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#18274 Summary

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Author comments

Dear Prof. Srinivasan Alavandar
Editor-in-Chief
International Review of Automatic Control (IREACO)

We would like to submit a manuscript entitled “A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance” to International Review of Automatic Control (IREACO) for possible evaluation. It is a research paper aimed to develop a novel, innovative, and affordable soft exoskeleton glove for assisting the human’s hand motion. The soft actuator is controlled using modified on-off and PI compensator to regulate the dual-slack enabling actuator. It may be interest to your readers/audiences and enhance the content of your journal especially in soft robotics area.

We affirm that this manuscript is original, has not been published before, and is not currently being considered for publication elsewhere.

Thank you very much for your attention to our paper.

Sincerely yours,
Authors

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Title and Abstract

Title: A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance

Abstract: Hand paralysis can inhibit daily activities, for example, grasping a particular food or an object. With the advancement of science and technology today especially in wearable robot technology, normal hand function can be recovered with the help of wearable soft robotic glove. This robot has a mechanism that resembles the working mechanism of the hand itself. The purpose of this study is to develop a low-cost soft exoskeleton glove made from silicone rubber using a tendon-based mechanism. The molding of the soft glove is designed using SolidWorks CAD software. Dual-slack enabling actuators are designed and manufactured as the actuator system of the soft exoskeleton glove. The proposed actuator is used as flexion and extension motion for the human hand. This motion enables the soft exoskeleton glove to provide mechanical support for the human hand. A potentiometer sensor is used in the dual-slack enabling actuator for measuring the rotating angle of the actuator that is connected to the tendon and soft exoskeleton glove. The actuator is controlled using on-off and Proportional-Integral (PI) control. After the soft exoskeleton glove system is integrated, the soft robot is implemented on a healthy human hand to assist the grasping of various objects. The measurement for the wearable robot is performed by using serial communication between Arduino Nano microcontroller and the host computer. Based on the experimental results, the soft glove can successfully assist and support the user's hand for various object grasping.

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A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance

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Lampiran
original manuscript

Joga D. Setiawan[1], Mochammad Ariyanto[2], Sri Nugroho[3], M. Munadi[4], Rifky Ismail[5]

Abstract – *Hand paralysis or impaired hand can inhibit daily activities such as in the process of grasping a particular food or object. With the advancement of science and technology today especially in wearable robot technology, normal hand function can be recovered with the help of wearable soft robotic glove. This robot has a mechanism that resembles the working mechanism of the hand itself. The purpose of this study is to develop a low-cost soft exoskeleton glove made from silicone rubber using a tendon-based mechanism. The molding of the soft glove is designed using SolidWorks CAD software. Dual-slack enabling actuators are designed and manufactured as the actuator system of the soft exoskeleton glove. The proposed actuator is used as flexion and extension motion for human hand. This motion enables the soft exoskeleton glove to provide mechanical support for the human hand. A potentiometer sensor is employed in the dual-slack enabling actuator for measuring the rotating angle of the actuator that is connected to tendon and soft exoskeleton glove. The actuator is controlled using on-off and Proportional-Integral (PI) control. After the soft exoskeleton glove system is integrated, the soft robot is implemented on the healthy human hand to assist the grasping of various objects. The measurement for the wearable robot is performed by using serial communication between Arduino MEGA 250 microcontroller and the host computer. Based on the experimental results, the soft glove can successfully assist and support the human hand for various object grasping.*

***Keywords**: Dual-slack enabling actuator, Soft exoskeleton, Wearable robot, PI control*

I. Introduction

Soft robot is a further development of hard automation or hard robot. Soft robots are a sub-field of robotics designed using "compliant" materials (adapted to suit the needs), similar to those found in living organisms [1]. In the working principle, the function of a wearable exoskeleton soft robot is the same as a hard exoskeleton robot hand, only material used in this kind of robot is different. If the wearable exoskeleton robot hand still uses rigid material, then wearable exoskeleton soft robot hand utilizes soft material made of material in the form of synthetic resin or silicon rubber.

In the actuation system type, soft robot uses a variety of actuators to move. The actuator can resemble the mechanism of human finger motion to the animal. PneuNets (pneumatic networks) is one of the soft robot actuators developed by the Whitesides Research Group at Harvard University. Actuators of pneumatic networks are made of a series of chambers in elastomeric material. This room will expand when pressured and produce bending movements such as human fingers [2]. Naturally, this movement is controlled by modifying the geometry and material properties of its chamber walls. When the PneuNets actuator is pressured, expansion occurs in a softer area [3]. When PneuNet consists of a single and homogeneous elastomer, the greatest expansion will occur in the thinnest structure. Researchers can program the working mechanism of the actuator by choosing the wall thickness that causes the desired movement [4].

In addition, different materials can be combined to enable better actuator control. When the PneuNets actuator contains several layers of material having different elastic properties, a more elastic material expand larger than a less elastic material when the actuator is pressurized. In this configuration, the less elastic material is called strain-limiting layers, as its function is to limit the strain that occurs. This strain effect difference can be used to achieve the desired movement such as bending and twisting [5]. In most research on soft exoskeleton hand, the actuator is pneumatic network type [6]–[11]. The fluid used in the soft wearable robot also comes from a hydraulic network such us [12], [13]. One of Soft robotics developed by Harvard University is a soft robotic glove. The purpose of the development is to assist disabled people with hand motor skills. The motor skills of this hand can be lost partially or totally. In the design developed by Harvard, the five fingers of the user can be re-functioned by using soft robotic glove, pneumatic or hydraulic based actuator is employed as the actuation system on the soft robotic glove.

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Shape memory alloy (SMA) has been developed and utilized as the actuator of soft wearable robot especially on the soft exoskeleton hand [14], [15]. The research combines SMA with tendon actuation system. Based on the results, the proposed of SMA has a potential to be implemented in the soft wearable robot. The soft glove based on SMA actuation can flex and extend fingers in the designed range of motion and grasp object efficiently.

Motor-tendon actuation is one type of actuator in a soft robot that utilizes a DC motor to manipulate soft materials in order to move. Tendon is an intuitive solution for soft robot actuator because it is a continuum structure that can adapt to soft joints. The mechanism of action of this actuator motor- tendon is to shorten the soft body and extend it back to produce controlled motion resulting from friction that arises when the material is shortened larger than when elongated so that the soft body can move. In this type of actuators, strings or Bowden cables are widely used as a towing medium embedded into the actuator. Actuator based tendons utilized on soft wearable robots have been developed by researchers with the purposes of both rehabilitation and assistive devices [16]–[19]. This type of actuator can produce a relatively large grasping force. Soft tendon routing system is a system that in principle works inspired by the human musculoskeletal system, resembles the working principle of muscle tendons working on the hands. There is a power transmission component developed inherent in the human body. All elements of the routing system include actuators, designed to work without air pressure so that the system can improve safety and comfort in its use and efficient in terms of mechanical design.

In this study, a low-cost soft wearable robot based on tendon mechanism is developed and manufactured. A soft glove is developed and manufactured using RTV (Room-Temperature-Vulcanizing silicone) Silicone material. A novel low-cost dual-slack enabling actuator (DSEA) is designed as an actuation system of the soft exoskeleton glove to assist the user's hand for finger flexion and extension. On-off and PI compensators are employed for controlling the motion of DSEA. Two Bowden cables are used for transmitting the power from DSEA to the soft glove. After the soft glove prototype has been built, the robot is implemented on the healthy human hand to assist for various object grasping.

II. Design and Prototype Development of Soft Exoskeleton Glove

T The initial stage of this research of wearable soft exoskeleton glove is to develop a 3D model of soft exoskeleton glove. It is adjusted to the average dimensions of the hands and fingers of the impaired hands so that the resulting model will be appropriate to the dimensions of the user's fingers. In the early stages of the design, 3D model of soft glove is detailed by creating two-dimensional images using SolidWorks computer-aided design (CAD) software. This section presents the design process to be used in soft exo-glove molding fabrication and soft exo-glove manufacturing process from raw material in the form of silicone rubber dough to the ready to use prototype of soft glove. The 3D design of proposed exoskeleton glove using motor-tendon actuation is presented in Fig. 1.

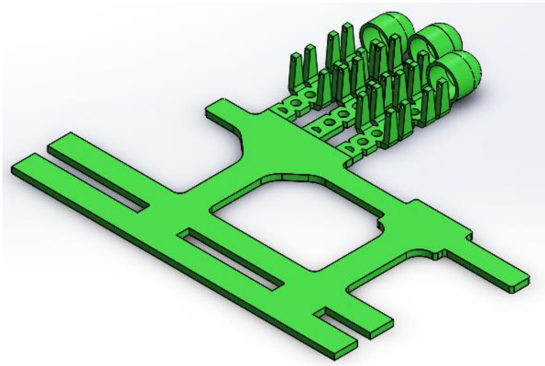


Fig. 1. Design of Soft Exoskeleton Glove.

II.1. *Design of Soft Exoskeleton Glove*

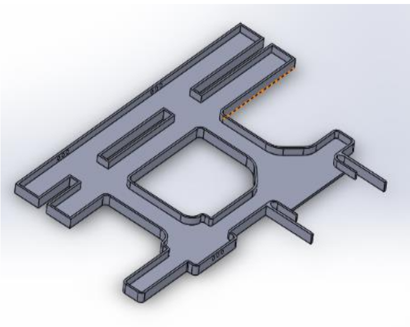
Actuators on wearable exoskeleton glove have an important role as the main driving system. In the selection of actuator types, the researchers considered three types of actuators to be used, namely PneuNets (Pneumatics network), Combustion driven actuators (CDA), and motor-tendon actuation. The motor-tendon actuation system was chosen in this study because in the development of soft glove there is concern itself in using Pneunets and CDA type actuators. Concerns that one of them is if there is cavitation (a hole in the soft glove caused bubbles during the casting process) where it influences the type of actuator Pneunets and CDA. While on the motor-tendon type, cavitation can be neglected. The soft glove developed should not have a hole caused by cavitation, as it will reduce the aesthetic value of the soft exoskeleton glove. Furthermore, motor-tendon actuators have characteristics of easy manufacturing process and maintenance.

The material used to develop soft glove is synthetic rubber. There are two types of silicon rubber based on the manufacturing temperature of synthetic rubber, which requires heating and does not require heating or is often called RTV (Room Temperature Vulcanization). RTV has many different types based on stiffness, heat resistance, and mixed type. In this study, synthetic rubber used is RTV type. Silicon rubber of RTV type was chosen to facilitate the manufacturing process, because it does not require additional tools such as heaters and this research works at low temperatures. The utilized materials are RTV 48, RTV 52 and RTV Platinum. The selection of the above three materials is based on several criteria such as stiffness, casting, and price. RTV

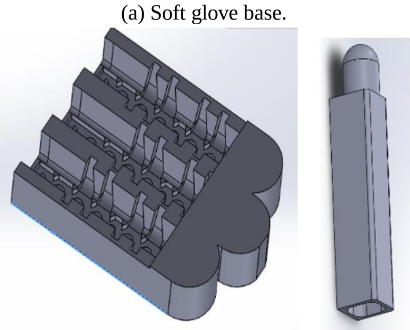
Platinum is chosen because it has the appropriate rigidity based on need, and also based on consideration of availability of the silicon rubber. RTV Platinum has a high stiffness point when compared to RTV 48 which stiffness is too low, so the soft glove using this material cannot work as desired because it is too soft. RTV 52 has a higher stiffness than RTV 48, but is not rigid enough for soft glove base material.

The advantages of RTV Platinum during casting process are the RTV Platinum can enter and fill the narrow gaps so that the results of soft glove can be formed perfectly, as well as other RTV silicon rubber. But the concern here is the casting result, where RTV 48 produces the final soft glove form that is not as expected, as the number of molding fibers are formed so that the casting surface becomes less attractive and the result is too soft. Furthermore, in terms of raw material prices RTV Platinum has the highest value compared with the price of RTV 48 and RTV 52.

In the soft exoskeleton glove mold design, the shape of the mold is measured according to the needs that refer to the average adult human finger size and consider the initial function of the soft glove to be used. Aesthetic aspect is also considered where the expected shape is in accordance with the desired. The mold of soft glove is designed using SolidWorks CAD software and manufactured by using 3D printer technology. Fig. 2.a and Fig. 2.b show the mold design of soft glove in CAD software. Fig. 2.c is the overall result of mold based on 3D print of soft glove that has been printed using a 3D printer. The mold is printed using polylactic acid (PLA) material.



(a) Soft glove base.



(b) Fingers.

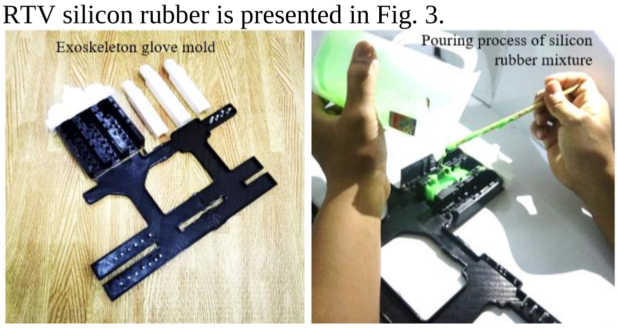
(c) Overall result of 3D printed mold design for exoskeleton glove.

Fig. 2. 3D mold design of the proposed soft glove

II.2. Prototype Development and Manufacture

In the molding process of soft exo glove, silicon rubber and the liquid catalyst and supporting equipment such as; scale, measuring cup, color pigment, stirrer, and soft glove moldings, etc. should be prepared first. After the preparation process has been completed, then the silicone rubber is weighed and taken as needed. In this research, the mass of silicon rubber RTV needed is 140 grams. The measured silicone rubber is then given a dye without a catalyst blend, then gently stirs the silicone rubber dye to blend perfectly but the dough does not quickly clot and dry. The silicon rubber dye used in this study is green. The Silicon rubber and catalyst are mixed with a 10:1 dose with the amount of silicon rubber in grams. The silicon rubber mixture and the catalyst are stirred gently until evenly to avoid air bubbles occurring.

The silicon rubber mixture is fastened to soft glove molding until it is evenly distributed and fills the mold volume, then the finger mold is placed on the soft glove mold according to Fig. 4 to soft glove molding that has been filled by a mixture of silicone rubber. The silicone rubber mixture already poured in the mold is dried at room temperature for four to six hours until the soft glove is formed. Demolding process of the formed soft exoskeleton glove is conducted after the silicon rubber is completely dry and perfectly formed. Demolding process can be carried out by separating the silicone rubber that has been formed and dry with the mold. The overall manufacturing process of the soft glove based on the RTV silicon rubber is presented in Fig. 3.



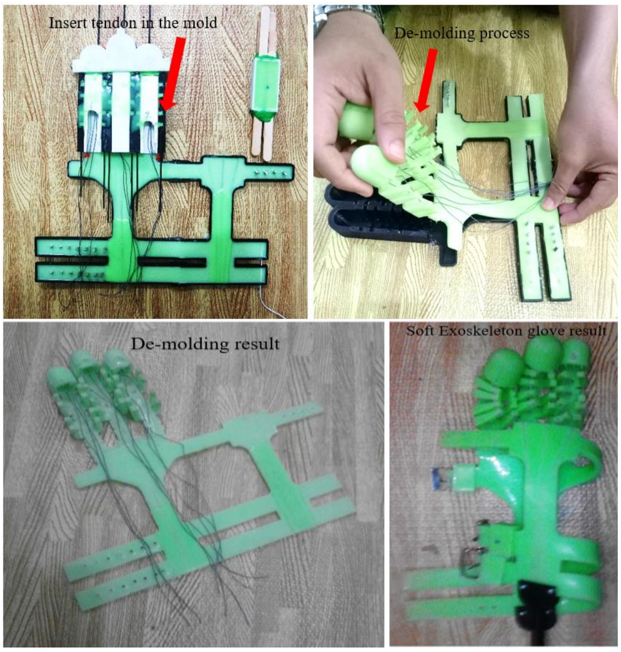


Fig. 3. Molding process of soft exoskeleton glove

III. Dual Slack Enabling Actuator (DSEA)

From a mechanical design aspect, the Dual Slack Enabling Actuator (DSEA) element consists of several components which are presented in Fig. 4. Dual Slack Enabling Actuator component consists of servo motor mount, base component, Pulley with the diameter of 10 mm, pulley with diameter of 15 mm printed by using 3D printer. The pulleys are printed using Poly Lactic Acid (PLA) material. MXL timing belt pulley, MXL pulley, and shaft are DSEA components with aluminum materials that are easily found in the market.

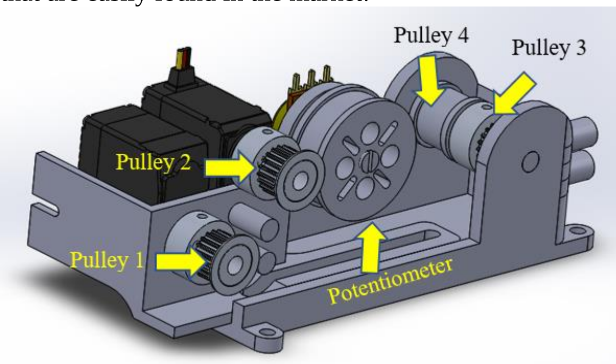


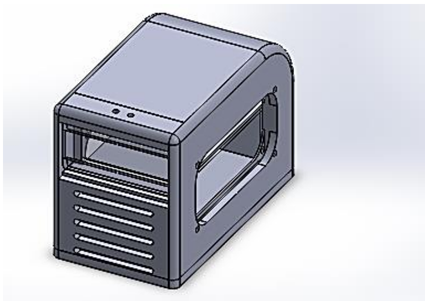
Fig. 4. Dual slack enabling actuator (DSEA) design in the CAD software

In the working principle of proposed DSEA, the rotation source of the servo motor is transmitted through the timing belt of the pulley MXL to the pulley 3 in which the pulley is coupled with a pulley 4 with a diameter of 10 mm. The rotation received by pulley 3 is then transmitted again to a potentiometer pulley with a diameter of 15 mm through the belt. The potentiometer pulley rotates the potentiometer according to the rotation direction of the servo motor. For example, the direction of rotation of the pulley 1 is clockwise, then the potentiometer will automatically rotate clockwise.

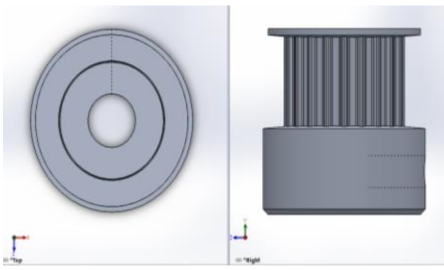
In this study, DC motor with a gearbox from servo motor is employed. The Motor has a torque of ± 35 Kg/cm. DC motor/ servomotor is easy to get in the market, therefore it is selected as a soft glove system actuator. Pulley system is chosen for mechanical power transmission in the mechanical design of DSEA. This pulley is used to transmit power from the motor to the pulley that rotates the potentiometer and the pulley to pull the tendon sheath. The selection of a belt as power transmission because it is suitable to the desired condition of the system. The braided string is utilized because it has the ability to withstand tensile forces up to 30.8 kg, strong and easy in the installation process. The tendon is used as the power transmission of the actuator system, in which will pull or extend the soft tendon.

The case is the part used to cover the DSEA and protect the DSEA components from a variety of liquid spills such as water, oil, oil and so on. The case itself is divided into 3 parts namely the bottom, middle and top. The 3D design drawing of the case is shown in Fig. 5. Pulley is used to transmit the rotation of the DC motor. The pulley system is employed to pull and extend tendon cables. The reduction gear on the power transmission in the DSEA is designed with more number of gears. The amount of reduction gear used is three pieces which means three times reduction. The design drawings of the DSEA case and the pulleys are shown in Fig. 5.

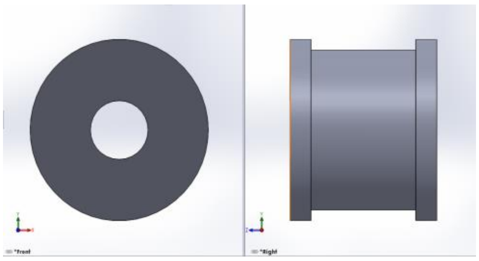
The motor holder of DSEA serves as a holder of a DC motor/servo motor actuator on the soft glove. Fig. 5.e shows 3D design motor holder in the CAD software. Actuator base serves as a place to join the components needed to become a DSEA system. Fig. 5.f shows the 3D design of the proposed actuator base.

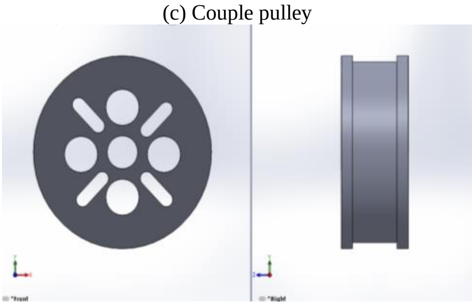


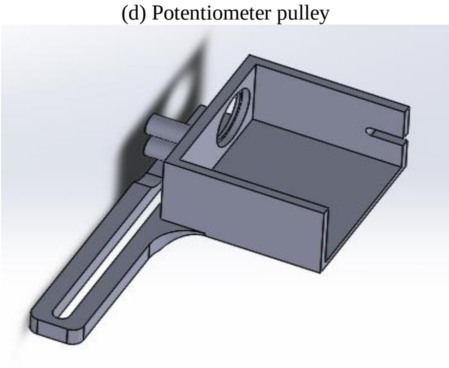
(a) Case design



(b) MXL timing belt pulley


(c) Couple pulley


(d) Potentiometer pulley


(e) Motor holder

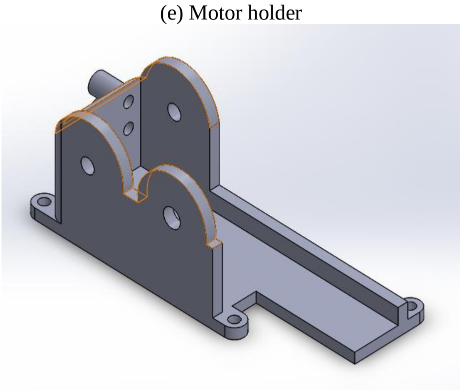
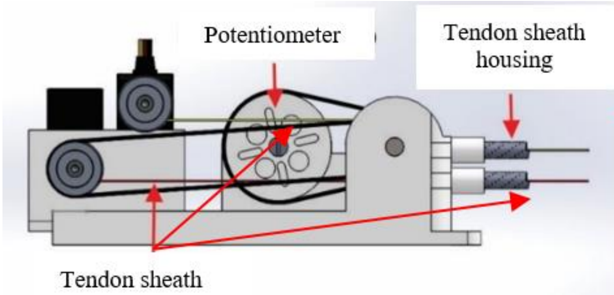
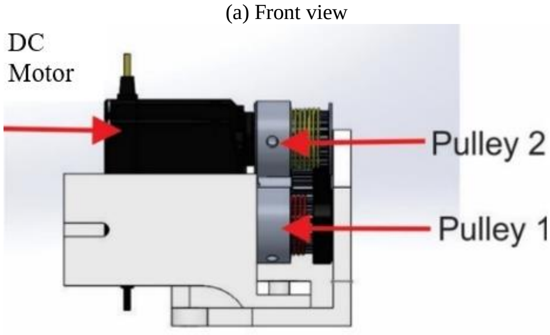

(f) Actuator base

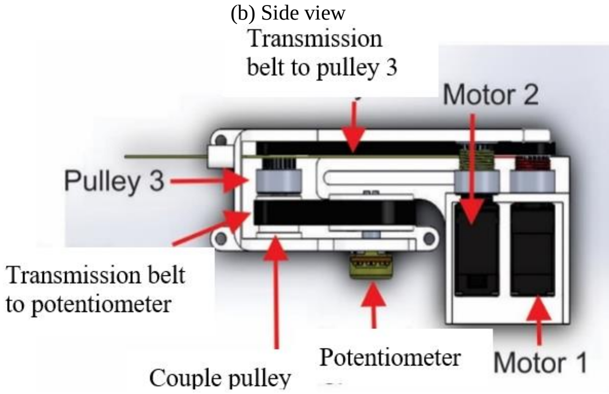
Fig. 5. Case and pulley design of DSEA in CAD software



(a) Front view



(b) Side view



(c) Top view

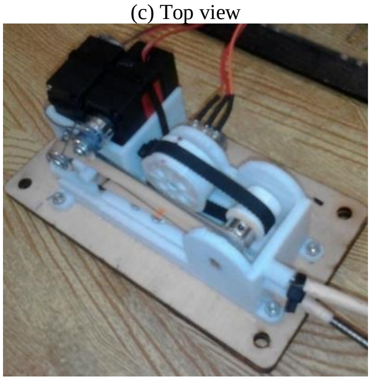

(d) Prototype

Fig. 6. DSEA design and prototype

Main parts of DSEA mechanical components are printed with PLA material using a 3D printer. Figures 6a through 6c show the assembly of DSEA components in the CAD software. The assembly result of the proposed DSEA prototype is shown in Fig. 6d. The DSEA has two Bowden cables for finger flexion and extension motion. When the lower tendon is pulled, the upper tendon is extended simultaneously.

This section discusses the kinematic motion modeling of a dual slack enabling actuator with rotation input from the servo motor. The motor is used as the prime mover to pull and extend the tendon sheath. The translational motion calculation of the DSEA is used to calculate the rotation of the potentiometer pulley. The rotational angle obtained is used for position control feedback.

The purpose of kinematic modeling on a dual slack enabling actuator is to provide a position feedback to the motor actuator. The required position feedback is a signal from the potentiometer pulley. The potentiometer used in this study has a range of motion from 00 to 2700, while the used DC motor rotation to pull the tendon sheath from its normal position to full grip of the soft glove requires more than one rotation. Therefore, the reduction gear is required between the rotation of the potentiometer pulley and the rotation of the DC motor/servomotor so that the actuator rotation does not exceed the range of motion of the potentiometer. The proposed of a reduction gear system utilizing four pulleys is shown in Fig. 7.

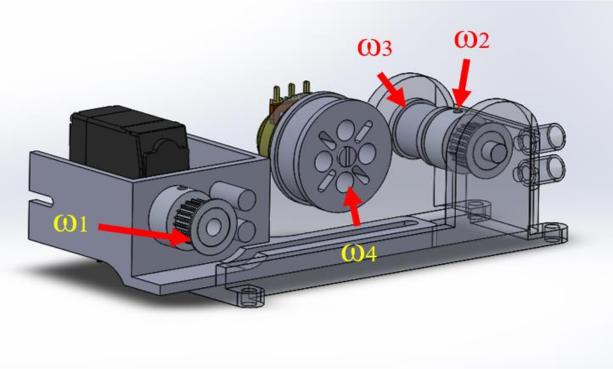


Fig. 7. Gear reduction system on the DSEA

The rotational speed of the DC motor pulley is represented by ω1 as the initial reference point of rotation or acting as the actuator, while the pulley rotational speed in the coupled shaft via timing belt is represented by ω¬2 and ω3, and the potentiometer pulley represented by ω4. The calculation of this gear reduction system has the purpose to find out how much reduction occurs in DSEA. This pulley reduction calculation starts from a DC motor connected with a pulley

Pulley 1 and pulley 2 are connected with a belt, the linear velocity of pulley 1 and pulley 2 are equal and the equation can be written as equation (1)

$$\begin{gathered} v_1 = v_2 \\ \omega_1 r_1 = \omega_2 r_2 \end{gathered} \tag{1}$$

Because of $r_1=r_2$, then $\omega_1=\omega_2$

Pulley 2 and pulley 3 are coupled using a shaft, then $\omega_2=\omega_3$ resulting in a relationship of $\omega_1=\omega_2=\omega_3$. Pulley 3 and pulley 4 are also connected by using a timing belt, so the linear velocity between the two pulleys is equal and the equation can be written as in equation (2)

$$\begin{gathered} v_3 = v_4 \\ \omega_3 r_3 = \omega_4 r_4 \\ \omega_3(10) = \omega_4(30) \\ \frac{\omega_3}{\omega_4} = \frac{\omega_1}{\omega_4} = 3 \end{gathered} \tag{2}$$

Through the calculations of equations (1), (2), and (3), the range of motion (ROM) of the tendon-sheath for finger flexion and extension motion can be calculated. It is known that the diameter of the DC motor pulley is 10 mm, the maximum value from potentiometer signal in the form of analog to digital converter (ADC) signal on the 8 bit Arduino Nano microcontroller is 746 and its minimum value is 57. The ROM calculation of the tendon-sheath linear displacement on the DSEA can be calculated as expressed in the equations (3), (4), and (5) as follows:

$$\begin{gathered} \theta_4 = \frac{(ADC_{\max} - ADC_{\min})}{1023} \cdot 360° \\ \theta_4 = \frac{(746-57)}{1023} \cdot 360° \\ \theta_4 = 242.46° \end{gathered} \tag{3}$$

$$\begin{gathered} \frac{\theta_1}{\theta_4} = \frac{\omega_1}{\omega_4} \\ \frac{\theta_1}{242.46} = \frac{3}{1} \\ \theta_1 = 727.39° \end{gathered} \tag{4}$$

$$\begin{gathered} x = \pi d_1 \frac{\theta_1}{360°} \\ x = 63.44mm \end{gathered} \tag{5}$$

From the results of equations (3), (4), and (5), it is known that the maximum length of the retractable tendon sheath is 63.44 mm.

The manufacturing process of the soft glove and DSEA which has been presented in the previous is one of the processes of several stages conducted in this research. Assembly is performed from components such us a soft glove, dual slack enabling actuator, DSEA case, and electrical component circuit into a complete system. Fig. 8 shows the wearable exoskeleton of soft robotic glove system prototype that has been carried out in the assembly process. Soft glove and DSEA are connected using two Bowden cables.

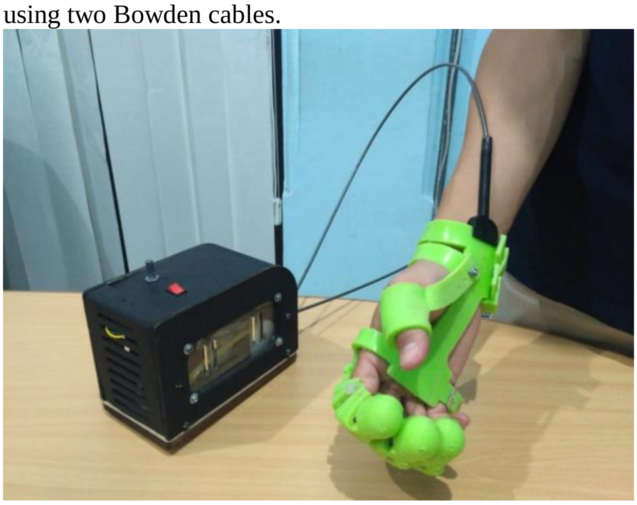
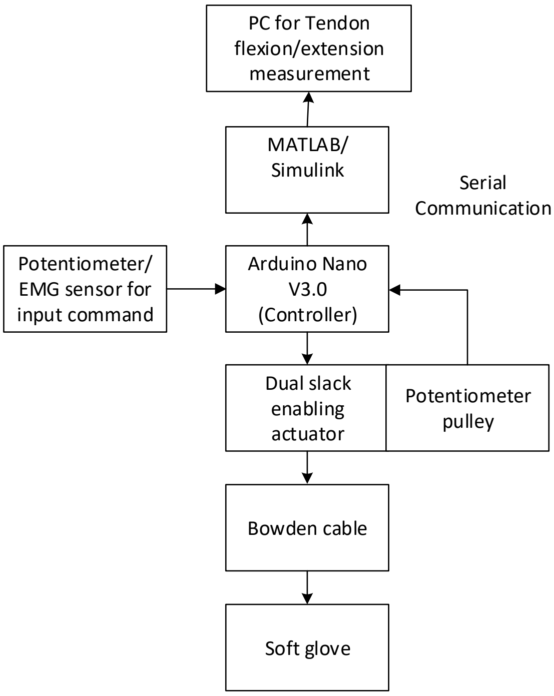


Fig. 8. Overall final prototype of soft exoskeleton glove incorporating a dual slack enabling actuator

IV. Exoskeleton Soft Glove Control

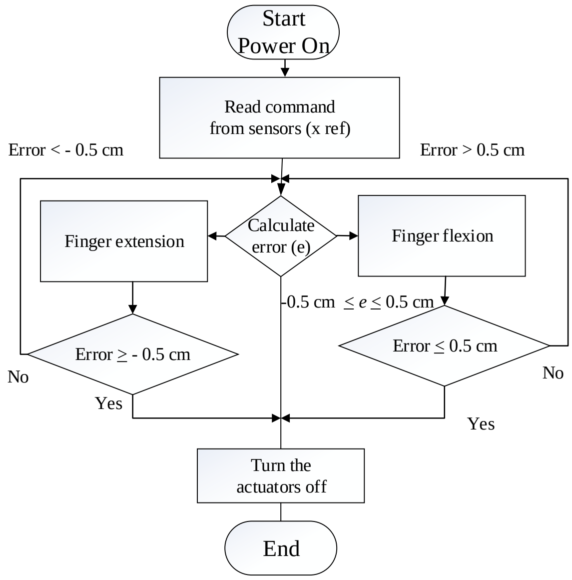
In this study, two controllers applied are on-off and proportional-integral (PI) control. In this test, the measurement is acquired using Simulink Support

Package for Arduino Hardware under MATLAB / Simulink environment. The package can be obtained freely on the MathWorks website. The potentiometer or electromyography sensor is used to give a pull or extend command on the tendon sheath. The overall system of the proposed wearable soft glove is presented in Fig. 9.

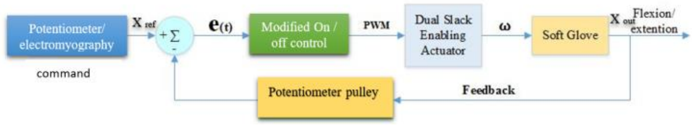


IV.1. Modified On-Off Control

In this test, the maximum displacement on the tendon sheath is 5.5 cm and the minimum displacement is 0.5 cm. The on-off control algorithm proposed in this test is shown in Fig. 10.a. When the error reaches a value between -0.5 cm and 0.5 cm, then the motor will be fully turned off. When the error occurs more than + 0.5 cm, then the PWM command will be given to the motor as shown in Fig. 11. The value of the PWM command is positive (+) means the controller will give the motor command to pull the tendon sheath or soft glove to do the finger flexion motion. When the PWM command is negative (-), the controller will give DSEA command for finger flexion or extension motion. The block diagram of On-off control as shown in Fig. 10.b is developed in MATLAB/Simulink environment. The control is embedded into Arduino Nano using Simulink Support Package for Arduino Hardware.



(a) Flow diagram



(b) Block diagram of modified on/off control in soft exoskeleton glove

Fig. 10. The purpose on/off control for controlling finger flexion/extension soft exoskeleton glove

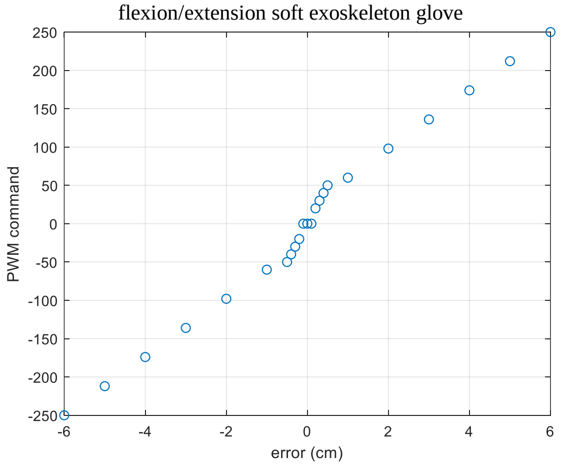
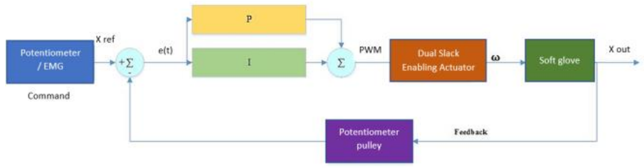


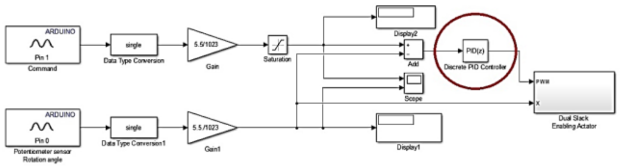
Fig. 11. Resulted error vs given PWM command in the modified on-off control

IV.2. Proportional Integral (PI) Control

Proportional - Integral (PI) control used in this study aims to gain better position control and get the desired response. Similar to previous On-Off controls, the PI control also uses an input signal derived from a potentiometer or electromyography signal as the command giver. Potentiometer pulley is employed to measure the rotation angle of the pulley and the converted into the displacement of the tendon pulling the wearable soft glove. The PI control implemented in the soft glove system is shown in Fig. 12.a. The PI control is developed under Simulink block diagram as revealed in Fig. 12.b. The reading of potentiometer sensor is applied using Analog Input block with the sampling frequency of 50 Hz. The overall control both in On-Off and PI control run with the sample time of 0.02 s.



(a) Employed PI compensator in soft exoskeleton glove



(b) Embedded discrete PI control in MATLAB /Simulink environment

Fig. 12. Block diagram of PI Control

V. Result and Discussion

In this section, the wearable robot glove performance control test is performed, and worn on the user with a healthy hand. Performance control test is conducted by comparing the measurement results of the given command with its response. The performance control test is performed by comparing the results in without load and with load. Without load test means that the soft glove is not worn by the user, whereas with load test means that the soft glove is worn by the user on a healthy hand. The results of the performance control tests that have been performed are presented in this section.

V.1. Modified On-Off Control

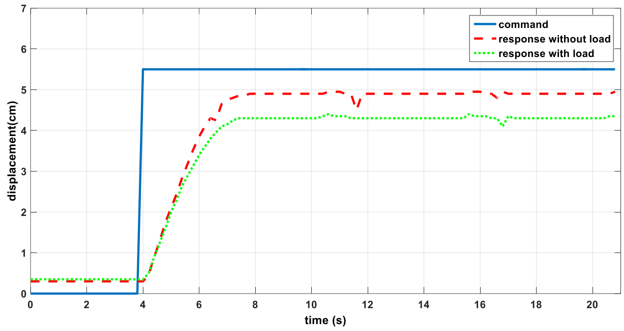
Performance testing of On-Off control performed by providing input command in the form of step signal with the maximum displacement of 5.5 cm. The response signal is acquired on the computer running Simulink block diagram of the controller in real time. The communication between Arduino and computer is performed by using serial communication with baud rate of 57,600 b/s. In Fig. 13.a., it can be seen the acquired signals from Arduino Nano. The command signal is represented by the continuous blue line, the without response signal is represented by the red dash line, and the response signal with the load is represented by the green dot line. From the figure, it can be concluded that the steady-state error occurs larger when the soft glove is worn by the user. This slow response can occur due to the gear reduction system in the DSEA. The transient performance of the controller is summarized in Table I.

TABLE 1
ON-OFF CONTROL PERFORMANCE.

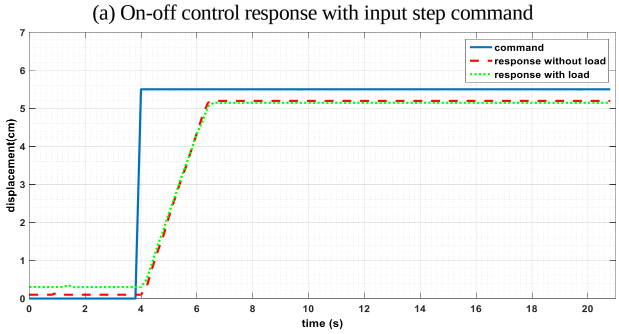
Response	Performance		Unit
	Without Load	With Load	
Time Constant (τ)	1.8	2	s
Rise time (tr)	1.1	1.3	s
Peak time	2.7	2.6	s
Delay time (td)	1	1	s
Steady state error	0.52	1.2	cm

V.2. PI Control

As the test performed on On-Off control performance, the test procedure is also performed on PI control. The initial test is performed for searching the optimum value of Kp and Ki experimentally. The obtained optimal values of Kp and Ki are 130 and 50 respectively. The result of the PI control performance test with the given step input command is presented in Fig. 13.b. Slow response also still appears in the PI control, this can occur because of the gear reduction system in the DSEA. The transient performance of the PI control on the soft glove is summarized in Table II. The result obtained in the PI control test shows that there is no significant response difference between without load and with load on the soft glove. The performance of the proposed controls under trajectory command is presented in Fig. 14.



(a) On-off control response with input step command

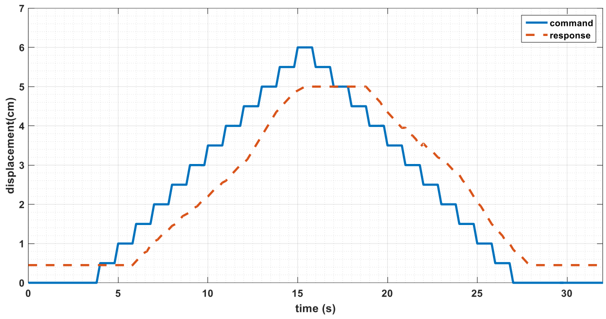


(b) PI control response with input step command

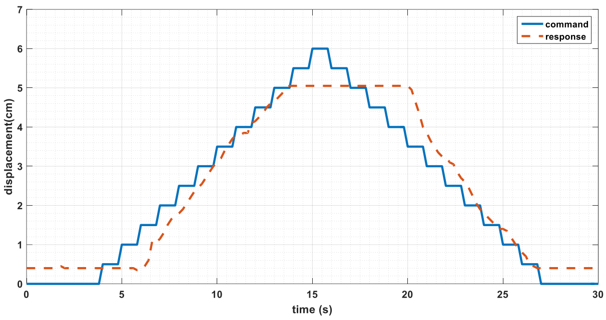
Fig. 13. Performance results to the step input

TABLE 2
PI CONTROL PERFORMANCE.

Response	Performance		Unit
	Without Load	With Load	
Time Constant (τ)	1.3	1.3	s
Rise time (tr)	0.9	0.9	s
Peak time	1.2	1.23	s
Delay time (td)	0.9	0.95	s
Steady state error	0.3	0.25	cm



(a) On-off control response with input trajectory command



(b) PI control response with input trajectory command

Fig. 14. Performance results to the trajectory input signal

V.3. Object Grasping Test

In this test, the soft glove is pulled by the DSEA through two tendons for every one cm. The curvature that occurs is observed in the soft glove. Fig. 14 indicates the position changes of the fingers from a normal position to the handgrip. Oppose grip mode is designed for the grasping support with the wearable soft glove. In order to perform a perfect handgrip, the four fingers do not need to do the full closing/flexion motion. Fig. 15 shows the curvature changes of the finger in the soft glove when they are pulled by DSEA.

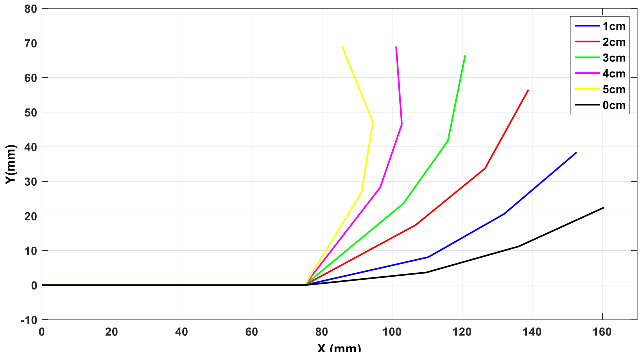


Fig. 15. The trajectory of the finger when the soft glove is worn by user

In the next test, the prototype of the wearable glove is employed for assisting and providing the mechanical support to the human hand. In this test, the user/wearer with healthy hand wears the proposed of the soft glove. To wear the soft glove, the user takes no more than one minute. The results of the test are shown in Fig. 16. Based on the test result, the proposed wearable soft glove can assist and provide the mechanical support for grasping various objects ranging in size, shape, and mass.

VI. CONCLUSION

This research has successfully developed a prototype of a wearable soft exoskeleton hand. The system is divided into three main parts, namely a soft glove, tendon sheath, and DSEA. The proposed of the soft glove has an overall length of 25 cm measured from the tip of the middle finger to the bottom. The overall width is 10 cm, and the thickness of the soft glove in all parts is 4 mm. Tendon sheath itself has a length of 84 cm, while the tendon sheath housing has a length of 72 cm. The actuator case has 15.5 cm in length, 9 cm in width and 12 cm in height. The raw materials used in this prototype are silicone rubber, polylactic acid (PLA), plywood, acrylic, and others. The weight of the soft glove is 190 grams while the actuator weight is 623 grams. The overall weight of this prototype is under 1 kg. The prototype of the wearable soft robotic glove uses a tendon type actuator that resembles the working mechanism of the human-hand muscle system. The resulted soft glove can successfully assist and support the human hand for various object grasping. The soft glove is ready to be implemented as an assisting device to provide mechanical support for an impaired human hand.

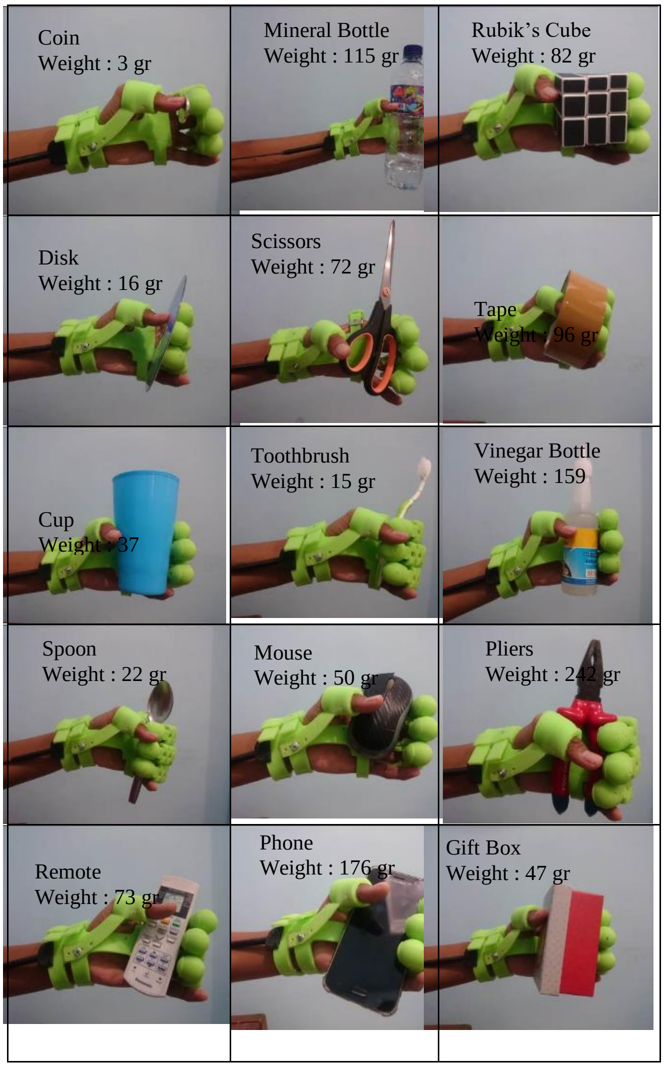


Fig. 16. Wearable glove provides mechanical support to the user's hand

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Currently, he is a lecturer in the Mechanical Engineering Department of Diponegoro University, Indonesia. Dr. Joga has published more than 50 papers in book chapters, international journals, and conference proceedings in the area of control system, intelligent system, and mechatronics. He is member of The Institute of Electrical and Electronics (IEEE).

Mr. **Mochammad Ariyanto** received B.Sc. and M.Sc. degrees from Department of Mechanical Engineering, Diponegoro University, Indonesia, in 2010 and 2013 respectively.
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Currently, he is a lecturer at Department of Mechanical Engineering, Diponegoro University, Semarang, Indonesia. His research interests are failure analysis, and composites.

Dr. Eng. **Munadi** received the B.E. degree in Mechanical Engineering from Diponegoro University, Semarang, Indonesia in 2001. From 2001-2005 he joined Pura Group Corp., Kudus, Indonesia. In 2007, he received the M. Eng. degree from Mechanical Engineering, Bandung Institute of Technology, Bandung, Indonesia. In 2011, he received the Dr. Eng. degree from the Graduate School of Engineering, University of Fukui, Fukui, Japan. He is currently a lecturer in the Department of Mechanical Engineering, Diponegoro University, Indonesia. His current research interests relate to hybrid adaptive and learning controller for robot manipulators, intelligent control, and soft robot.

Dr. **Rifky Ismail.** received B.Sc. degree from Department of Mechanical Engineering, Diponegoro University, Indonesia, in 2003, and M.Sc. degree from Gadjah Mada University, Indonesia in 2007. He obtained Ph.D. degree from University of Twente, the Netherlands in 2013.
He is a lecturer and researcher at Department of Mechanical Engineering Diponegoro University (Undip), Semarang, Indonesia. He is a Founder and Director of Center for Bimomechanics, Biomaterial, Biomechatronics and Biosignal Processing (CBIOM3S). He has published many book chapters, journals, and conference proceedings in the area of biomechanics, biomaterial, and biomechatronics.

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1b

[IREACO] Submission Acknowledgement

Editorial Staff <editorialstaff@praiseworthyprize.com> 25 October 2019 at 14:35
To: joga.setiawan@ft.undip.ac.id

Dear Joga D. Setiawan:

Thank you for submitting your manuscript entitled "A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance" to our journal International Review of Automatic Control (IREACO).

With the online journal management system that we are using, you will be able to track its progress through the editorial process by logging in to the journal web site:

Manuscript URL:
https://www.praiseworthyprize.org/jsm/index.php?journal=ireaco&page=author&op=submission&path[]=18274

and clicking on My Journals->Active submissions.

With this submission the review process starts.
According to the review procedures, your proposal will be send to the Editor-in-Chief that, after evaluated the publication suitability of the paper, will indicate three reviewers for a full evaluation.
More info regarding the review process can be found at the following link:
http://www.praiseworthyprize.org/jsm/index.php?journal=ireaco&page=about&op=editorialPolicies#peerReviewProcess

If you have any questions, please don't hesitate to contact me. In all the correspondence please indicate in the subject of your e-mail the identification number of the paper that is Id 18274.
[Quoted text hidden]

Faculty of Engineering Diponegoro University

joga setiawan <joga.setiawan@ft.undip.ac.id>

[IREACO] Editor Decision

Editorial Staff <editorialstaff@praiseworthyprize.org> 9 March 2020 at 21:12
To: joga.setiawan@ft.undip.ac.id

2a

Dear dr. Joga D. Setiawan

Manuscript ID 18274 entitled "A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance" which you submitted to our Journal "International Review of Automatic Control (IREACO)" has been reviewed. The comments of the reviewer(s) are included at the bottom of this email.

The reviewer(s) have recommended a MAJOR REVISION.
This is an opportunity for you to respond to their major concerns and to incorporate improvements in the paper according to their suggestions. It is also an opportunity for you to add new results.
We normally only permit one major revision before an accept or reject decision is made. So please take the concerns of the reviewers seriously.

Therefore, I invite you to respond to the reviewer(s)' comments and revise your manuscript within two weeks from the date of this email.

If it is not possible for you to submit your revision in a reasonable amount of time, we may have to consider your paper as a new submission.
You should revise your manuscript using a word processing program and save it on your computer. Please also highlight the changes to your manuscript within the document by using the colored text in red.
Once the revised manuscript is prepared, you can upload it and submit it through your on-line submission system.
In order to expedite the processing of the revised manuscript, please be as specific as possible in your response to the reviewer(s).

Once again, thank you for submitting your manuscript to our Journal and I look forward to receiving your revision.

Sincerely,
Dr. Srinivasan Alavandar, Editor-in-Chief of International Review of Automatic Control (IREACO)
seenu.phd@gmail.com

Reviewer Responses:

Reviewer A:

Do you think the content of this paper is appropriate for this journal?:
Yes

Originality::
3. Satisfactory

Contribution::
3. Satisfactory

References::
3. Satisfactory

Presentation style::
4. Unsatisfactory

Quality of language::
4. Unsatisfactory

Final result::
Accepted if improved

Suggestion for improving the paper::
- English is understandable but needs correction of grammatical errors and style. We suggest to use our service "English Language Editing". More information can be found to http://www.praiseworthyprize.com/english_service.htm
- For a better readability of the article, before the Introduction section, a Nomenclature section, not numbered, should be added with a list, in alphabetic order, of all the used symbols and their meaning.
- Unit of measure in the equations should be not in the italic style, they are not physical quantities.
- The revised version of the paper should be sent in doc or docx version.

Reviewer B:

Do you think the content of this paper is appropriate for this journal?:
Yes

Originality::
3. Satisfactory

Contribution::
3. Satisfactory

References::
4. Unsatisfactory

Presentation style::
3. Satisfactory

Quality of language::
4. Unsatisfactory

Final result::
Accepted if improved

Suggestion for improving the paper::
- At the end of the Introduction add a paragraph on how the rest of the paper is organized and developed, typically a summary on the rest.
- English grammar and style should be carefully revised.
- The reference list is brief and partially outdated. 50% of the references to be from 2017-2019 are expected. We strictly encourage the authors to visit our wide database of titles where they could search for references, at the page
http://www.praiseworthyprize.org/jsm/index.php?journal=index&page=search

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For any questions don't hesitate to contact us.
Best regards,
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Faculty of Engineering Diponegoro University

joga setiawan <joga.setiawan@ft.undip.ac.id>

A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance

3 messages

Joga - Setiawan <joga.setiawan@ft.undip.ac.id> 16 March 2020 at 16:10
To: editorialstaff@praiseworthyprize.org
Cc: mochammad_ariyanto@ft.undip.ac.id

2b

Dear Prof. Dr. Srinivasan Alavandar,
Editor-in-Chief
International Review of Automatic Control (IREACO)

We have thoroughly revised the manuscript ID 18274 entitled “A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance”.

We have addressed the reviewer comments and made a revision based on the reviewer's suggestions. The revision is written in the colored text in red.

Please, find the attached manuscript in .docx word format via this email or online submission system.

Please, let us know if we have miss the required document or something to do concerning the next process of review.

Best regards,
On behalf of authors,
Joga D. Setiawan

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IREACO_Development of A Low-Cost Soft Exoskeleton Glove Using Tendon-Driven Mechanism_150320202JS2 AM.docx
7655K

Praise Worthy Prize Editorial Staff <praiseworthyprize@gmail.com> 17 March 2020 at 18:26
To: Joga - Setiawan <joga.setiawan@ft.undip.ac.id>

2c

Dear dr. Joga Setiawan
thank you for your e-mail.
I confirm you that your revised version has been received and now it is under evaluation.
Now our reviewers will check if all their recommendations have been satisfied
If they consider the paper acceptable, in few days you will receive the acceptance with all the instructions to proceed further with the publication of your paper.
Best Regards

Angela Tafuro
Head of the Editorial Staff

****

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Editorial Staff

editorialstaff@praiseworthyprize.com

[Quoted text hidden]

Joga - Setiawan <joga.setiawan@ft.undip.ac.id> 19 March 2020 at 10:15
To: Praise Worthy Prize Editorial Staff <praiseworthyprize@gmail.com>

Dear Dr. Angela Tafuro
Head of the Editorial Staff

Thank you very much for your information.

We are looking forward to hearing from you soon regarding the review process.

Best regards,
Authors
[Quoted text hidden]

Faculty of Engineering
Diponegoro University

joga setiawan <joga.setiawan@ft.undip.ac.id>

[IREACO] Editor Decision

Editorial Staff <editorialstaff@praiseworthyprize.org> 20 March 2020 at 17:03
To: joga.setiawan@ft.undip.ac.id

2d

Dear Joga D. Setiawan:

It is my great pleasure to inform you that your paper ID 18274: "A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance" has been accepted AS IT IS and will be published on the International Review of Automatic Control (IREACO).

If you want to publish the paper on the current issue of the Journal, please, accomplish the following requirements as soon as possible:

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seenu.phd@gmail.com

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Faculty of Engineering
Diponegoro University

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Article publication fee Proof of payment and other required documents
1 message

Joga Setiawan <joga.setiawan@ft.undip.ac.id> Tue, Mar 24, 2020 at 6:39 PM
To: Editorial Staff <editorialstaff@praiseworthyprize.com>, info@praiseworthyprize.it
Cc: Editorial Staff <editorialstaff@praiseworthyprize.org>, mochammad ariyanto <mochammad_ariyanto@ft.undip.ac.id>

2e

Dear Dr. Angela Tafuro
Head of the Editorial Staff

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We have filled the required documents and send them to you via this email.
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Best regards
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A Soft Exoskeleton Glove Incorporating Motor-Tendon Actuator for Hand Movements Assistance

3

published article

Joga D. Setiawan, Mochammad Ariyanto, Sri Nugroho, M. Munadi, Rifky Ismail

Abstract – *Hand paralysis can inhibit daily activities, for example, grasping a particular food or an object. With the advancement of science and technology today especially in wearable robot technology, normal hand function can be recovered with the help of wearable soft robotic glove. This robot has a mechanism that resembles the working mechanism of the hand itself. The purpose of this study is to develop a low-cost soft exoskeleton glove made from silicone rubber using a tendon-based mechanism. The molding of the soft glove is designed using SolidWorks CAD software. Dual-slack enabling actuators are designed and manufactured as the actuator system of the soft exoskeleton glove. The proposed actuator is used as flexion and extension motion for the human hand. This motion enables the soft exoskeleton glove to provide mechanical support for the human hand. A potentiometer sensor is used in the dual-slack enabling actuator for measuring the rotating angle of the actuator that is connected to the tendon and soft exoskeleton glove. The actuator is controlled using on-off and Proportional-Integral (PI) control. After the soft exoskeleton glove system is integrated, the soft robot is implemented on a healthy human hand to assist the grasping of various objects. The measurement for the wearable robot is performed by using serial communication between Arduino Nano microcontroller and the host computer. Based on the experimental results, the soft glove can successfully assist and support the user's hand for various object grasping.*

***Keywords**: Dual-Slack Enabling Actuator, Soft Exoskeleton, Wearable Robot, PI Control*

Nomenclature

ADC	Analog-to-Digital Converter
CAD	Computer-Aided Design
DSEA	Dual-Slack Enabling Actuator
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
SMA	Shape Memory Alloy
r_i	Radius of pulley i (i=1,4), [m]
v_i	Linear velocity of pulley i (i=1,4), [m/s]
x	Maximum tendon-sheath linear displacement [m]
θ_i	Angular displacement of pulley i (i=1,4), [rad]
ω_i	Angular velocity of pulley i (i=1,4), [rad/s]

I. Introduction

Soft robot is a further development of hard automation or hard robot. Soft robots are a sub-field of robotics designed using "compliant" materials (adapted to suit the needs), similar to those found in living organisms [1]. In the working principle, the function of a wearable exoskeleton soft robot is the same as a hard exoskeleton robot hand, the only material used in this kind of robot is different. If the wearable exoskeleton robot hand still uses rigid material, then wearable exoskeleton soft robot hand utilizes soft material made of material in the form of synthetic resin or silicon rubber. For the actuation system, soft robots use a variety of actuators. PneuNets (pneumatic networks) is one of the soft robot actuators developed by the Whitesides Research Group at Harvard University. Actuators of pneumatic networks are made of a series of chambers in elastomeric material. This room will expand when pressured and produce bending movements such as human fingers [2]. Naturally, this movement is controlled by modifying the geometry and material properties of its chamber walls. When the PneuNets actuator is pressurized, expansion occurs in a softer area [3]. For PneuNet that consists of a single and homogeneous elastomer, the greatest expansion will occur in the thinnest structure. Researchers can program the working mechanism of the actuator by choosing the wall thickness that causes the desired movement [4]. In addition, different materials can be combined to enable better actuator control. When the PneuNets actuator contains several layers of material having different elastic properties, more elastic material expands larger than the less elastic material when the actuator is pressurized. In this configuration, the less elastic material is called strain-limiting layers, as its function is to limit the strain to occur. This strain effect variation can be used to achieve the desired movement such as bending and twisting [5]. In most research on soft exoskeleton hands, the actuator is pneumatic network type [6]-[10].

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The fluid used in the soft wearable robot also comes from a hydraulic network such us in [11] and [12]. One of soft robotics developed by Harvard University is a soft robotic glove. The purpose of the development is to assist people with disabilities in hand motor skills. The motor skills of this hand can be lost partially or totally. In the design developed by Harvard, the five fingers of the user can be re-functioned by using the soft robotic glove, pneumatic, or hydraulic based actuator is employed as the actuation system on the soft robotic glove. SMA has been developed and utilized as the actuator of the soft wearable robot, especially on the soft exoskeleton hand [13], [14]. The research combines SMA with a tendon actuation system. Based on the results, the proposed SMA has the potential to be implemented in the soft wearable robot. The soft glove based on SMA actuation can flex and extend fingers in the designed range of motion and grasp objects efficiently. Motor-tendon actuation is one type of actuator in a soft robot that utilizes a DC servo motor to manipulate soft materials in order to move. Tendon is an intuitive solution for soft robot actuator because it is a continuum structure that can adapt to soft joints. The mechanism of action of this actuator motor- tendon is to shorten the soft body and extend it back to produce controlled motion resulting from friction that arises when the material is shortened larger than when elongated so that the soft body can move. In this type of actuator, strings or Bowden cables are widely used as a towing medium embedded into the actuator. Actuator based motor-tendon utilized on soft wearable robots have been developed by researchers with the purposes of both rehabilitation and assistive devices [15]-[19]. This type of actuator can produce a relatively large grasping force. The soft tendon routing system is a system that, in principle, works inspired by the human musculoskeletal system, resembles the working principle of muscle tendons working on the hands. There is a power transmission component developed inherent in the human body. All elements of the routing system include actuators designed to work without air pressure so that the system can improve safety and comfort in its use and efficiency in terms of mechanical design. In this study, a low-cost soft wearable robot based on motor-tendon mechanism is developed and manufactured. A soft glove is developed and manufactured using RTV (Room-Temperature-Vulcanizing) Silicone material. A novel low-cost dual-slack enabling actuator (DSEA) is designed as an actuation system of the soft exoskeleton glove to assist the user's hand for finger flexion and extension. On-off and PI compensators are employed for controlling the motion of DSEA. PID and PI controllers have been implemented successfully in position and speed controllers that are implemented DC servo motor as the actuator of the system [19]-[25]. Two Bowden cables are used for transmitting the power from DSEA to the soft glove. After the soft glove prototype has been built, the robot is implemented on the healthy human hand to assist for various object grasping. This study proposes the development of a novel soft exoskeleton glove based on the motor-tendon actuator for providing mechanical assistance for finger flexion-extension.

Soft exoskeleton glove design and prototype are presented in Section II. Motor-tendon actuator for driving the soft glove is discussed in section III. The utilized control for soft glove is presented in Section IV. The result and conclusion of the experimental work of the soft glove are outlined in sections V and VI, respectively.

II. Design and Prototype Development of Soft Exoskeleton Glove

The initial stage of this research is to develop a 3D model of soft exoskeleton glove. It is adjusted to the average dimensions of the hands and fingers of the impaired hands so that the resulting model will match the size of the user's fingers. In the early stages of the design, the 3D model of the soft glove is detailed by creating two-dimensional images in SolidWorks computer-aided design (CAD) software. This section presents the design process to be used in soft exo-glove molding fabrication and soft exo-glove manufacturing process from raw material in the form of silicone rubber dough to the ready to use the prototype of the soft glove. The 3D design of the proposed exoskeleton glove using motor-tendon actuation is presented in Fig. 1.

II.1. Design of Soft Exoskeleton Glove

Actuators on wearable exoskeleton glove have an important role as the main driving system. In the selection of actuator types, the researchers considered using three types of actuators, namely PneuNets (Pneumatics network), Combustion driven actuators (CDA), and motor-tendon actuation. The motor-tendon actuation system was chosen in this study because, in the development of soft glove, there was concern itself in using Pneunets and CDA type actuators. One of the concerns is if there is cavitation (a hole in the soft glove caused bubbles during the casting process). The cavitation can lower the performances of Pneunets and CDA actuators. While on the motor-tendon type, cavitation can be neglected. The soft glove developed should not have a hole caused by cavitation, as it will reduce the aesthetic value of the soft exoskeleton glove.

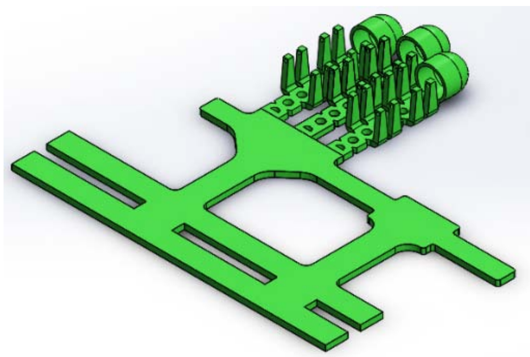
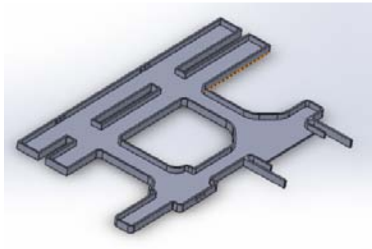
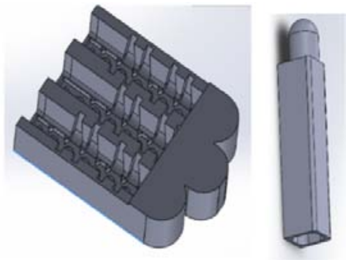


Fig. 1. Design of Soft Exoskeleton Glove

Furthermore, motor-tendon actuators have characteristics of easy manufacturing process and maintenance. The material used to develop soft glove is a synthetic rubber. There are two types of silicon rubber based on the manufacturing temperature of synthetic rubber, which requires heating and does not require heating or is often called RTV (Room Temperature Vulcanization). RTV has many different types depending on stiffness, heat resistance, and mixed type. In this study, a synthetic rubber used is RTV type. Silicon rubber of RTV type was chosen to facilitate the manufacturing process because it does not require additional tools such as heaters, and this research works at low temperatures. The utilized materials are RTV 48, RTV 52, and RTV Platinum. The selection of the above three materials is based on several criteria, such as stiffness, casting, and price. RTV Platinum is chosen because it has the appropriate rigidity based on need, and also based on consideration of the availability of the silicon rubber in the market. RTV Platinum has higher stiffness point compared to RTV 48. RTV 52 has a higher stiffness than RTV 48. However, RTV 48 is not rigid enough for soft glove base material;thus this will produce a finished soft glove form that is too soft. The advantages of RTV Platinum during the casting process are the RTV Platinum can enter and fill up the narrow gaps so that the results of the soft glove can be formed perfectly. However, in terms of raw material price, RTV Platinum is more expensive compared to RTV 48 and RTV 52. In the soft exoskeleton glove mold design, the shape of the mold is measured according to the size needs of the average adult human finger and consideration in the primary function of the soft glove beside the aesthetic aspect. The mold of the soft glove is designed using SolidWorks CAD software and manufactured by using 3D printer technology. Fig. 2(a) and Fig. 2(b) show the mold design of soft glove in CAD software. Fig. 2(c) is the overall result of the mold printed using a 3D printer. The mold is printed using polylactic acid (PLA) material.



(a) Soft glove base



(b) Fingers

(c) The overall result of 3D printed mold design for exoskeleton glove

Figs. 2. 3D mold design of the proposed soft glove

II.2. Prototype Development and Manufacture

In the molding process of soft exo glove, silicon rubber and the liquid catalyst and supporting equipment such as; scale, measuring cup, color pigment, stirrer, and soft glove moldings, etc. should be prepared first. After the preparation process has been completed, then the silicone rubber is weighed and taken as needed. In this research, the mass of silicon rubber RTV needed is 140 grams. The measured silicone rubber is then given a dye without a catalyst blend, then gently stirs the silicone rubber dye to blend perfectly, but the dough does not quickly clot and dry. The silicon rubber dye used in this study has a green color. The Silicon rubber and catalyst are mixed with a 10:1 dose with the amount of silicon rubber in grams. The silicon rubber mixture and the catalyst are stirred gently until evenly to avoid air bubbles occurring.

The silicon rubber mixture is fastened to soft glove molding until it is evenly distributed and fills the mold volume. The finger mold is placed on the soft glove mold to the soft glove molding that has been filled by a mixture of silicone rubber as shown in Fig. 3. The silicone rubber mixture poured in the mold is dried at room temperature for four to six hours until the soft glove is formed. The demolding process of the formed soft exoskeleton glove is conducted after the silicon rubber is completely dry and perfectly formed. The demolding process can be carried out by separating the silicone rubber that has been formed and dry with the mold. The overall manufacturing process of the soft glove based on the RTV silicon rubber is presented in Fig. 3.

III. Dual Slack Enabling Actuator (DSEA)

From a mechanical design aspect, the Dual Slack Enabling Actuator (DSEA) element consists of several components which are presented in Fig. 4. It consists of a servo motor mount, a base component, two pulleys having a diameter of 10 mm and 15 mm. The pulleys are made by a 3D printer using Poly Lactic Acid (PLA) material. The MXL timing belt pulley, MXL pulley, and shaft are DSEA components with aluminum materials that are readily available in the market.

Fig. 3. Molding process of soft exoskeleton glove

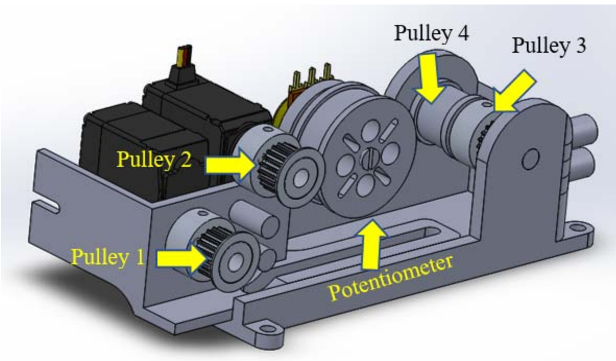


Fig. 4. Dual slack enabling actuator (DSEA) design in the CAD software

In the working principle of proposed DSEA, the rotational motion of the servo motor is transmitted through the timing belt of the pulley MXL to the pulley 3, causing rotation of the pulley 4 having a diameter of 10 mm. The rotation received by the pulley 3 is also transmitted to a potentiometer's pulley having a diameter of 15 mm through a belt, causing the potentiometer to rotate in the same direction of the servo motor. For example, if the direction of rotation of the pulley 1 is clockwise, then the potentiometer will also rotate clockwise. In this study, a DC servo motor with a gearbox is used. The motor has a torque of ± 35 kg/cm.

The DC motor servomotor is easy to obtain in the market; thus, it is selected as a soft glove system actuator.

Pulley system is chosen for mechanical power transmission in the mechanical design of DSEA. This pulley is used to transmit power from the motor to the pulley that rotates the pulley that pulls the tendon sheath with three stages of speed reduction, and the potentiometer.

The selection of a belt as power transmission because it is suitable for the desired condition of the system. The braided string is utilized because it is quite strong and makes the installation process easy. It can withstand tensile forces up to 30.8 kg.

The tendon is used as the power transmission of the actuator system, which will pull or extend the soft tendon. The casing is the part used to cover the DSEA and protect the DSEA components from liquid spills and other debris. The casing itself is divided into three sections, namely the bottom, the middle, and the top parts. The 3D design drawing of the casing is shown in Figs. 5. The design drawings of the DSEA casing and the pulleys are shown in Figs. 5. The motor holder of DSEA serves as a holder of a DC servo motor actuator on the soft glove. Fig. 5(e) shows the 3D design of the motor holder in the CAD software. The actuator base serves as a place to join the components needed to become a DSEA system. Fig. 5(f) shows the 3D design of the proposed actuator base. The main parts of DSEA mechanical components are printed with PLA material using a 3D printer. Figs. 6(a)-(c) show the assembly of DSEA components in the CAD software.

The assembly result of the proposed DSEA prototype is shown in Fig. 6(d). The DSEA has two Bowden cables for finger flexion and extension motion. Pulling the lower tendon will simultaneously cause the upper tendon to extend.

This section discusses the kinematic motion modeling of the DSEA, having a rotation input from the servo motor. The motor is used as the prime mover to pull and extend the tendon sheath.

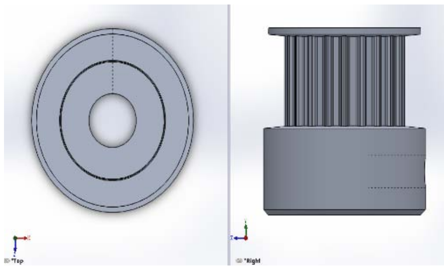
The translational motion calculation of the DSEA is used to calculate the rotation of the potentiometer's pulley. The rotational angle obtained is used for position control feedback.

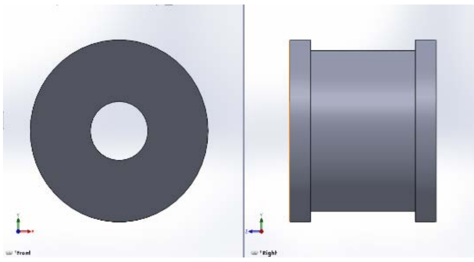
The purpose of kinematic modeling on the DSEA is to provide position feedback to the motor actuator. The required position feedback is a signal from the potentiometer, which has the range of motion from 0° to 270°.

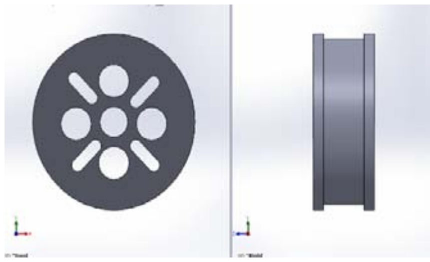
The rotation of the DC servo motor pulls the tendon sheath from its normal position to a full grip of the soft glove that requires more than one rotation.

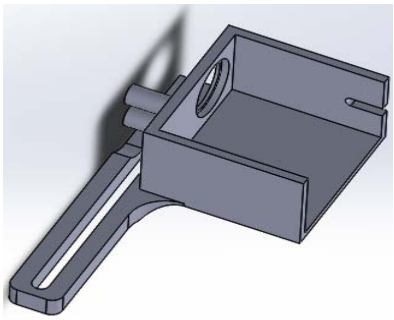
Therefore, the reduction gear is required between the rotation of the potentiometer pulley and the rotation of the DC servo motor such that the actuator rotation does not exceed the range of motion of the potentiometer. The proposed of a reduction gear system utilizing four pulleys is shown in Fig. 7.

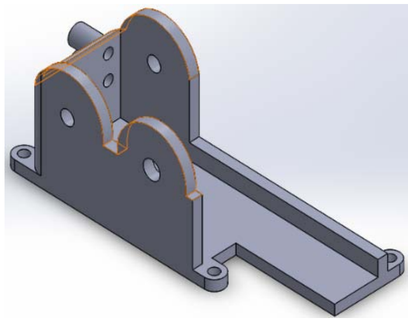

(a) Casing design


(b) MXL timing belt pulley

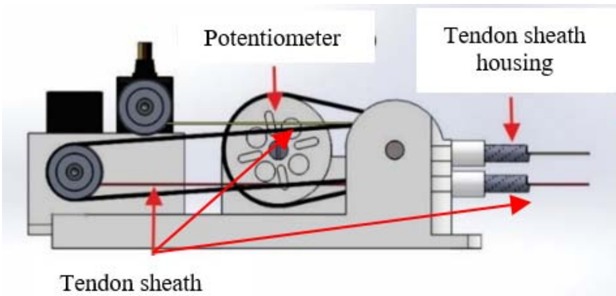

(c) Couple pulley


(d) Potentiometer pulley

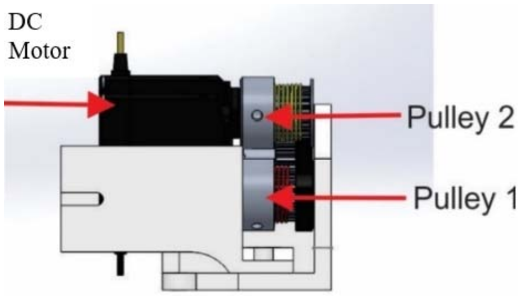

(e) Motor holder


(f) Actuator base

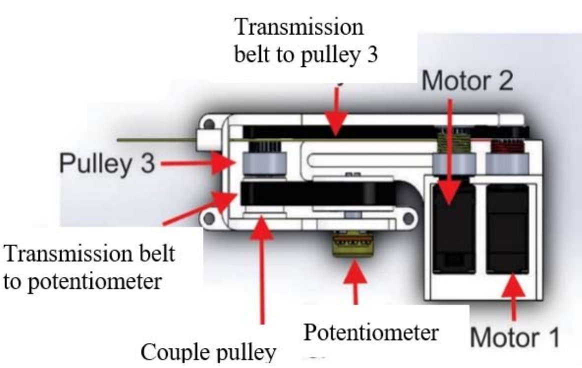
Figs. 5. Casing and pulley design of DSEA in CAD software



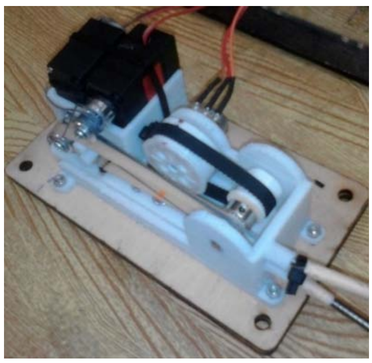
(a) Front view



(b) Side view



(c) Top view


(d) Prototype

Figs. 6. DSEA design and prototype

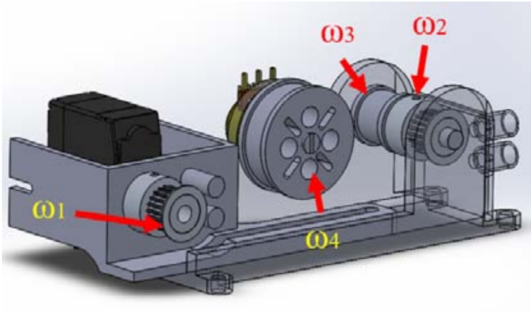


Fig. 7. Gear reduction system on the DSEA

The rotational speed of the DC motor pulley is represented by ω_1 as the initial reference point of rotation or acting as the actuator, while the pulley rotational speed in the coupled shaft via timing belt is represented by ω_2 and ω_3, and the potentiometer pulley is represented by ω_4. The purpose of the calculation on this gear reduction system is to find the amount of speed reduction occurs in DSEA. This pulley reduction calculation starts from a DC motor connected with a pulley. Pulley 1 and pulley 2 are connected with a belt, the linear velocity of the pulley 1 and the pulley 2 are equal, and the equation can be written as Equation (1):

$$\begin{aligned} v_1 &= v_2 \\ \omega_1 r_1 &= \omega_2 r_2 \end{aligned} \tag{1}$$

Since $r_1=r_2$, then $\omega_1=\omega_2$. Pulley 2 and pulley 3 are coupled using a shaft, then $\omega_2=\omega_3$ resulting in a relationship of $\omega_1=\omega_2=\omega_3$. Pulley 3 and pulley 4 are also connected by using a timing belt, so the linear velocity between the two pulleys is equal and the relation can be written in Equation (2):

$$\begin{aligned} v_3 &= v_4 \\ \omega_3 r_3 &= \omega_4 r_4 \\ \omega_3(10) &= \omega_4(30) \\ \frac{\omega_3}{\omega_4} &= \frac{\omega_1}{\omega_4} = 3 \end{aligned} \tag{2}$$

Through the calculations of equations (1), (2), and (3), the range of motion (ROM) of the tendon-sheath for finger flexion and extension motion can be determined. It is known that the diameter of the DC motor pulley is 10 mm, the maximum value from the potentiometer signal in the form of analog to digital converter (ADC) signal on the 8 bit Arduino Nano microcontroller is 746 and its minimum value is 57. The ROM calculation of the tendon-sheath linear displacement on the DSEA can be calculated using the equations (3), (4), and (5) as follows:

$$\begin{aligned} \theta_4 &= \frac{(ADC_{\max} - ADC_{\min})}{1023} \cdot 360^\circ \\ \theta_4 &= \frac{(746-57)}{1023} \cdot 360^\circ \\ \theta_4 &= 242.46^\circ \end{aligned} \tag{3}$$

$$\begin{aligned} \frac{\theta_1}{\theta_4} &= \frac{\omega_1}{\omega_4} \\ \frac{\theta_1}{242.46} &= \frac{3}{1} \\ \theta_1 &= 727.39^\circ \end{aligned} \tag{4}$$

$$\begin{aligned} x &= \pi d_1 \frac{\theta_1}{360^\circ} \\ x &= 63.44 \text{ mm} \end{aligned} \tag{5}$$

From the results of equations (3), (4), and (5), it is found that the maximum length of the retractable tendon sheath is 63.44 mm.

The manufacturing process of the soft glove and DSEA which has been presented in the previous is one of the processes of several stages conducted in this research.

Assembly is performed from components such as a soft glove, DSEA's casing, and electrical component circuit into a complete system. Fig. 8 shows the wearable exoskeleton of the soft robotic glove system prototype that has been built in the assembly process. Soft glove and DSEA are connected using two Bowden cables.

IV. Exoskeleton Soft Glove Control

In this study, two controllers applied are on-off, and proportional-integral (PI) controls. In this test, the measurement is conducted using the Simulink Support Package for Arduino Hardware under MATLAB/ Simulink environment. The package can be obtained freely on the MathWorks website. The potentiometer or electromyography sensor is used to give a pull or extend command on the tendon sheath. The overall system of the proposed wearable soft glove is presented in Fig. 9.

IV.1. *Modified On-Off Control*

In this test, the maximum displacement on the tendon sheath is 5.5 cm, and the minimum displacement is 0.5 cm.

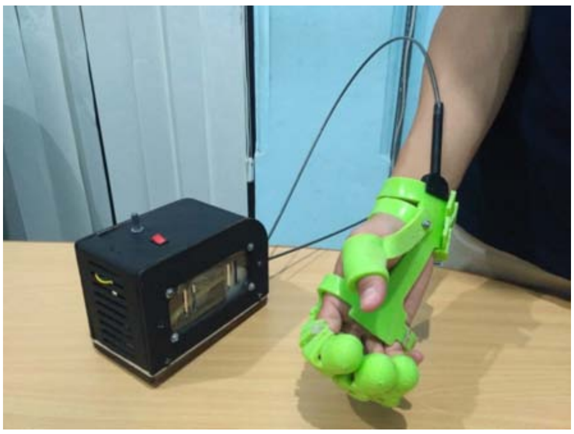


Fig. 8. The overall final prototype of soft exoskeleton glove incorporating a dual slack enabling actuator

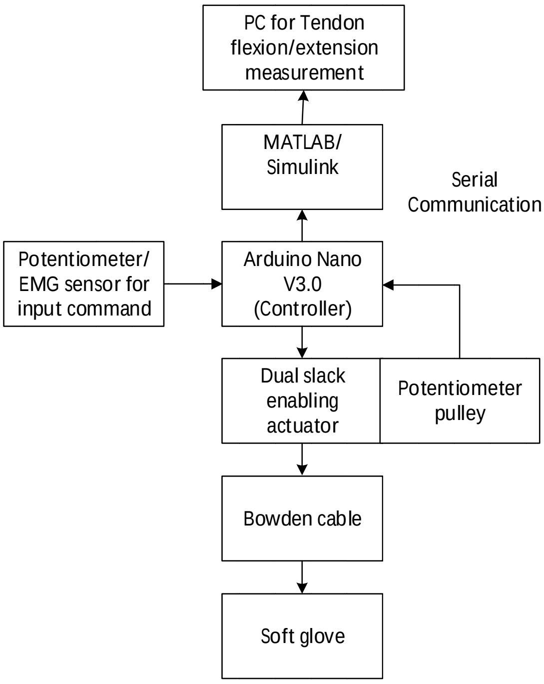
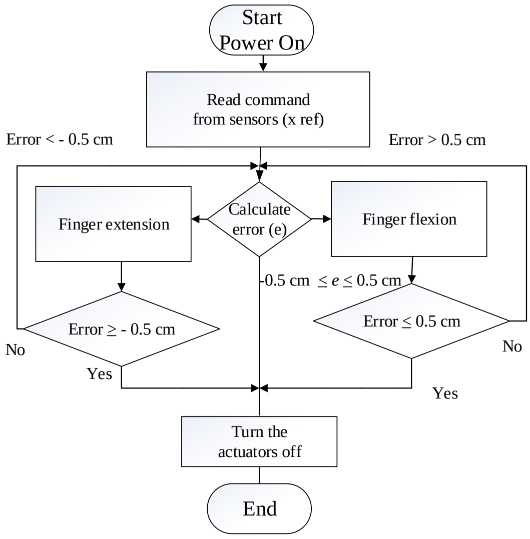
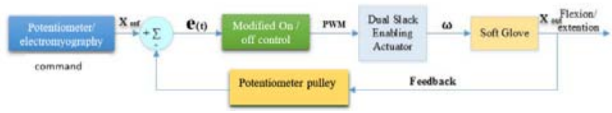


Fig. 9. The overall system of the proposed wearable soft glove



(a) Flow diagram



(b) Block diagram of modified on/off control in soft exoskeleton glove

Figs. 10. The purpose on/off control for controlling finger flexion/extension soft exoskeleton glove

The on-off control algorithm proposed in this test is shown in Fig. 10(a). When the error reaches a value between -0.5 cm and 0.5 cm, then the motor will be fully turned off. When the error is more than + 0.5 cm, then the PWM command will be given to the motor, as shown in Fig. 11.

The value of the PWM command is positive (+) means the controller will cause the motor command to pull the tendon sheath or soft glove to produce the finger flexion motion. When the PWM command is negative (-), the controller will give DSEA command for finger flexion or extension motion. The block diagram of On-off control, as shown in Fig. 10(b) is developed in MATLAB/Simulink environment. The control is embedded into Arduino Nano using Simulink Support Package for Arduino Hardware.

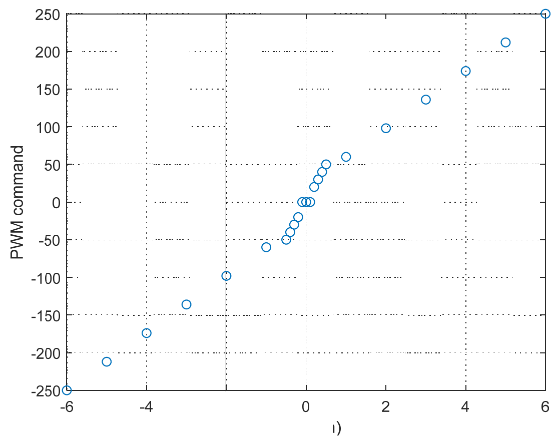


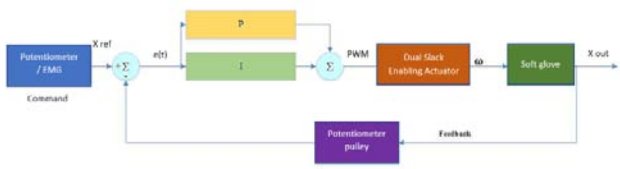
Fig. 11. Resulted error vs given PWM command in the modified on-off control

IV.2. Proportional Integral (PI) Control

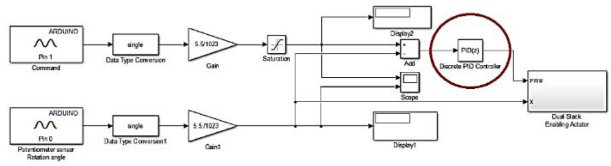
Proportional - Integral (PI) controller used in this study aims to gain better position response. Similar to previous On-Off controllers, the PI controller also uses the command input signal generated by a potentiometer or electromyography.

The potentiometer is employed to measure the rotation angle of the pulley and then converted into the displacement of the tendon pulling the wearable soft glove. The PI control implemented in the soft glove system is shown in Fig. 12(a). The PI control is developed under a Simulink block diagram shown in Fig. 12(b).

The reading of the potentiometer sensor is applied using an Analog Input block with a sampling frequency of 50 Hz. Both On-Off and PI controllers run with the sample time of 0.02 s.



(a) Employed PI compensator in soft exoskeleton glove



(b) Embedded discrete PI control in MATLAB /Simulink environment

Figs. 12. Block diagram of PI Control

V. Result and Discussion

In this section, a control test for the performance of the wearable robot glove is conducted by a user with a healthy hand. The performance control test is performed by comparing the measurement results of the given command to its response. The performance control test is performed by evaluating the results “without-load” and “with-load”. Without-load test means that the soft glove is not worn by the user, whereas the with-load test indicates that the soft glove is worn by the user on a healthy hand. This section presents the results of the performance control tests.

V.1. Modified On-Off Control

Performance testing of On-Off control is conducted by providing an input command in the form of a step signal with the maximum displacement of 5.5 cm. The response signal is acquired on a computer running Simulink block diagram of the controller in real-time. The communication between the Arduino and the computer is carried out by serial communication having baud rate of 57,600 b/s. Fig. 13(a) shows the acquired signals from the Arduino. The continuous blue line, the red dash line, and the green dot line represent the command signal, the without response signal, and the response signal with the load, respectively. From the figure, it can be concluded that a larger steady-state error occurs when the soft glove is worn by the user. This slow response can occur due to the gear reduction system in the DSEA. The transient performance of the controller is summarized in Table I.

V.2. PI Control

As the test conducted on On-Off control performance, the test procedure is also performed on PI control. The initial test is performed for searching the optimum value of Kp and Ki experimentally. The obtained optimal values of Kp and Ki are 130 and 50, respectively. The result of the PI control performance test with the given step input command is presented in Fig. 13(b). Slow response also still appears in the PI control; this can occur because of the gear reduction system in the DSEA.

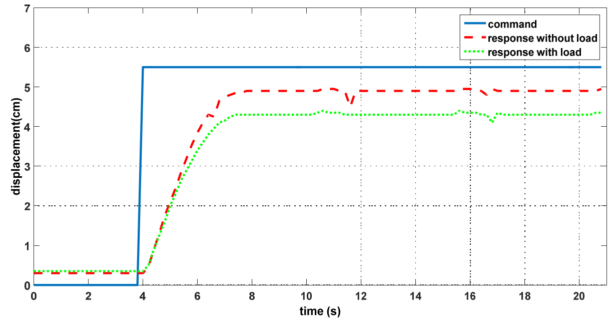
The transient performance of the PI control on the soft glove is summarized in Table II. The result obtained in the PI control test shows that there is no significant response difference between the without-load and the with-load on the soft glove. The performance of the proposed control under trajectory command is presented in Figs. 14.

TABLE I
ON-OFF CONTROL PERFORMANCE

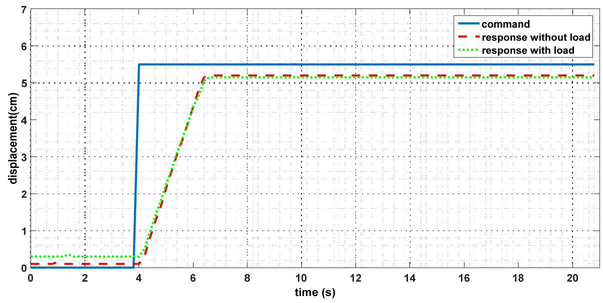
Response	Performance		Unit
	Without-load	With-load	
Time Constant (τ)	1.8	2	s
Rise time (tr)	1.1	1.3	s
Peak time	2.7	2.6	s
Delay time (td)	1	1	s
Steady state error	0.52	1.2	cm

TABLE II
PI CONTROL PERFORMANCE

Response	Performance		Unit
	Without Load	With Load	
Time Constant (τ)	1.3	1.3	s
Rise time (tr)	0.9	0.9	s
Peak time	1.2	1.23	s
Delay time (td)	0.9	0.95	s
Steady state error	0.3	0.25	cm

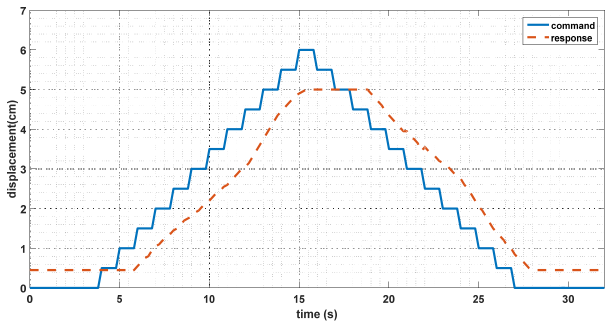


(a) On-off control response with the input step command

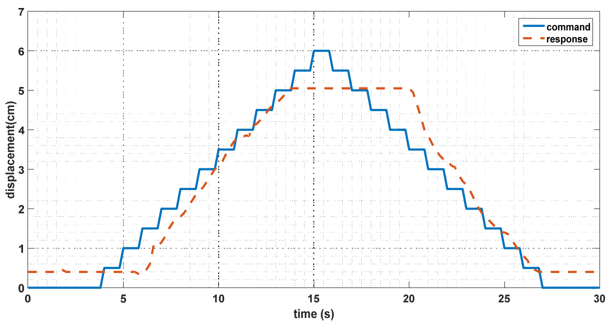


(b) PI control response with the input step command

Figs. 13. Performance results to the step input



(a) On-off control response with input trajectory command



(b) PI control response with input trajectory command

Figs. 14. Performance results to the trajectory input signal

V.3. Object Grasping Test

In this test, the soft glove is pulled by the DSEA through two tendons for every one cm. The curvature that occurs is observed in the soft glove. Figs. 14 indicate the position changes of the fingers from a normal position to the handgrip. The proposed grip mode is designed for the grasping support with the wearable soft glove. To perform a perfect handgrip, the four fingers do not need to make the full closing/flexion motion. Fig. 15 shows the curvature changes of the fingers in the soft glove when DSEA pulls them. In the next test, the prototype of the wearable glove is employed for assisting and providing mechanical support to the human hand. In this test, the user/wearer with a healthy hand wears the soft glove. To wear the soft glove, the user takes no more than one minute. The results of the test are shown in Fig. 16. Based on the test result, the proposed wearable soft glove can assist and provide mechanical support for grasping various objects ranging in size, shape, and mass.

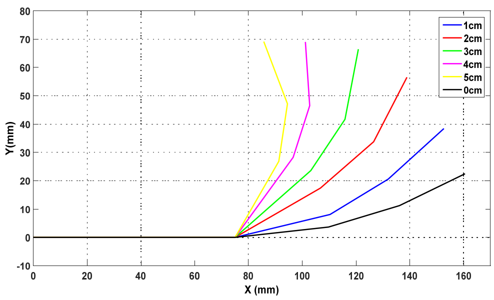


Fig. 15. The trajectory of the finger when the soft glove is worn by user

Fig. 16. The wearable glove provides mechanical support to the user's hand

VI. Conclusion

This research has successfully developed a prototype of a wearable soft exoskeleton hand. The system is divided into three main parts, namely a soft glove, tendon sheath, and DSEA. The proposed soft glove has an overall length of 25 cm measured from the tip of the middle finger to the bottom. The overall width is 10 cm, while the thickness of the soft glove in all parts is 4 mm. Tendon sheath itself has a length of 84 cm, while the tendon sheath housing has a length of 72 cm. The actuator case has 15.5 cm in length, 9 cm in width, and 12 cm in height. The main raw materials used in this prototype are silicone rubber, polylactic acid (PLA), plywood, and acrylic. The weight of the soft glove is 190 grams, while the actuator weight is 623 grams. The overall weight of this prototype is under 1 kg. The prototype of the wearable soft robotic glove uses a tendon type actuator that resembles the working mechanism of the human-hand muscle system. The resulted soft glove can successfully assist and support the human hand for various object grasping. The soft glove is ready to be implemented as an assisting device providing mechanical support for an impaired human hand.

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