this FLC. The output of this PI CONTROLLER is reference current. The reference current is compared with the actual current of the DC MOTORS. The error between the reference and actual current and the change in this error are entered to the inner loop FLC-PI-current controller. The output of the second PI CONTROLLER is the reference DC MOTORS voltage. For DC MOTORS, the direction is either forward, backward, or stop depending on how positive or negative the reference speed is. Figure 23 shows the schematic of the control circuit. The control program is written in Arduino, however it uses [29] to convert the

fuzzy file to an ion file. This program is larger than the PI CONTROLLER program so the Arduino mega is used.

The control circuit is linked to the PSAAP model. Next, the PSAAP is used to see if it can replicate an amputee's ankle motion. The figures 24 and 25 show how the different states correspond to the normal gait cycle. Also displayed are frames from a video of an experiment showing the gait cycle of the amputee. This figure displays that the motion of the PSAAP model using FLC-PI controller is very similar to the motion of non-amputee than the only PI CONTROLLER [15].

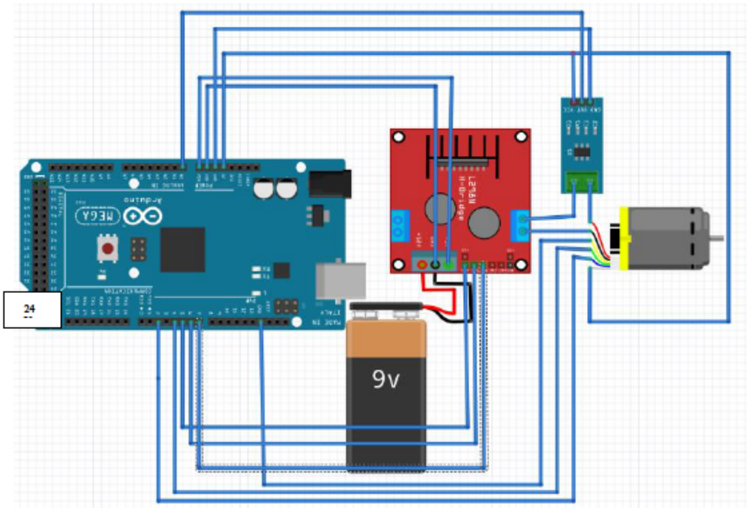

Fig. 23: The schematic of the control circuit.

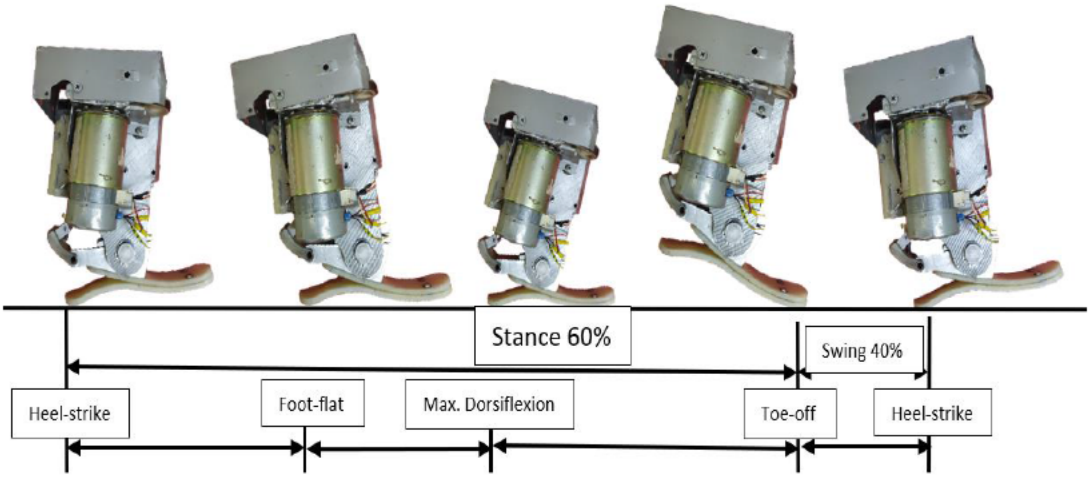

Fig. 24: the gait cycle of the PSAAP model using FLC-PI controller.

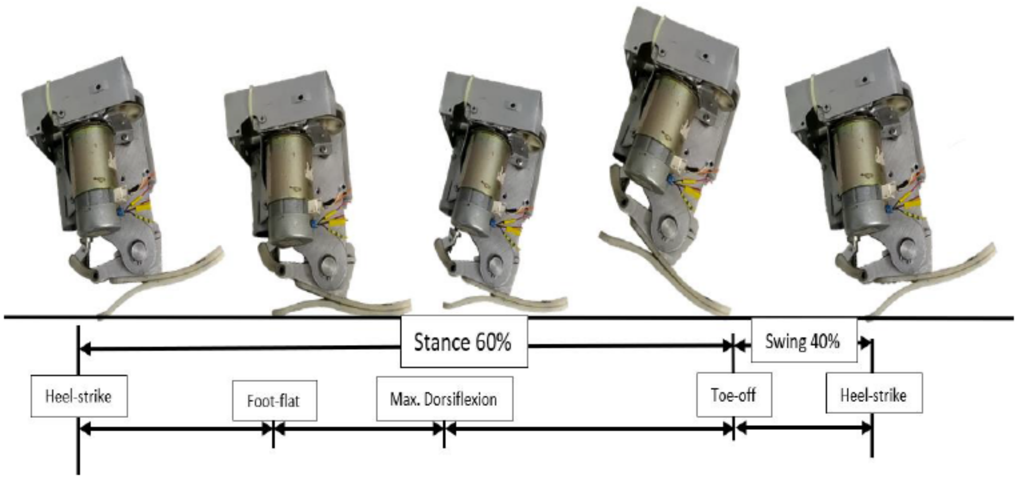

Fig. 25: the gait cycle of the PSAAP model using PI CONTROLLER.

5 Conclusions

In this paper, the mechanical design of a novel PSAAP is studied. It is like the lower limb joint of the human body, and it can better meet the humanoid requirements of artificial leg. Simulation results show that the PSAAP can follow the target trajectory well. This paper presents a FLC-PI control approach of the human lower limb. The proposed strategy achieved good tracking performance compared to a healthy limb joint displacement even in presence of perturbation. Comparisons are made for the system with PI CONTROLLER and FLC-PI controllers. The performance of the transtibial prosthetic limb using both controllers is also shown. The results show that implementing the FLC-PI controller in the system gives better performance. The results reveal that a PSAAP with an FLC-PI controller method outperforms a PI CONTROLLER alone. And in simulation, the load and the parameters of DC MOTORS are increased with 20% and 50%. The results show that FLC-PI controller can adjust the system when the load and the parameters of DC MOTORS are increased with 20% and 50%. An experimental model for testing the performance of the PSAAP is similar to biological muscle. This research presents the PI CONTROLLER and FLC-PI methods for a PSAAP. Also, in the practical the FLC-PI controller is better than the only PI CONTROLLER.

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