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Soft Elbow Exoskeleton for Upper Limb Assistance Incorporating Dual Motor-Tendon Actuator

Rifky Ismail [1], Mochammad Ariyanto [1], Inri A. Perkasa [1], Rizal Adirianto [1], Farika T. Putri [1,2], Adam Glowacz [3] and Wahyu Caesarendra [4,*]

1 Center for Biomechanics, Biomaterial, Biomechatronics, and Biosignal Processing (CBIOM3S), Diponegoro University, Semarang 50275, Indonesia; rifky_ismail@ft.undip.ac.id (R.I.); mochammad_ariyanto@ft.undip.ac.id (M.A.); adipandiangan13@gmail.com (I.A.P.); rizaladrianto@gmail.com (R.A.); farikatonoputri@gmail.com (F.T.P.)
2 Semarang State Polytechnic, Jalan Prof. Soedarto, SH. Tembalang, Semarang, Central Java 50275, Indonesia
3 Department of Automatic Control and Robotics, AGH University of Science and Technology, Al. A. Mickiewicza 30, 30-059 Kraków, Poland; adglow@agh.edu.pl
4 Faculty of Integrated Technologies, Universiti Brunei Darussalam, Jalan Tungku Link, Gadong BE1410, Brunei
* Correspondence: wahyu.caesarendra@ubd.edu.bn; Tel.: +673-7345-623

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Abstract: Loss of muscle functions, such as the elbow, can affect the quality of life of a person. This research is aimed at developing an affordable two DOF soft elbow exoskeleton incorporating a dual motor-tendon actuator. The soft elbow exoskeleton can be used to assist two DOF motions of the upper limb, especially elbow and wrist movements. The exoskeleton is developed using fabric for the convenience purpose of the user. The dual motor-tendon actuator subsystem employs two DC motors coupled with lead-to-screw converting motion from angular into linear motion. The output is connected to the upper arm hook on the soft exoskeleton elbow. With this mechanism, the proposed actuator system is able to assist two DOF movements for flexion/extension and pronation/supination motion. Proportional-Integral (PI) control is implemented for controlling the motion. The optimized value of Kp and Ki are 200 and 20, respectively. Based on the test results, there is a slight steady-state error between the first and the second DC motor. When the exoskeleton is worn by a user, it gives more steady-state errors because of the load from the arm weight. The test results demonstrate that the proposed soft exoskeleton elbow can be worn easily and comfortably by a user to assist two DOF for elbow and wrist motion. The resulted range of motion (ROM) for elbow flexion–extension can be varied from 90° to 157°, whereas the maximum of ROM that can be achieved for pronation and supination movements are 19° and 18°, respectively.

Keywords: elbow soft exoskeleton; dual motor-tendon actuator; PI control; flexion/extension; pronation/supination

1. Introduction

Wearable robot exoskeleton can be used as a device to facilitate the user in carrying out an activity or work. The exoskeleton robot can be used in the medical field as a healing therapeutic device for people with paralysis due to stroke or paralysis due to accident, which is often called brachialis plexus injury (BPI). Wearable exoskeletons are a very good development for people with disabilities and provide mechanical assistance in their activities.

In terms of the material used, the exoskeleton robot is divided into two classes: Hard exoskeleton and soft exoskeleton. A hard exoskeleton is widely used when high mechanical force, precise position, and fast dynamics are required [1]. On the other hand, a soft exoskeleton is utilized when it needs portability and comfortability for people who wear the exoskeleton robot. In order to enhance the performance of the exoskeleton, some researchers combine these two kinds of exoskeleton robots.

Researchers have developed a hard exoskeleton elbow for assisting people with the upper limb [2–8]. They succeeded in building a hard elbow exoskeleton robot to provide mechanical assistance for a user/wearer mostly for flexion and extension motion. A DC motor is widely used for both elbow and hand exoskeletons. By applying this hard robot mechanism, high force and torque can be achieved to provide mechanical support for the wearer. Surface electromyography is a widely used sensor in exoskeletons. The surface electromyography sensor functions as interface between the healthy muscle and the exoskeleton [9–12].

Soft robotics is one of the areas of robotic research aimed to solve a challenge faced by traditional robotics. Wearable exoskeleton in this research is part of soft robotic area, which consists of manufactured flexible structure [13]. There are some benefits gained from the use of a wearable exoskeleton robot as health assisting device: A soft exoskeleton tends to be lightweight, thus, people can comfortably use it, and, most importantly, the soft exoskeleton is flexible and can therefore accomplish difficult motions that a traditional robotic can not [13,14].

Actuator design plays an important role in soft exoskeleton development. A soft robotic elbow sleeve designed by a researcher from the National University of Singapore used the combination of flexion and extension actuator. Flexion actuator is being forced into a stiff fixture with the intention of nonlinear effect minimization. An experiment is conducted to test the deflection of the extension actuator. Weight variation is attached at one side of the extension actuator. Meanwhile, the other end is being put to fix [13]. Soft robotic wearable elbow exoskeleton made by researchers from Carlos III Univesity of Madrid, Spain, used a shape memory actuator (SMA) with some advantages, e.g., lightweight, minimal noise when operated, and low cost to be produced. SMA actuator transducer material uses wires or springs to convert thermal energy into mechanical energy. Electric current circulates through SMA, causing a heated effect in SMA. Electric energy is converted into mechanical energy in SMA, called the Joule effect. The thermal energy leads to the SMA element recovery process to its original form. The SMA's recovery energy then being transformed into mechanical work [15].

One of the most widely used actuators in the soft exoskeleton is Bowden cable connected to a DC motor. A researcher from the Czech Technical University developed a smart upper limb orthosis utilizing Bowden cable attached to one end of a limb and a motor stepper to another end [16]. Another upper limb exoskeleton employing the Bowden cable transmission in their actuator is made by some researchers from China [17]. In this study, Bowden cable is used to minimize the man–machine interaction force. Bowden cable is commonly used as a transmission force in an elbow and hand exoskeleton [18–22]. Some researchers have conducted a study in combining pneumatic with Bowden cable [23,24] for the exoskeleton actuator system.

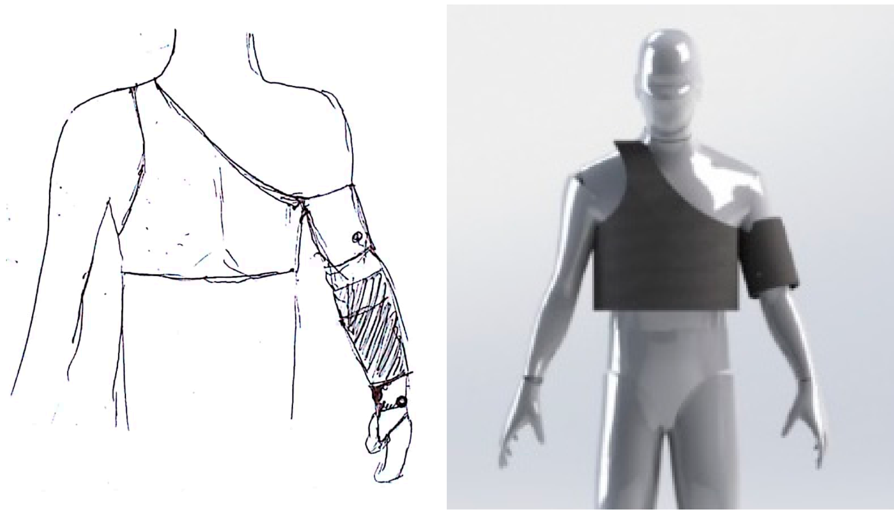
In this study, an affordable and lightweight soft elbow exoskeleton incorporating dual motor-tendon actuation is developed. The actuation system consists of a Bowden cable connected to a lead screw, which is coupled with a DC motor in order to move the elbow or wrist. An infrared sensor is placed in the actuator system to measure the obstacle movement. This non-back drivable mechanism enables the proposed soft elbow exoskeleton to provide mechanical support/force for the elbow to move the user's elbow and wrist in two DOF, i.e., flexion/extension and pronation/supination. This actuation system is easy to manufacture and the components are widely available in online and offline stores. Proportional-Integral (PI) control is utilized for controlling the linear displacement of the motor-tendon actuation for pulling/pushing the elbow and wrist. PID and PI compensators are widely used in controlling the motion of both hard and soft exoskeletons [7,13,25,26]. The proposed soft elbow exoskeleton is tested by a user to provide the mechanical force for flexion/extension and pronation/supination movements.

Most of the elbow exoskeletons resulted from previous research. Both hard and soft elbow exoskeletons can provide mechanical support for flexion and extension movements without assisting the pronation and supination motion [7,12,13,22,24–26]. Therefore, we propose an affordable dual motor-tendon actuator that can provide mechanical force for flexion/extension and pronation/supination movements. The flexion/extension motion can be attained by pulling/pushing the two Bowden cables simultaneously, whereas the pronation/supination movement can be obtained by pulling and pushing the two Bowden cables in the opposite direction.

There are some advantages of the aforementioned exoskeleton compared to other soft and hard exoskeleton designs that have been studied. User comfortability is one of the concerns in producing this soft exoskeleton which is achieved through the usage of fabric that is delicate yet has the ability to assist in supporting mechanical force and support. It has a simple method for fixing, alignment, and is easy to use for a user. The soft exoskeleton uses affordable materials and spare parts are easy to find, which can be beneficial to the exoskeleton user when there is any need for replacement during exoskeleton usage. As a result, the soft elbow exoskeleton can be affordable. The non-backdriveable mechanism allows holding/maintaining a user's hand during the flexion/extension movement without consuming more electric power from the battery. This indicates that the proposed exoskeleton is an energy-efficient device. The motor-tendon actuation system enables to convert motion directly from linear displacement from the actuator output to flexion/extension and pronation/supination motion on the user's arm. This also increases the safety of a user when the exoskeleton is worn and operated. The challenge for this exoskeleton is to provide a range of motion ability for flexion/extension and pronation/supination. The mechanism requires more space in the actuator system for a longer range of motion (ROM).

2. Soft Elbow Exoskeleton and Motor-Tendon Actuator Design

A user has to wear the elbow exoskeleton comfortably. Based on this consideration, the fabric is selected as a material of the proposed soft exoskeleton elbow which is worn by a user. Bowden cable is chosen as a force transmission in the soft exoskeleton actuation system. The proposed exoskeleton elbow is equipped with an upper vest exoskeleton suit. Figure 1 below is a soft elbow exoskeleton with two DOF in elbow and wrist movement. Two motor-tendon actuators are implemented for controlling each DOF. The first DOF is for flexion and extension motion while the second DOF is for pronation and supination movements.

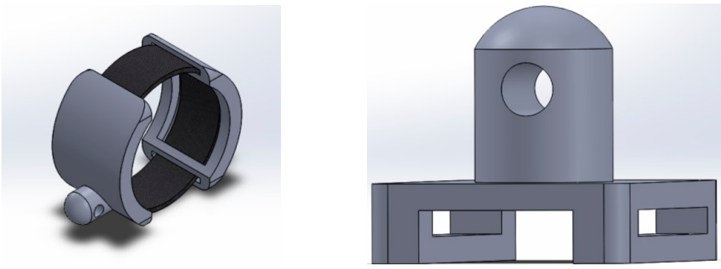


(**a**) (**b**)

Figure 1. Soft elbow exoskeleton (**a**) proposed 2D design; (**b**) proposed 3D design in computer-aided design (CAD) software.

2.1. Fabric-Based Soft Elbow Exoskeleton Design

At this stage, 3D modeling of the robot elbow exoskeleton is conducted according to the dimensions of the arm of the patients with brachialis plexus injury. Modeling is conducted by developing a 2D design and modeling them into a 3D model using SolidWorks computer-aided design (CAD) software. The modeled component is a vest, wrist strap, and upper arm hook designed based on the average size of the Indonesian people. Figure 1 shows the resulted design of the soft elbow exoskeleton which is worn by a user. The hook design in the upper arm and wrist is presented in Figure 2.



(**a**) (**b**)

Figure 2. Hook design for soft exoskeleton elbow. (**a**) Wrist hook; (**b**) upper arm hook.

2.2. Motor-Tendon Actuation Design

In this study, actuator motor-tendon was chosen because of the ease in the manufacturing process which only requires a motor and a tendon to pull and stretch/push the hook on the upper arm and wrist. The motor used is a DC motor, and the Bowden cable is utilized as a tendon in this actuator. This wire/tendon is used as a connector between the arm hook and the nut that is on the lead screw on the actuator to move the elbow. In addition, an important component used is the infrared sensor which functions as a proximity sensor to provide feedback on the control system that is applied. The sensor is employed to measure an obstacle that represents the displacement or length of pull/push performed by the DC motor. The illustration of the motor-tendon actuator mechanism is shown in Figure 3. Limit switches are applied to limit the number of rotation of the DC motor.

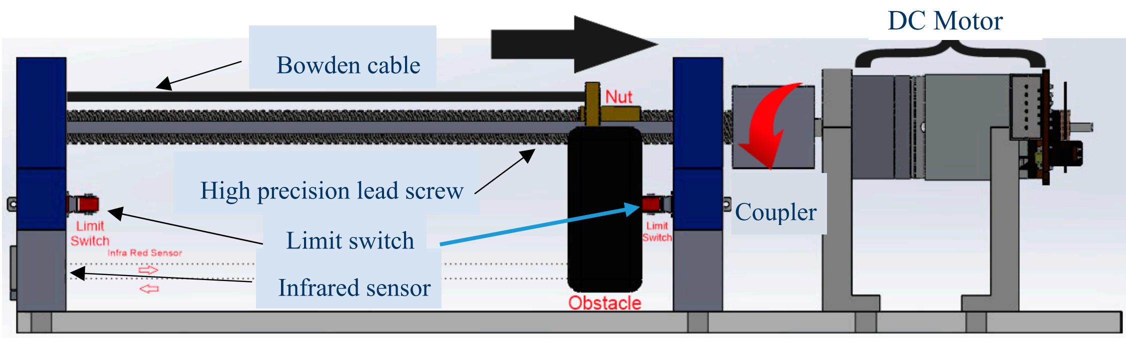


Figure 3. The mechanism of the proposed motor-tendon actuator.

2.2.1. Components

High precision lead screw with 8 mm in diameter and 150 mm in length is assembled to a nut serving as Bowden cable puller that is connected to the arm hook of the soft exoskeleton and driving the flexion and extension motion. A coupler is placed between the lead screw and DC motor to stretch the Bowden cable which acts as tendon which is connected to the arm. In this study, a DC motor with a JGA25-370 encoder is chosen and a L298N type motor driver is employed to regulate the direction and speed of the rotation of the motor. Arduino MEGA is used as the center of embedded control and data acquisition (DAQ) through serial communication.

SHARP GP2Y0A51SK0F infrared sensor is selected to measure the linear displacement of the Bowden cable, which will pull/push the user's arm. The sensor is able to measure at a distance from 2 cm to 15 cm with a size of 29.5 × 13.0 × 21.5 mm with analog output voltage. This range is suitable for the proposed motor-tendon actuation system. All mechanical and electrical components are placed strategically in actuator case and housing in order to produce an efficient and neat case design as well as comfortable to use. The actuator is powered by three 18650 Li-ion batteries with 3000 mAh and 3.7 V.

2.2.2. Infrared Sensor Calibration and Filter

The output voltage from the infrared sensor needs to be converted into a suitable signal (displacement of the actuator). Several signal acquisitions are recorded in the voltage read in terms of analog to digital converter (ADC). The polynomial equation obtained from third order polynomial curve fitting is expressed in (1).

$$y = -3 \times 10^{-7}x^3 + 0.0003x^2 - 0.1193x + 19.006 \quad (1)$$

The result from the obtained polynomial equation is applied to software processing. Because the infrared sensor produces noise signals in high frequency, a low-pass filter is employed in the filtering stage with the selected transfer function as expressed in (2). The measured infrared output voltage and the obtained third order polynomial are shown in Figure 4.

$$H(s) = \frac{1}{0.1\,s + 1} \quad (2)$$

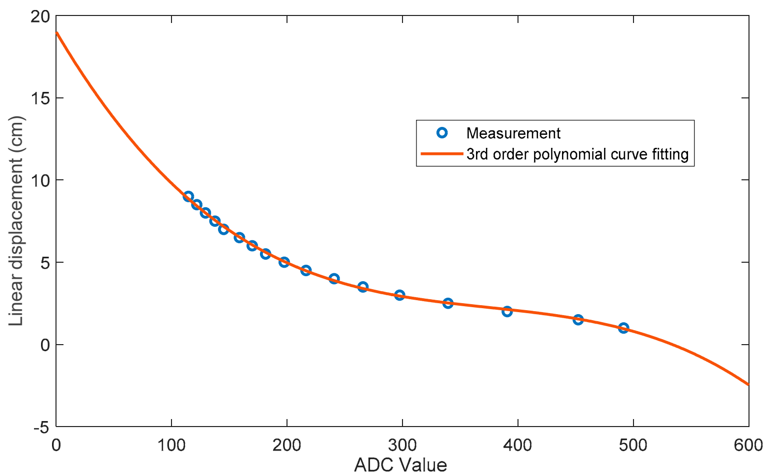


Figure 4. Obtained distance vs. analog to digital converter (ADC) infrared sensor output in the actuator system.

3. Two DOF Soft Elbow Exoskeleton and Control

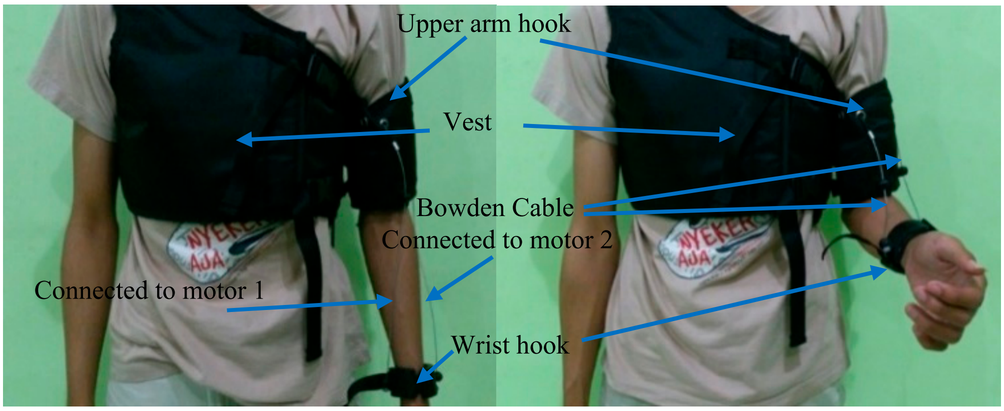
3.1. Wearable Soft Elbow Exoskeleton System

When the soft exoskeleton is worn, the position of the attachment of the arm connected to the vest on the user's chest must be considered because it will affect the desired movement. In addition, the actuator case position must also be treated carefully because it is very influential for comfort in the use of soft exoskeleton. Figure 5 is an image of the 3D model of soft exoskeleton elbow, which was assembled and worn by a user.

Figure 5. Final assembly of the proposed soft elbow exoskeleton.

3.1.1. Vest, Arm, and Wrist Hook

Figure 6a,b is the result of a prototype of a vest and an overall arm hook when it is worn by a user. Two Bowden cables are connected from the wrist hook to the two DC motors trough vest. The DC motors can rotate independently and allows the wrist hook to provide mechanical force for flexion/extension and pronation/supination. The total mass of the resulted soft elbow exoskeleton including arm and wrist hook is 358 g.



(**a**) (**b**)

Figure 6. Final prototype of the proposed soft exoskeleton elbow (**a**) flexion; (**b**) extension

3.1.2. Motor-Tendon Actuator with Case

In this study, actuator motor-tendon incorporating lead screw is preferred to the soft exoskeleton because it can produce force high enough to assist flexion/extension and pronation/supination motion. Figure 7 reveals the result of the proposed motor-actuator tendon case. This actuator has several components where the function is to move the elbow soft exoskeleton on the user's arm. Several components contained in the actuator case can be seen clearly in Figure 7, and the parts of its components are described as in Table 1. The resulted prototype of the motor-tendon actuation system with the case design is presented in Figure 8. The dual motor-tendon actuator has a mass of 1655 g.

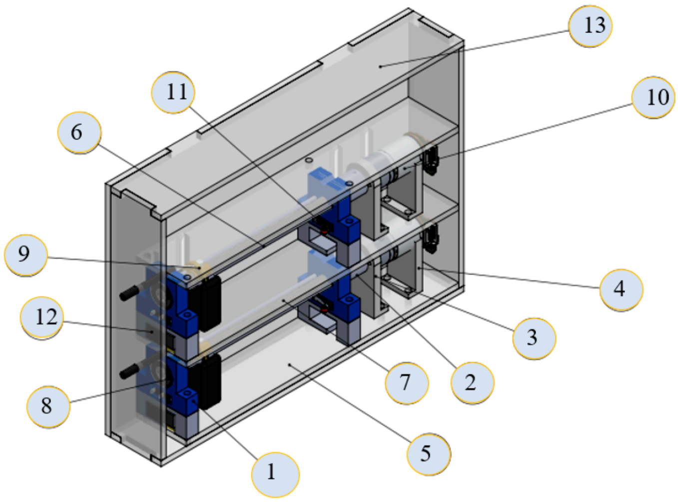


Figure 7. The dual motor-tendon actuator system.

Table 1. Proposed actuator components.

No	Dual Motor-Tendon Component	Total
1	Bearing stand	4
2	Coupler	2
3	Upper/first motor stand	2
4	Lower/second motor stand	2
5	Base	2
6	Push Rod	4
7	Lead screw	2
8	Bearing	2
9	Nut	2
10	Motor DC	2
11	Limit Switch	4
12	Infrared Sensor	2
13	Case	1

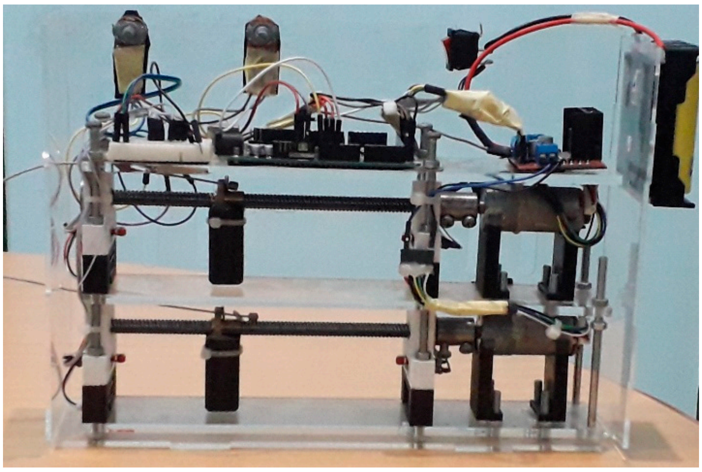


Figure 8. The result of dual motor-tendon actuator system.

3.2. PI Control

3.2.1. PID Tuner

Auto-tuning process is performed to identify the transfer function from the plant which is implemented in the PID tuner. It is utilized to identify the transfer function parameters for both motor-tendons. The parameters obtained are in the forms of K and τ (time constant) values. The transfer function parameters of both motors are identified according to the best result from the experiments that have been carried out. In this study, a PWM signal in the form of a step signal with a final value of 100 is employed as the input signal. The output signal is the linear displacement of Bowden cable measured by an infrared sensor. The acquired input and output signals are processed using the Matlab plant identification toolbox. The measurement and identification are performed twice to the exoskeleton when it is attached or not attached to the user.

From the identification of the plant that has been performed by using the MATLAB software, the obtained transfer function for the first and second motors in the form of second-order plant are expressed in Equations (3) and (4).

$$G_m(s) = \frac{1.2}{0.63\,s^2 + 17\,s} \tag{3}$$

$$G_m(s) = \frac{3.2}{1.9044\,s^2 + 45\,s} \tag{4}$$

Plant identification is also applied when the exoskeleton is paired/worn with the user. The user in this study is a person who has a normal healthy arm and hand. From the identification of the plant that has been conducted, the attained transfer function of the first and the second motor can be approached by a second-order plant as written in Equations (5) and (6).

$$G_m = \frac{0.1464}{0.36\,s^2 + 15\,s} \tag{5}$$

$$G_m = \frac{1.5}{1.9881\,s^2 + 35\,s} \tag{6}$$

3.2.2. Proportional-Integral (PI) Control

In this study, proportional-integral (PI) control aims to obtain better and appropriate position control for assisting the elbow flexion/extension and pronation/supination movements. The command used in this study is a potentiometer and programmed automatic signal as the input position/angle command and a proximity sensor to determine the displacement of the wire to move the arm while the motor as an output pulls or extends the Bowden cables. To obtain the optimal PI value, tests are performed when the exoskeleton is worn and not worn by a user. These tests are conducted to acquire the proportional constant (Kp), and the Integral constant (Ki) which are the most appropriate so that the control runs well between inputs and outputs for both with or without a user. The basic equation of PI control is expressed in Equation (7). The Simulink PI control block which is used in this study can be seen in Figure 9, while the embedded control block of controlling the soft elbow exoskeleton with PI control is presented in Figure 10. This block diagram is embedded into an Arduino Mega microcontroller.

$$PWM = Kp\,e(t) + \int_0^t Ki\,e(t)dt \tag{7}$$

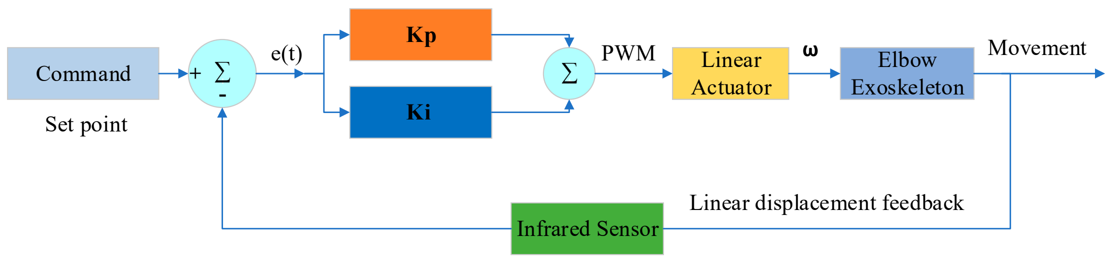


Figure 9. Proportional-Integral (PI) control block for the motor-tendon actuator.

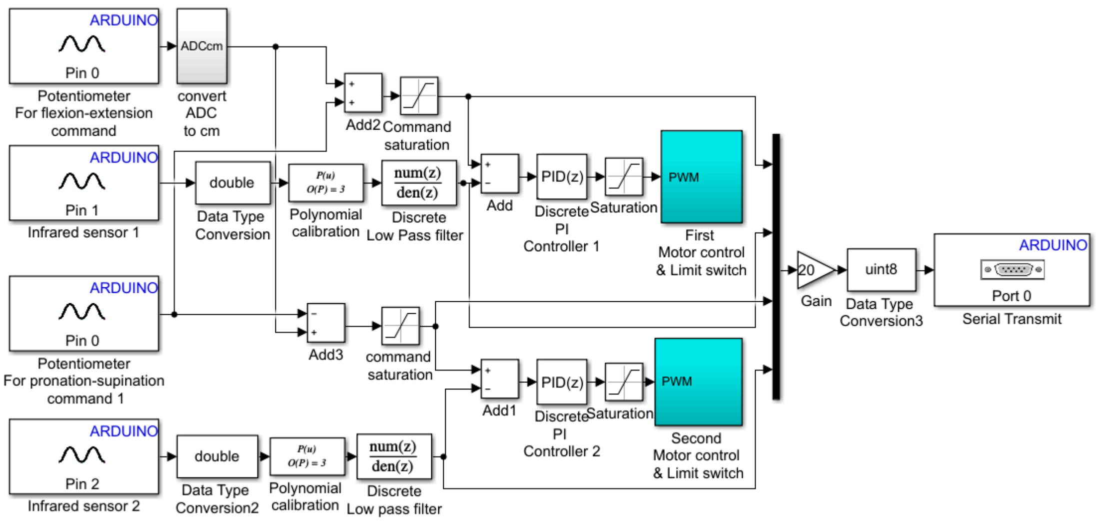
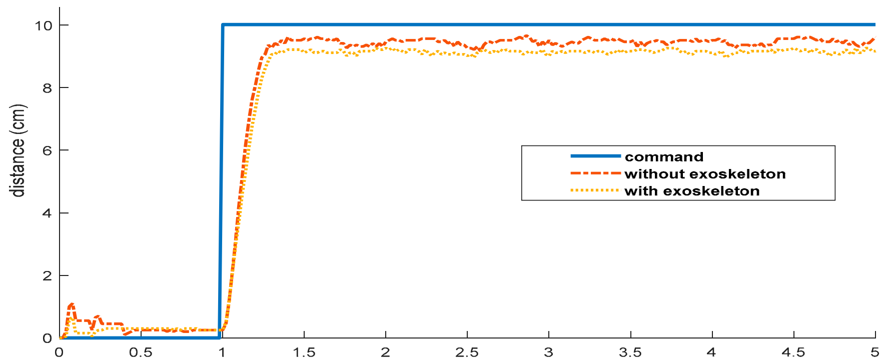


Figure 10. Embedded PI controller for controlling the dual motor-tendon actuator.

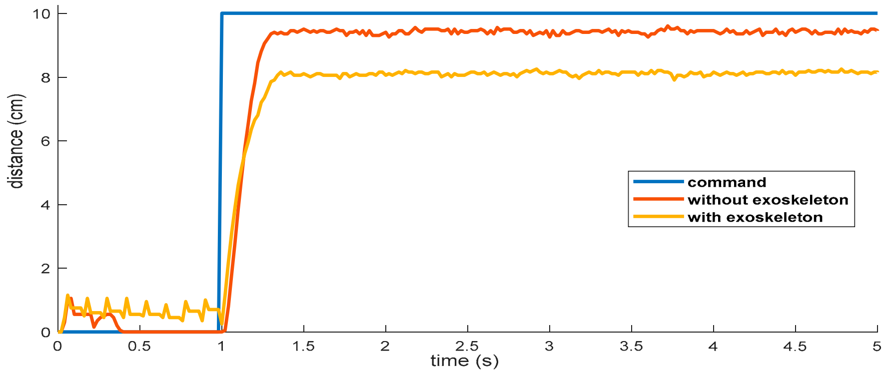
To obtain the optimum PI values, experiments are performed several times so that the best values of Kp and Ki are acquired. The tuning process of the PI parameters is easier to conduct in Simulink embedded control using Simulink Support Package for Arduino Hardware. The obtained parameters of the PI compensator should have a good response and precision control, which the output signal is able to follow the input signal well, and has a low steady-state error, less time constant, and a fast response.

4. Result and Discussion

The constant parameters of Kp and Ki are acquired based on the experimental works when the exoskeleton is attached and not attached to the user. A study participant with a normal healthy hand and arm at the age of 24 was selected for this test. The exoskeleton was designed with a range of motion (ROM) for flexion/extension of up to 70 degrees. This ROM was chosen because of the safety purpose of a study participant in wearing the exoskeleton. The study participant will not get an injury when he carries out experimental tests to determine the optimal values of Kp and Ki. Based on the tests conducted for attaching or not attaching to the study participant, the acquired optimal parameters for Kp and Ki were 200 and 20, respectively. The results of transient performance for the selected Kp and Ki are presented in Figure 11. It provides the transient response for both worn (without an exoskeleton) and not worn (with an exoskeleton) by a study participant for the first and second motor, respectively.



(**a**)



(**b**)

Figure 11. Step input response for the (**a**) first motor and (**b**) second motor.

In Figure 11, the command signal is represented by a continuous blue line, the response when it is not worn by a user is depicted by a red graph, and the response when it is worn is illustrated by a yellow graph. Based on the result test in Figure 11, the steady-state response for the second motor is higher than the steady-state error that occurred from the first motor.

The summarized transient performances of the proposed PI control are shown in Tables 2 and 3. In terms of transient response for the exoskeleton when it is worn and not worn, there is a slight difference in the transient performance in both the first and the second motor. However, if it is viewed on the steady-state performance, the occurred steady-state error in exoskeleton which is worn by a study participant has a higher value than that of an exoskeleton which is not worn by a user. The obtained time constant of 1 s is fast enough for the user and it will not harm the user.

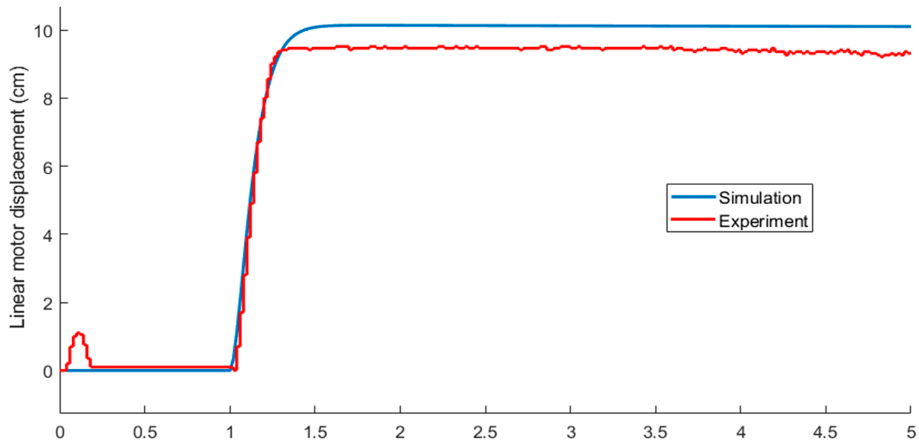
Table 2. Performance of transient response on the first motor.

Performance	Symbol	Unattached	Attached	Unit
Time constant	τ	1.095	1.106	s
Rise time	T_r	1.129	1.148	s
Settling time	T_s	4.384	4.427	s
Delay time	T_d	1.072	1.079	s
Steady-state error	E_s	0.21	0.95	cm

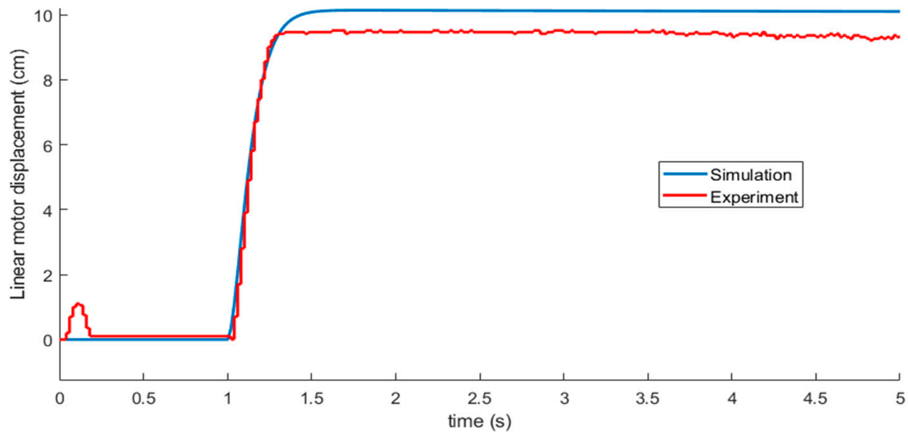
Table 3. Performance of transient response on the second motor.

Performance	Symbol	Unattached	Attached	Unit
Time constant	τ	1.102	1.059	s
Rise time	T_r	1.135	1.093	s
Settling time	T_s	4.409	4.237	s
Delay time	T_d	1.078	1.040	s
Steady-state error	E_s	0.23	1.93	cm

In this study, the approached transfer function of the exoskeleton is simulated by giving the step input and then compared to the experimental result. The test results are shown in Figure 12 for both motors. In the figures, the simulated signal is represented by a blue line and a red graph illustrates the experimental signal. The performance for steady-state response in the experimental work has a higher steady-state error than the steady-state error in the simulation based on the transfer function model in Equation (3) through (6). This can occur because of the un-modeled dynamic of the friction force between lead screw and nut, as well as Bowden cable and the exoskeleton.



(**a**)



(**b**)

Figure 12. The result of simulation vs. experiment during flexion movement: (**a**) First motor; (**b**) second motor.

The obtained Kp and Kd from the previous test are then utilized as the controller for controlling the motion for flexion/extension and pronation/supination. The command for flexion/extension can be achieved by giving the same linear displacement command for both motors, whereas the pronation/supination movement for the exoskeleton is performed by providing the same linear displacement command signal in the opposite direction. The direction of pronation and supination implemented in this study is presented in Figure 13. The first motor is connected to the right side of the wrist hook while the second motor is connected to the left side of the wrist hook. The soft elbow exoskeleton is worn by the user on the left arm as shown in Figure 13.

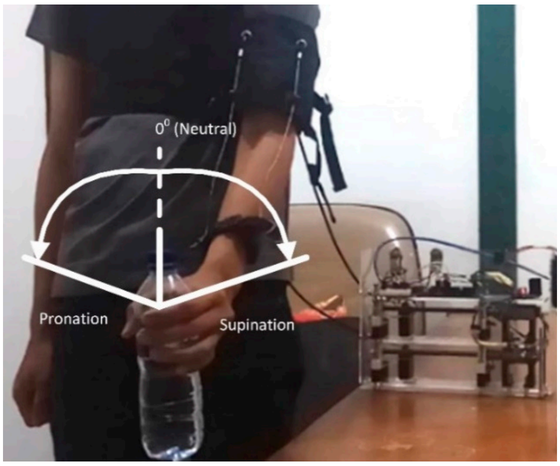


Figure 13. Pronation and supination movements in the exoskeleton.

In the first test for pronation/supination assistance, the exoskeleton is given by a commanded signal to provide the mechanical assistance for pronation movement from a neutral position. In this case, the Bowden cable from the second motor will pull the exoskeleton worn by the user and the Bowden cable from the first motor will stretch with the actuator initial position of 6 cm. Because of this mechanism, the resulted steady-state error on the second motor has a higher value than the occurred steady-state error on the first motor as shown in Figure 14.

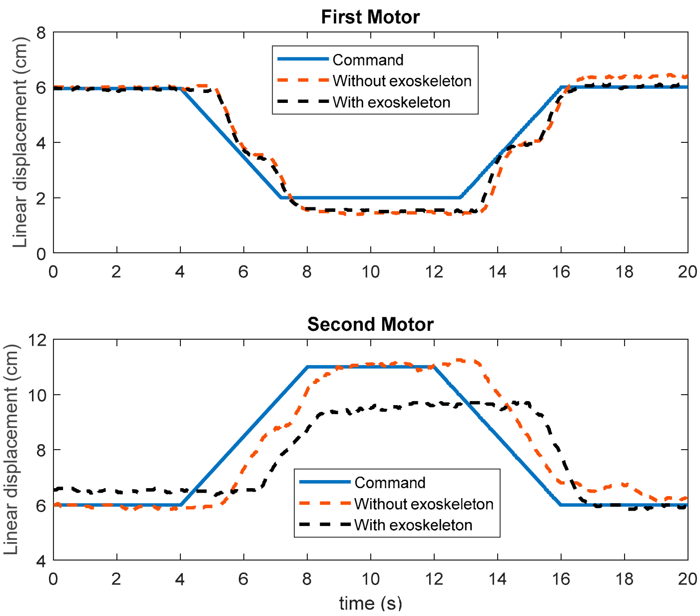


Figure 14. Pronation test.

In the second test, the soft exoskeleton is provided by commended signals to move the user arm and wrist from the neutral position to supination motion and hold for five seconds, then go back to the neutral position again. The first motor will pull the wrist and arm, and the second motor will stretch the Bowden cable. In this test, the initial position on the actuator starts at 6 cm. This will contribute to the resulted steady-state error in the first motor as shown in Figure 15.

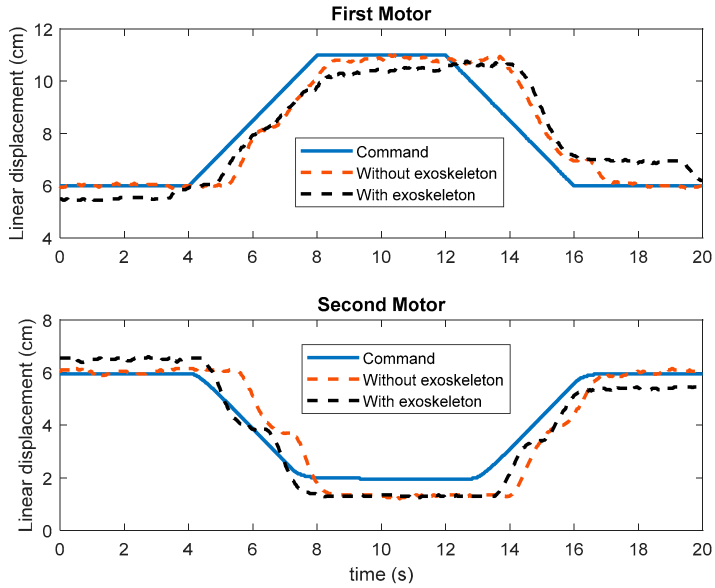


Figure 15. Supination test.

The soft exoskeleton is worn to provide mechanical support for combined motion such as flexion, extension, pronation, and supination movements. In this test, the user is grasping bottled water weighing 300 g. The exoskeleton is assigned to provide mechanical force assistance in the following order: The initial position, flexion motion, hold, supination, hold, back to the neutral position, hold, pronation, hold, back to the neutral position, hold, extension, back to initial position. The commanded signal and the response for both motors are presented in Figure 16. The sequence images of the test are documented in Figure 17. Based on the test result, the developed soft elbow exoskeleton can successfully provide mechanical assistance for the user for flexion, extension, pronation, and supination movements. Moreover, the soft exoskeleton is easily attached and detached on the user's arm and wrist.

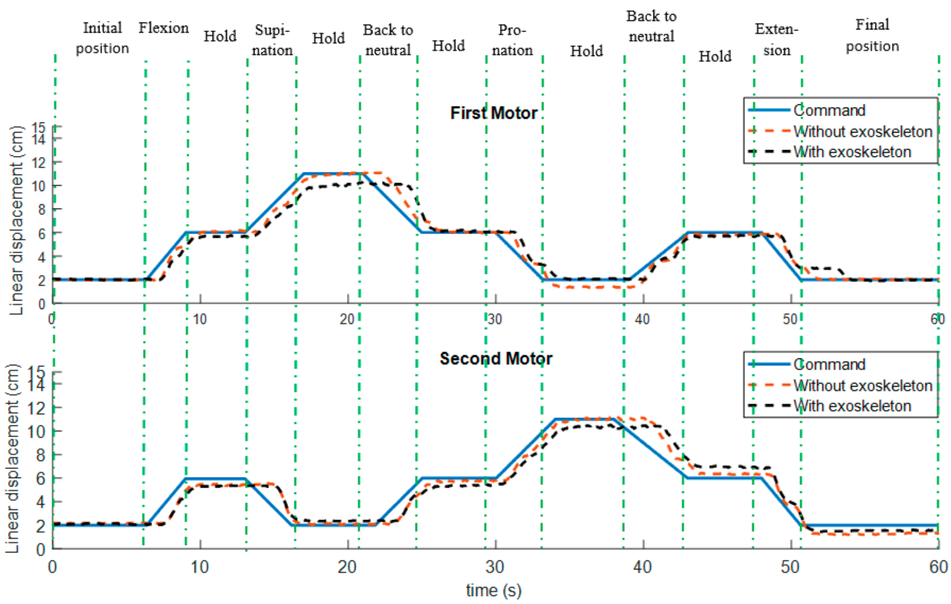


Figure 16. Two DOF mechanical assistance for flexion/extension and pronation/supination motion.

Figure 17. Sequence images of two DOF mechanical assistance for flexion/extension and pronation/supination motion.

In order to determine the correlation between the motor-tendon displacement and the resulted angular displacement on the elbow (flexion/extension motion), the motion test is performed by providing the displacement input signal on the motor-tendon actuation system and recording the angular displacement of the elbow. This test is carried out by attaching the soft exoskeleton to the user and then record the changes in the rotational motion of elbow movement that occurs in the soft elbow exoskeleton per unit of distance of the motor-tendon displacement implemented in this study. Table 4 shows the summarized results of the motion tested by acquiring the changes in the angular motion of movement at the elbow.

Table 4. Testing for flexion motion assistance.

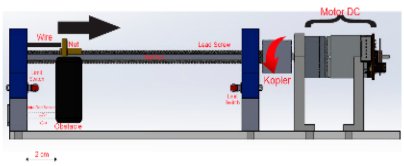
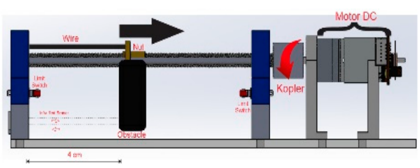
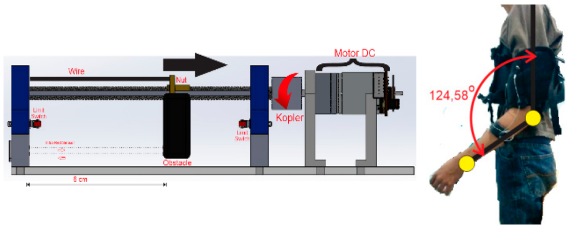
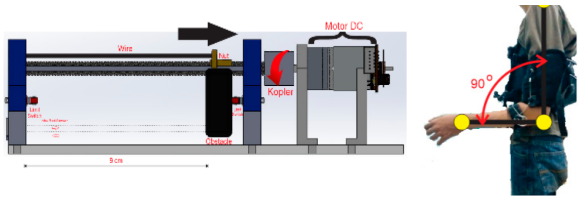
No	Obstacle Position	Motor-Tendon Actuator and Soft Elbow Position	
1.	**Initial/Normal Position** The reading of the IR-Sensor starts from 2 cm which is the starting point (= 0 cm in the starting position).		
2.	**134.91° Position** The IR-Sensor reading is 4 cm in position, moving the arm to an angle of 134.91°.		

Table 4. *Cont.*

No	Obstacle Position	Motor-Tendon Actuator and Soft Elbow Position
3.	**124.58° Position** The IR-Sensor reading is at 6 cm, moving the arm to form an angle of 124.28°.	
4.	**90° Position** The IR-Sensor reading is 9 cm in position, moving the arm in the angle of 90°.	

The working principle of the proposed motor-tendon actuation system for flexion/extension motion is illustrated in Figure 18. It shows the displacement on 'x' axis coordinate measurements in the soft elbow exoskeleton test. This displacement affects the angular changes in elbow movement which occurs on the 'y' axis shown in Figure 19. The initial position starts from 2 cm which means the zero point (0 cm) testing is at 2 cm because the sensor reading starts at 2 cm and the maximum pulling distance is 12 cm. The initial position of 2 cm is the normal position when the device is attached to the study participant (157.33°) and 9 cm is the final position in the test (90°). In this study, the elbow angle of 90° is sufficient for the flexion/extension motion. This angle is selected based on the consideration of the possible displacement and the safety reason in the actuator although the maximum possible displacement is 12.5 cm.

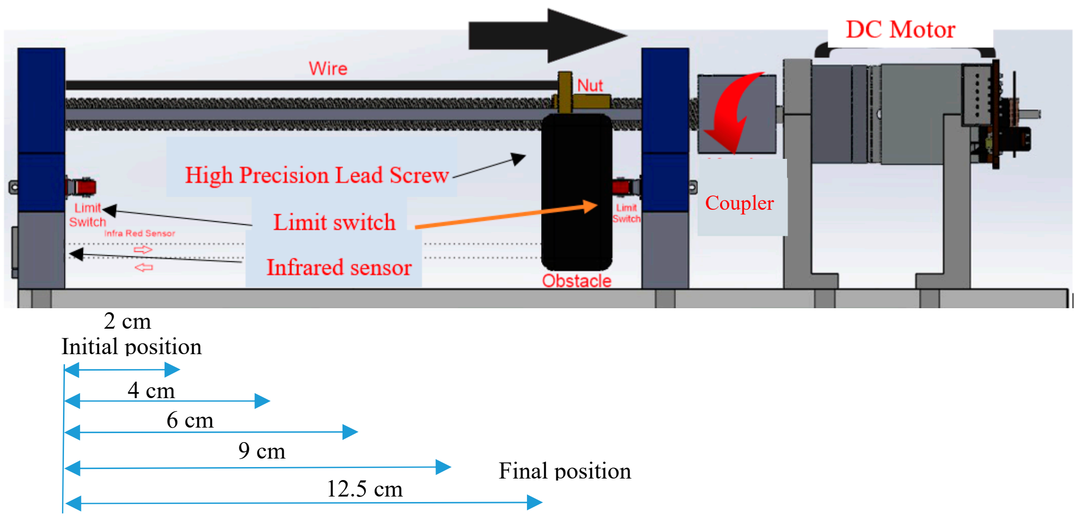


Figure 18. Obstacle displacement in motor-tendon actuator.

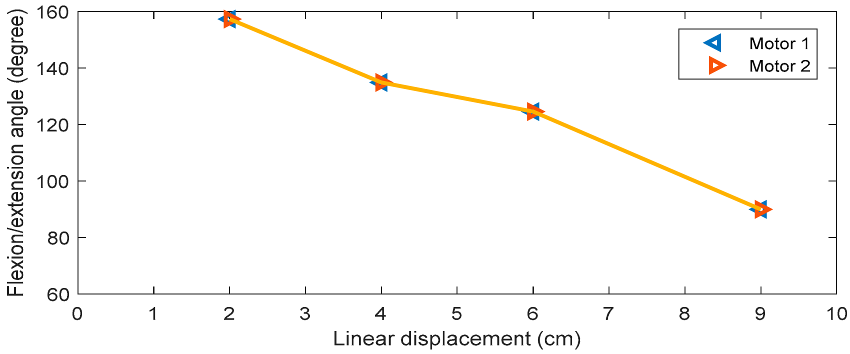


Figure 19. Displacement of the motor-tendon actuator vs. elbow output angle for flexion/extension assistance.

The tests carried out on the movements of the angular elbow motion in accordance with Table 4 produces a form of movement in Figure 18. This change is obtained from the displacement of the obstacle distance (cm) to the changes in angular displacement of an elbow in a degree (°). Based on the obtained elbow angle measurement with respect to the linear displacement on the actuator, the soft exoskeleton can provide flexion-extension motion from 157° to 90° as shown in Figure 19. On the other hand, the resulted ROM for flexion/extension motion is 67°. This ROM can be increased by giving the linear displacement command more than 9 cm and less than 12.5 cm.

The resulted angles of the pronation and supination movements are presented in Figure 20. This test is performed without grasping an object. The pronation and supination angles are measured on the user's wrist. Based on the test result, there is similar pattern between the pronation and supination angles as shown in Figure 20. The obtained ROM for the maximum pronation angle is 19° while the acquired maximum supination angle is 18°. These angles are attained when the upper right arm hook is connected to the right wrist hook and the left upper arm hook is connected to the left side of the wrist hook.

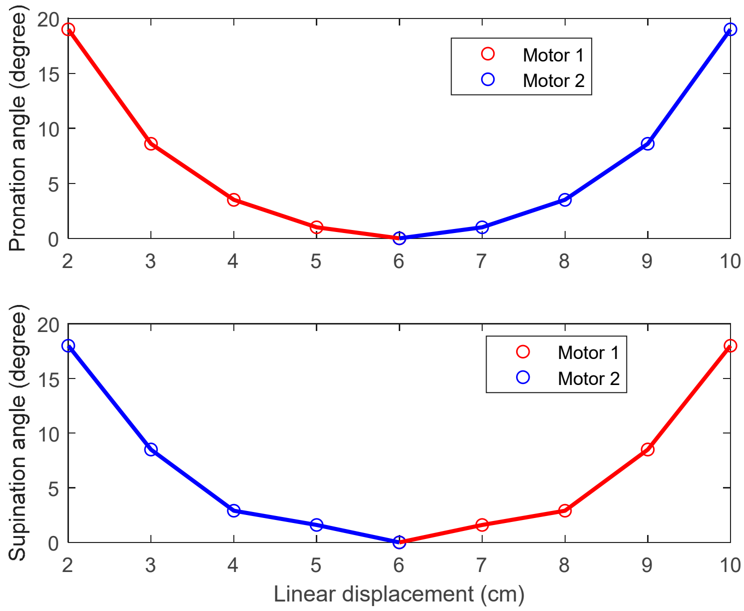


Figure 20. Displacement of the motor-tendon actuator vs. output angle for pronation and supination assistance.

5. Conclusions

A motor-tendon actuator system for the soft elbow exoskeleton mechanism which is able to assist two DOF elbow and wrist motion is presented. Compared to another actuator mechanism in other previous research, this research employs a motor-tendon actuator which can accommodate elbow and wrist movement in two DOF. Flexion and extension movement for the first DOF, pronation and supination for the second DOF. PI control with a gain value of Kp = 200 and Ki = 20 are applied in both motors resulting in good precision and transient response performance. The output signal from both motors can follow the input with a low value of steady-state error and fast response. When the exoskeleton is worn and not worn on the tests, there is a slight difference in the transient performance on the motor-tendon actuator. The resulted steady-state error in exoskeleton worn by a user has a higher value than that of exoskeleton that is not worn by a study participant. The Bowden cable mechanism applied on the motor-tendon actuator can provide mechanical support for the user's elbow which is needed for a person with muscle function loss in the elbow.

The proposed exoskeleton can provide mechanical assistance for flexion and extension motion ranging from 90° to 157°. The selected maximum ROM for the flexion/extension motion is 67°. This angle can be increased by providing the linear displacement on the actuator more than 9 cm and less than 12.5 cm. The acquired maximum for pronation and supination angles is 19° and 18°, respectively. In the next study, the maximum of pronation and supination angles will be improved by connecting the left upper arm hook to the right wrist hook and the right upper arm hook to the left wrist hook. This can extend the moment arm for pronation-supination motion.

The proposed soft exoskeleton elbow has a lightweight mass that can be worn by the user comfortably. The total mass of the resulted soft elbow exoskeleton including arm and wrist hook is 358 g, while the dual motor-tendon actuator has a mass of 1655 g. The soft exoskeleton can be easily attached and detached by a user. The detailed specification of the proposed soft exoskeleton is summarized in Appendix A. The Simulink block diagram of embedded control and data acquisition block can be found and downloaded in the Supplementary Materials. The PI control block is embedded into Arduino MEGA and the data acquisition block is run on the computer. The 3D design in SolidWorks, engineering drawings, and the STL files, as well as the video of the exoskeleton can be downloaded in our website. It can be found in the Supplementary Materials.

Based on the conducted previous test results, the soft upper arm exoskeleton was successfully developed in providing the mechanical force/support for flexion, extension, pronation, and supination movements. This two DOF movement is relatively easy to control by employing the PI control. The control is commonly widely used for upper arm hard and soft exoskeletons which are mostly used for flexion/extension motion. The performance of the proposed elbow soft exoskeleton for providing mechanical assistance in flexion/extension and pronation/supination tests can be seen online on YouTube at http://y2u.be/M1AKREg3WaY.

In the future, the prototype of the soft exoskeleton will be enhanced in terms of the control input using two channels sEMG signals incorporated machine learning technique such as a neural network. The machine learning will be implemented to discriminate the intended gesture to drive the flexion/extension and pronation/supination movement. A nonlinear control technique will be developed in order to reduce the steady-state error. The size of the actuator system for soft exoskeleton is still big enough to wear. The size of the motor-tendon actuation system will be optimized in order to achieve the optimal size, which is easy to attach on a user's waist. Inertial measuring unit (IMU) which is comprised of accelerometer, gyroscope, and magnetometer will be incorporated on the elbow soft exoskeleton. The IMU will enable the exoskeleton to be controlled directly by flexion/extension and pronation/supination angle command.

Supplementary Materials: The Simulink block diagram for controlling the soft exoskeleton utilizing PI compensator, technical drawings, STL files, and 3D design can be downloaded from the following website: https://cbiom3s.undip.ac.id/elbow-exoskeleton/.

Author Contributions: R.I. developed the design of the soft elbow exoskeleton, performed the experiment, and wrote the experimental results. M.A. determined the optimized PI control and performed experimental work. I.A.P. and R.A. developed and built the soft elbow exoskeleton using material from fabric. F.T.P. wrote the introduction and provided plots and tables from the experimental work. A.G. provided the suggestion to improve the research such as measurement and experiment as well as the analysis. W.C. proposed and analyzed the result of the measurement and the experimental results. All authors read and approved its content.

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Appendix A

To provide a clear technical specification of the developed soft exoskeleton, this appendix summarizes the test results that have been carried out and presented in this study.

Table A1. The developed soft elbow exoskeleton specification.

Specification	Value
Upper arm and wrist hook	Polylactic acid (PLA)
Vest material	Polyester
Vest mass and hooks	358 g
Dual motor-tendon actuator	1655 g
Dual motor-tendon actuator	29 × 9.5 × 21 cm
Bowden cable length of the first motor and second motor	70 cm
Input voltage	12 V DC
Microcontroller	Arduino MEGA 2560
Maximum of the actuator linear displacement	12.5 cm
Feedback	Infrared sensor
Control	Proportional-Integral compensator
Feedback	Infrared sensor
Motor type	Brushed DC motor
Mechanical drive system	Precision lead screw
Number of DOF	Two (flexion/extension and pronation/supination)
Limit or home sensing	Limit switch
Maximum pull force of the first motor	33 N
Maximum pull force of the second motor	31 N
Input sensor as a command	potentiometer
Communication interface	USB
ROM for flexion/extension	90°–157°
ROM for pronation	0°–19°
ROM for supination	0°–18°

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