Simulation And Modeling Of Hybrid Assistive Robotic Neuromuscular Dynamic Stimulation For Upper Limb Rehabilitation

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Hybrid assistive robotic neuromuscular dynamic stimulation (HARNDS) is an integration between functional electrical stimulation (FES) and an exoskeleton. The HARNDS control system has the potential to offer a promising technology for the rehabilitation of post-stroke patients. The design of the HARNDS control system requires good planning to enable safety and comfort for post-stroke patients. However, most FES and exoskeleton integration design procedures do not consider modeling and simulation of the control system as an alternative to testing system behavior to ensure the device can work optimally and meet rehabilitation needs. This article aims to simulate the DC motor based on actuator requirement for exoskeletons used for upper limb rehabilitation in post-stroke patients, as well as the control system model in HARNDS using parameters of the electrical components used in the FES. The control system model approach was carried out using Matlab/Simulink software to model the DC motor control system and Proteus 8 Professional software to model the FES circuit control system. The research results show that the exoskeleton, through the DC motor control system model, has fulfilled the requirements for calculating the torque required as an actuator with a lifting load in flexion/extension movements of 8.88 $N.m$. and supination/pronation of 0.88 $N.m$. Meanwhile, the FES circuit used is capable of producing an output voltage signal pattern of 80 VAC with an input voltage of 5 VDC. The system response test shows that the exoskeleton and FES can be used as recommendations for rehabilitation needs in post-stroke patients.

1. Introduction

Stroke is the second largest cause of disability in the world after dementia [1]. The majority of long-term disabilities are caused by stroke, namely hemiparesis with symptoms of limited use of the arm [2]. Lum et, al. [3] Their research explained that more than 65% of stroke sufferers were unable to use upper limb functions in daily life. In the last decade, the literature presents various concepts and techniques developed by integrating functional electrical stimulation (FES) and DC motor-type exoskeleton actuators used to activate motor-sensor systems through electrical stimulation and achieve task performance through the exoskeleton [4, 5]. The design of the FES device stimulation protocol ideally allows for generating current density [6]. stimulation waveform, charge balance and required voltage settings [7], making it possible to reduce muscle fatigue and improve patient safety after stroke [8].

FES integrated with an exoskeleton allows perfecting accuracy to achieve kinematics and reduces muscle fatigue so that muscle stimulation can be carried out intensively and repeatedly for the rehabilitation of post-stroke patients [8, 9]. In general, the active actuator model with a DC motor is used as a component to convert electromechanical en-

ergy because of its ability to regulate the speed and torque required in the exoskeleton [10, 11]. Several approaches for integrating FES and exoskeletons focusing on system control strategies such as cascade PID control, model predictive control (MPC), iterative learning control (ILC), and robust control are also being investigated to meet specific user needs and adapt to environmental conditions [12–16]. Several parameters of the control system used to integrate FES and exoskeleton are proven directly to the subject by accommodating changes in conditions that occur to individual users. The control system approach in several cases has been proven through direct testing on subjects by accommodating changes in orthosis conditions that occur in individual users [17]. However, in most FES and exoskeleton device design procedures, modeling and simulation have not been considered as an alternative for testing system behavior to avoid direct device design errors so that it can be estimated that the device is working optimally and according to the needs of upper limb rehabilitation in post-stroke patients. The model and simulation of the control system on the FES and exoskeleton can be used as a recommendation to realize the hybrid assistive robotic neuromuscular dynamic stimulation (HARNDS) concept by combining and coordinating the actuation strategy between the FES and the DC motor-type active actuator exoskeleton to restore residual post-stroke patients.

While stroke remains a prevalent cause of disability, particularly affecting upper-limb function, rehabilitation strategies are constantly evolving. This study delves into the exciting area of hybrid assistive robotic neuromuscular dynamic stimulation (HARNDS), which integrates functional electrical stimulation (FES) and DC motor-powered exoskeleton technology to restore residual motor function in post-stroke patients. Despite the undeniable promise of this approach, crucial gaps remain in its development. Our research aims to bridge these gaps by focusing on two key aspects: firstly, modeling the electrical components of the FES device to generate safe and dynamic stimulation patterns; and secondly, simulating DC motor actuators on exoskeletons by considering the need for movements for flexion/extension and supination/pronation for the upper limb rehabilitation of post-stroke patients. By addressing these limitations, HARNDS has the potential to revolutionize post-stroke rehabilitation. Imagine patients regaining lost mobility, performing daily tasks with ease, and experiencing improved quality of life. This is the vision that drives our research, and we are confident that by delving deep into the technical intricacies of HARNDS, we can unlock a brighter future for stroke survivors.

2. Control algorithm

2.1. Control system model design for exoskeleton actuator

The exoskeleton device used in HARNDS is a 3 DoF exoskeleton with two active actuators using a DC motor. System design and DC Motor control simulation to adjust the torque and speed requirements used for the post-stroke patient rehabilitation process. Calculating torque requirements and simulating a DC motor is carried out using the following steps:

1. Analysis of Actuator Requirements on Exoskeletons

2. Alternative Actuator using DC Motor

3. Criteria for DC Motors as Actuators in Exoskeletons

4. Create a simulation using Simulink/MATLAB R2022a

DC motor control system models are generally called field circuits and armature circuits. Because the transfer function is developed and if the constant becomes if (t), then the field current if, the armature current, and the torque (T) produced by the motor are calculated using Eq. (1).

$$T(t) = kt\, ia(t) \tag{1}$$

When the motor drives a load, the back electromotive force (back emf) voltage vb in the armature circuit is used to withstand the applied voltage. The voltage vb is directly proportional to the angular speed of the motor shaft:

$$vb(t) = kb\frac{d\theta(t)}{dt} \tag{2}$$

The armature circuit given a load is carried out using Eq. (3).

$$R_a i_a(t) + L_a\frac{di_a(t)}{dt} + v_a(t) = u(t)$$
$$\text{atau} \quad R_a i_a(t) + L_a\frac{di_a(t)}{dt} + k_b\frac{d\theta(t)}{dt} = u(t) \tag{3}$$

The transfer function equation is then applied to the Laplace transformation, assuming the initial conditions are zero to produce Eq. (4).

$$kt Ia(s) = Js^2\Theta(s) + fs\Theta(s) \text{ dan RaIa }(s)$$
$$+ \text{LasIa}(s) + kb\Theta(s) = U(s) \tag{4}$$

Eliminating *Ia* from both equations produces Eq. (5)

$$G(S) + L_a\frac{\theta(S)}{U(S)} = \frac{K_t}{S\left[(Js+f)\left(R_a+L_aS\right)+K_t k_b\right]} \tag{5}$$

The configuration scheme in Fig. 1 was carried out using Matlab/Simulink. DC motor modeling and simulation are
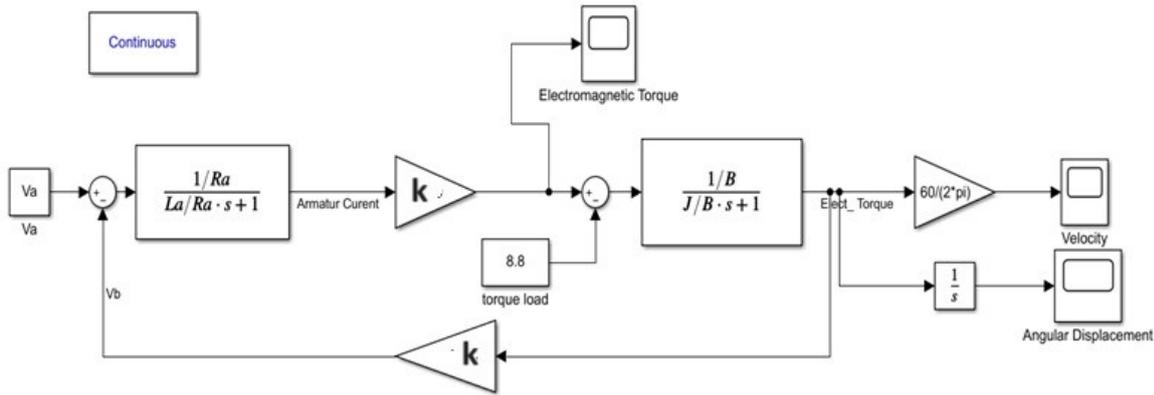
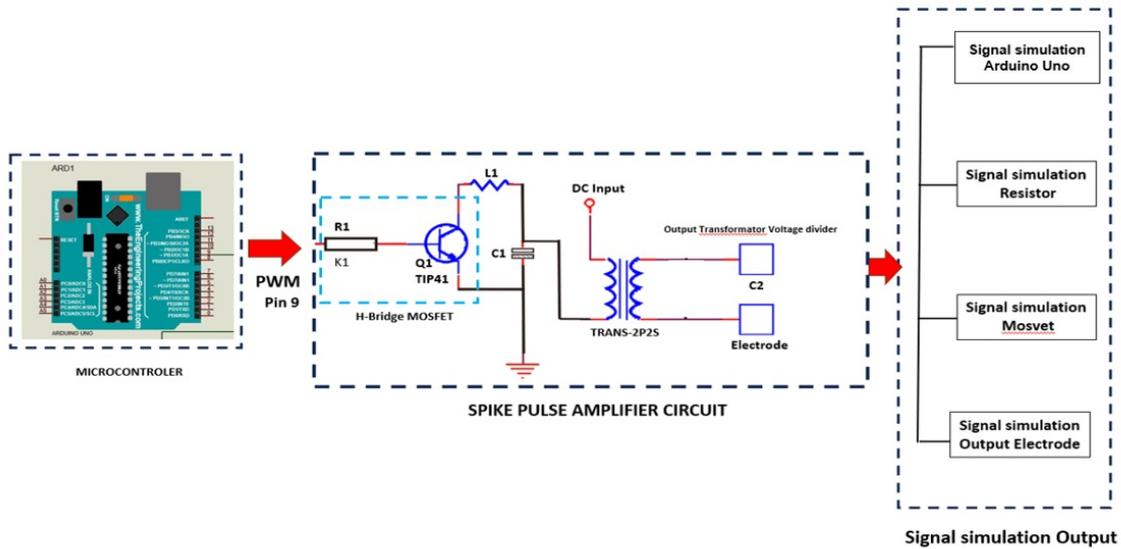**Fig. 1.** DC Motor Configuration via Matlab/Simulink.

Fig. 2. Schematic model of the FES circuit.

carried out by adding a torque load that is adjusted to the needs of the actuator on the exoskeleton, which is needed to move flexion/extension and supination/pronation in the upper extremities of post-stroke patients. The addition of torque load simulation is intended to test the stability of the torque response, rotation angle shift response, and speed response of the DC motor system when experiencing disturbances in the form of torque loads.

2.2. Design and Simulation Model of the FES Circuit Control System

The control algorithm model of the FES circuit can produce a voltage of 0 – 100 V [18]. The FES model is designed to produce biphasic pulses that stimulate the muscles via electrodes with a combination of short duration (600μs)

and frequency of 50 Hz [19]. The maximum current limit is assumed to be 40 mA. Consideration of a maximum stimulation current limit of 40 mA refers to an increase in the pulse frequency of post-stroke patients so that muscle contractions in post-stroke patients are only able to produce a frequency of around 40 Hz and above [20]. The skin resistance model in patients refers to research [21], which assumes skin resistance of 2 kΩ with a stimulation output voltage level of 80VAC. The equation used to calculate the output voltage and skin resistance can be done with the following equation:

$$V = I \times RP = 40\,\text{mA} \times 2\text{k}\Omega = 80\,\text{V} \qquad (6)$$

The circuit model to simulate FES was carried out using Proteus 8.9 Professional software. Fig. 2 explains the

design of using FES components, which are modified from research [18] and adjust the actual circuit parameters.

The accuracy of the FES circuit simulation model in Figure 2 was evaluated using Proteus 8 professional software. First, FES begins by selecting the pulse generator menu (Arduino Uno) using the pulse width modulation (PWM) provisions, which are used as a control in the spike pulse amplifier circuit. Adjusting the amplitude and frequency in the FES circuit is done by providing a PWM value to the pulse generator (Arduino Uno) to produce a square signal output that can be adjusted to the recommended FES circuit output criteria. The spike pulse amplifier circuit is used to convert DC voltage into AC voltage, using several circuits, including H-Bridge MOSFET and CT transformer. The resulting change in output voltage is in the form of spike pulses and has a very narrow pulse width, but the resulting pulse amplitude is very high. The accuracy of the FES circuit model is simulated to determine the output signal amplitude in each circuit used to produce an output that is safe and comfortable to use to provide electrical stimulation to the upper limb muscles of post-stroke patients. Simulation testing is carried out by measuring the output voltage at the circuit output as follows:

1. Arduino output signal amplitude input

2. Output signal amplitude Resistor circuit

3. Output signal amplitude MOSFET

4. Output signal amplitude Electrode that will connect the output voltage from the FES to stimulate muscles by simulating skin resistance of 2 kΩ.

3. Results and simulation

3.1. Analysis of Actuator Requirements on Exoskeletons

The exoskeleton design criteria to meet actuator requirements requires two motors to move the joint according to the rehabilitation needs of post-stroke patients. Fig. 3 is an exoskeleton design to produce elbow flexion/extension movements and supination/pronation movements.
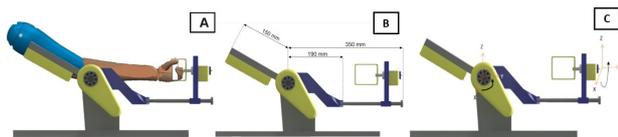

Fig. 3. (a) Use of the exoskeleton on the arm (b) structure of the size of the exoskeleton (c) structure of the direction of movement of the exoskeleton.

The exoskeleton design criteria in Fig. 3 use a DC motor actuator, so it is important to determine torque criteria that suit the rehabilitation needs of post-stroke patients. Based on anthropometric studies, the average body weight of Indonesians is 63 kg for men and 53 kg for women [22], and according to the Indonesian Minister of Manpower Regulation concerning elevator safety regulations, the reference standard for Indonesian human body weight is 68 kg with rounding to 70 kg [23]. Therefore, it is important to calculate the torque requirements to move the actuator on the exoskeleton based on the weight of the human upper limbs. According to Bruno et al. [24] The mass distribution percentage of the human Forearm body part is 3.2%, and the mass of the human Hand body part is 1.2% based on body weight (kg). The Forearm mass and Hand mass of the subject are calculated to determine the DC motor load requirements through the following calculations:

The weight of a pair of forearms = (70kg x 3.2%) + (70kg x 1,2%) = 3,08kg

So, the weight of 1 forearm = 1,54kg

The component design for the exoskeleton link section made using a 3D PLA filament printer is estimated to have a mass of 0.6 kg with a structure of the appropriate size in Fig. 3 so that the DC motor torque requirement for flexion/extension movements is calculated as follows:

Link length (1) $\quad = 0,35$ m

Motion angle $\quad = 0°\text{s/d}115°$

Estimated component mass $\; = 0,6$ kg

Total mass of arm $\quad$ Estimated mass of components

$+$ Weight of 1 forearm

$= 0,6 \text{ kg} + 1,54 \text{ kg} = 2,14 \text{ kg}$

$\tau = F \times l = (\text{massa} \; \times \; \text{gravitasi}) \times r(\sin\theta)$

$\tau = \left((2,14 \text{ kg} + 0,6)\text{kg} \times 9,8 \text{ m/s}^2\right) \text{N} \times 0,35 \text{ m} \times \sin(115)$

$\tau = 8,88\text{Nm}$

Calculation of torque requirements for pronation/supination movements is carried out in the same way; it is known that the percentage of hand weight is 1.2% of human body mass. So, with a human body weight of 70 kg, the hand mass is 2.24 kg for a pair and 1.12 kg for one hand (single). The hand link design has a length of 0.05 m with an estimated mass of 0.6 kg. With the same calculation, it is found that the motor torque requirement for the hand part of the supination pronation movement is 0.97 *N.m*.

3.2. Alternative DC Motors as Actuators on Exoskeletons

DC motors that meet the required power criteria are servo motor types because they are capable of producing large

amounts of power, and the physical form of the motor is relatively small, making it possible to provide comfort in using the exoskeleton [25]. Several servo-type options can be used as actuators on exoskeletons. Servo motor specification data used alternatively for flexion/extension movements is explained in Table 1.

The three servo motors were selected based on the value of the exoskeleton requirements for flexion/extension movements. In the first option, the drawbacks of the servo motor are that the dimensions need to be bigger and the motor weight is quite high. At the same time, the exoskeleton design is considered the element of being portable or easy to carry. The first option, the servo motor, is more suitable if the exoskeleton is made in a fixed condition, making the first option less suitable if implemented in existing designs. The second option, the servo motor, has suitable dimensions, but the torque required does not meet the criteria required by the exoskeleton.

The third servo motor option is the NFP-5840-31ZY, with a nominal torque specification of 9.80 Nm. Nominal torque is the safe limit torque that can be received continuously by the servo motor. Apart from the nominal torque above the torque requirement, the motor also has relatively small dimensions and a light load, making the third option motor more suitable for application to portable exoskeletons.

The actuator criteria for supination/pronation movements provide several options for the type of servo motor applied to the exoskeleton. The servo motor specification data used alternatively is explained in Table 2 for the supination pronation movement.

The servo motor for supination/pronation movements has three alternative options, which are selected based on the minimum torque requirement, namely 0.97 $N.m$. In the first option of the servo motor, the disadvantage is that there are two output shaft positions or two faces, while the need for the actuator component is only one shaft. In the second option, the disadvantage of the servo motor is that it is relatively heavy for use in the pronation/supination actuator. The supination/pronation movement servo motor requires as little weight as possible because it will affect the work of the flexion/extension part of the servo motor.

The third option for the supination/pronation movement servo motor is the Dynamixel AX-12A digital servo. The servo motor has a torque of 1.5 $N.m$. The Dynamixel AX-12A servo motor is also lightweight and is not too large, making it possible to use it as an actuator for supination/pronation movements.

3.3. Simulation Model of Servo Motor Actuator Control System

The NFP-5840-31ZY type servo motor simulation was carried out using a mathematical model simulation through a schematic diagram described in Fig. 1. The estimated values of the servo motor specifications used for flexion/extension movements were adopted from research by Pinto et al. [26], in contrast, the specifications of the Dynamixel AX-12A servo motor for supination/pronation movements were adopted from research by Maximo et, al. [27]. Table 2 estimates the NFP-5840-31ZY type servo motor and the Dynamixel AX-12A type servo motor.

The NFP-5840-31ZY type servo motor is simulated with a control system that is given an input voltage of 24 Volts and is given a constant value (K) of 4,148. Testing of the NFP-5840-31ZY type servo motor is carried out by providing transient conditions related to speed. Transient conditions are given in the form of a torque load (TL) of 8.88 Nm, which is adjusted to the needs of the exoskeleton. The step function is given to the system using the transfer function equation in Fig. 1, and the results of the torque response test are obtained, which are adjusted to the needs of the exoskeleton, the response to the displacement angle of rotation of the servo motor and the speed of the servo motor in Fig. 4.

The servo motor response in Fig. 4 shows that with a given input Torque Load (TL) of 8.88 $N.m$, the servo motor produces a speed response step and speed control system accuracy of 10 rpm. The resulting torque response, angular displacement and speed follow the needs of the exoskeleton to move flexion/extension in post-stroke patients. The resulting step response has an overshoot value for the system of 0.975%, a rise time value of 1.384 s and a settling time of 0 seconds. With the results of the step response test, it was found that the servo motor control system had a decent and stable response to be used as a recommendation for the need for actuators with flexion and extension types of movement in actual exoskeleton design in the future for upper limb rehabilitation needs in post-stroke patients.

Meanwhile, the dynamixel AX-12A servo motor is simulated with a control system with an input voltage of 12 Volts and a constant value (K), including 0.694. Testing the AX-12A dynamixel servo motor was carried out by providing transient conditions related to speed. The transient condition is given in the form of a torque load (TL) of 0.88 $N.m$, which is adjusted to the supination/pronation movement requirements of the exoskeleton. The step function is given to the system using the transfer function equation in Fig. 1. The torque response test results are obtained, which are adjusted to the needs of the exoskeleton, the displace-

Table 1. Servo Motor Type Options for flexion/extension movement.

Kinds Servo	ATO180STM21520	SPT70HV	NFP-5840-31ZY
Specification	Heavy: 22, 2 kg Torque: 20Nm; Size: 180 × 300 mm	Heavy: 0, 2 kg Torque: 6.80Nm; Size: 60 × 70 mm	Heavy: 0, 36 kg; Torque: 9.80Nm; Size: 41x115 mm

Table 2. Servo Motor Type Option flexion/extension movement.

Kinds Of Servo	RDS5160 Servo Digital	WINGXINE ASME-SQB Servo	Dynamixel AX-12A Servo Digital
Specification	Heavy: 0, 3 kg; Torque: 5, 8Nm; size: 61 × 70 mm;	Heavy: 0, 8 kg; Torque: 5Nm; size: −;	Heavy: 0, 3 kg; Torque: 1.50 N.m; size: 50x40 mm;

Table 3. Estimated servo motor.

Description	Servo motor type NFP-5840-31ZY	Dynamixel AX-12A type servo motor	Syim
Resistannce	8.6538	8.3	$R(\Omega)$
Inductance	0.0238	0.0203	$L(H)$
Moment of Inertia	0.85075	0.02941	$J\left(Kg \cdot m^2\right)$
Friction coefficient	0.59751	0.059751	$B(N.m.s)$

ment response Servo motor rotation angle and servo motor speed in Fig. 5.

The speed response of the servo motor in Fig. 5 shows that with a given input Torque Load (TL) of 0.88 *N.m*, the servo motor produces a speed response and accuracy of the control system at a speed of 10 rpm. The speed response, angular displacement and torque produced are by the needs of the exoskeleton to move Supination/pronation in post-stroke patients. The resulting step response has an overshoot value in the system of 0.501%, a rise time value of 535.129 s and a settling time of 0 seconds. With the results of the step response test, it was found that the dynamixel AX-12A type servo motor control system had a decent and stable response with a speed value that followed the needs of the exoskeleton used for the rehabilitation process of post-stroke patients, so it is suitable to be used as a recommendation for actual exoskeleton device design in the future.

3.4. S Device Circuit simulation testing

The FES device used in HARNDS is simulated to test the circuit to achieve the comfort and performance of the device to be designed. This simulation was used before it was carried out on patients using a skin model with a skin resistance of 2 kΩ according to the study's recommendations [19]. With a given input voltage of 5 V, MOSFET, and frequency of 50 Hz, the electrode at the output uses R3 2kΩ, and the conversion pulse circuit resistance uses R1 1kΩ, R2 1kΩ. Observations are made with the output of each circuit on the simulated components. The first observation is the

voltage input pulse from the Arduino; the second observation is the voltage output of the resistor component; the third observation is the output of the MOSFET component, and the fourth observation is the output of the transformer, which is loaded using a skin model with a resistance of 2 kΩ. Fig. 6 is a simulation result of the FES device.

The proposed simulation has been analyzed based on the performance of each circuit used in the FES device design. The simulation results show that with a PWM input value of 90 on the Arduino Uno is capable of producing an AC voltage output of 80 V and does not affect the predetermined frequency and pulse duration. Measurements from the oscilloscope model in Fig. 5 show the data V/DIV = 2 V/DIV, Time/DIV = 0.2 ms, wave height = 2.5 DIV, period 0.6 ms, and frequency 50 Hz, with varying voltages, namely the Arduino output voltage is 5 VDC, the resistor voltage output is 2 VDC, and the most voltage output is 12.5 VDC. The transformer's voltage output is 80 VAC. The suitability of the signal output parameters in the design and simulation of the FES circuit shows significant results for use as an FES device that will be developed in the future.

4. Conclusions

HARNDS modeling and simulation that integrates the exoskeleton and FES was carried out to obtain recommendations for several component parameters that will be used to implement the control system engineering process on the HARNDS device used for upper limb rehabilitation in the future. Several observations were obtained from simulations of control systems on exoskeletons with actuators us-
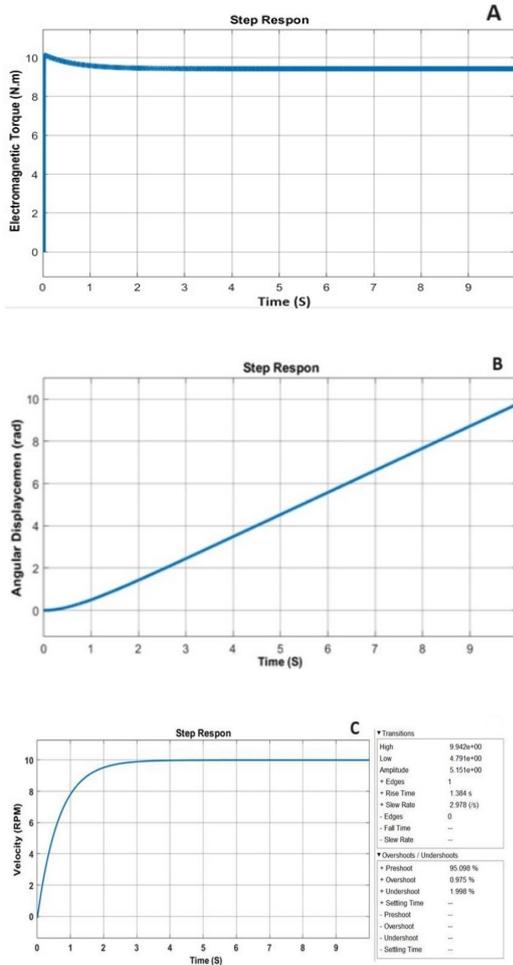
Fig. 4. Simulation of Step Response of Servo Motor control system Type NFP-5840-31ZY (a) Torque Response Step (b) Angular Displacement Response Step (c) Speed Response Step (RPM).

ing DC motors. Based on calculations of limb rehabilitation needs, the torque required by the actuator on the exoskeleton is 8.88 N.m for flexion/extension movements and 0.88 *N.m* for supination/pronation movements. The DC motor criteria used in this research are the NFP-5840-31ZY type servo motor (flexion/extension movement) and the AX-12A dynamixel type servo motor (supination/pronation movement). Each servo motor was then simulated by a torque load (TL) adapted to the torque requirements for upper limb rehabilitation. Based on the control system simulation, it was found that the control system on the servo motor had a decent and stable response with a speed response of 10 rpm, and torque that meets recommended upper extremity rehabilitation needs. Meanwhile, the simulation results of the FES signal characteristics show that
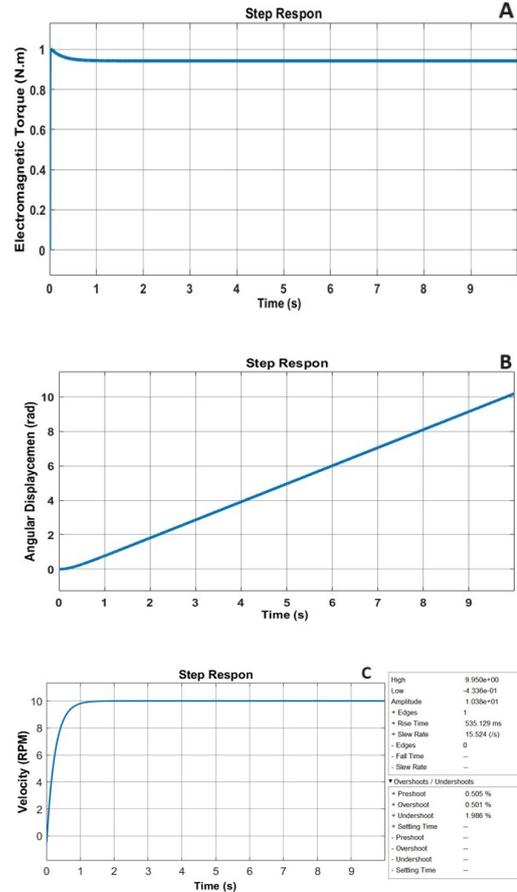

Fig. 5. Simulation of Step Response of Dynamixel AX-12A Type Servo Motor control system (a) Torque Response Step (b) Angular Displacement Response Step (c) Speed Response Step (RPM).
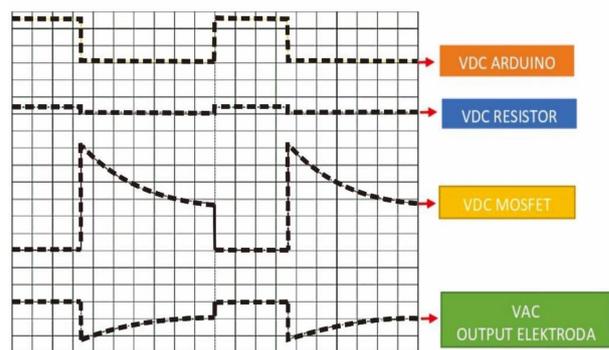

Fig. 6. FES stimulation pulse simulation results using Proteus 8 Professional software.

the components used in the device have variations in pulse width, amplitude, and frequency. This signal can be controlled using a pulse generator via a PWM signal from

Arduino. The FES circuit is simulated using a 5V supply voltage with a PWM pulse width verification input step value of 90, which can produce an output voltage of 80 VAC, a time period of 0.6 ms, and a frequency of 50 Hz. The simulation results show that the output simulation of the FES component circuit can produce a biphasic pulse signal with an amplitude that can be adjusted using PWM from the Arduino Uno. The FES circuit simulation developed will be a recommendation for developing FES devices for rehabilitation using electrical stimulation of muscles in post-stroke patients.

Acknowledgment

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