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Tendon Driven Assistive Hand for Mirror Based Robotic Therapy

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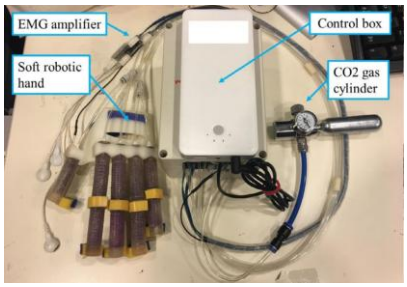
***Abstract*— Soft robotic hands, particularly those utilizing tendon-driven mechanisms, offer significant advantages in precision and adaptability for handling delicate objects. These soft robotic hands are designed to mimic the dexterity and flexibility of the human hand by employing variable stiffness materials. Despite recent advancements in tendon-driven soft robotic hands, there remains a gap in the development of simplified variable stiffness mechanisms with integrated sensors for real-time adaptability. This paper presents the development of a modular, bio-inspired, tendon-driven soft robotic hand, fabricated using 3D printing. Flexible material NinjaFlex TPU85A is used for flexible joint mechanism whereas rigid PLA is used for fingers and rest of the hand for structural support. The combination of these materials allows the soft robotic hands to dynamically adjust their stiffness, striking a balance between flexibility and strength. Following the muscle contraction model, the hand is actuated by servo motors while optimized tendon paths reduce friction for smooth motion. Additionally, force and flex sensors provide real-time feedback, allowing precise control of finger movements and grip pressures. Experimental tests conducted using both glove hand simulation and robotic prototypes confirmed the system's ability to replicate glove finger movements accurately. The presented design holds potential for applications in prosthetics, industrial automation, and delicate object manipulation, where precise, flexible handling is essential.**

Keywords—soft robot, tendon driven, bioinspired, 3d printing

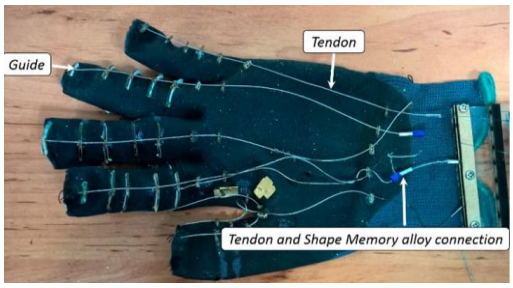
I. Introduction

The human hand is an intricate biomechanical system that plays a critical role in manipulation and dexterity. Its unique structure and range of motion serve as an ideal model for designing robotic hands, particularly in applications where flexibility, precision, and dexterity are crucial in areas like healthcare, agriculture, surgery etc. While rigid robotic hands can provide linear control with high precision, they are often heavy, less compliant, and challenging while dealing with delicate object handling. Recently, the soft robotic hand has emerged as a versatile technology offering significant potential across a range of applications, from delicate object manipulation to prosthetics and industrial automation. Several designs of soft robotic hands have been developed using materials like elastomers, silicone, and flexible plastics, fabricated through processes such as molding [1] and 3D printing [2]. Many of these systems are actuated by pneumatic/ hydraulic drives, Shape Memory Alloy (SMA) or tendon drives. Several soft robotic gloves based on pneumatic actuation have been developed [3] [4]. However, since pneumatic actuation usually depends on tethered air styles are provided throughout this document and are compressors, its use in portable systems remains challenging. Shi et al. [4] designed soft robotic glove implementing soft pneumatic actuators made from elastomeric and inextensible materials, which conform to the user's hand (Fig.1(a)). The system is controlled using surface electromyography (sEMG) signals that detect muscle activation in the forearm, operating through an open-loop control system. Therefore, lack of feedback in the control system can lead to inaccuracies in response to varying levels of muscle activation. Hadi et al. [5] utilize Shape Memory Alloy (SMA) tendons to assist and rehabilitate hand movements. These SMAs contract when heated and return to their original shape upon cooling, mimicking natural muscle movements (Fig.1(b)). However, SMAs have a slower response time compared to other actuation methods, which may affect the speed of movement assistance. The repeated heating and cooling cycles of SMAs may lead to material fatigue over time, impacting the glove's longevity. Consequently, soft tendon/cable-driven mechanisms are gaining attraction due to their ability to combine flexibility with structural support, mimicking the dexterity and adaptability of the human hand. Hussain et. al. [6] utilized 3D printing to develop a modular soft prosthetic hand using a single motor and flexible joints (Fig.1(c)). However, controlling it solely by an

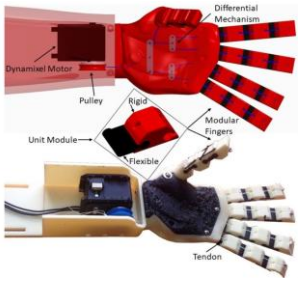
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(a) Soft pneumatic glove controlled through sEMG signals [4];



(b) Wearable glove driven by shape memory alloy [5]



(c) Tendon driven soft prosthetic hand [6]



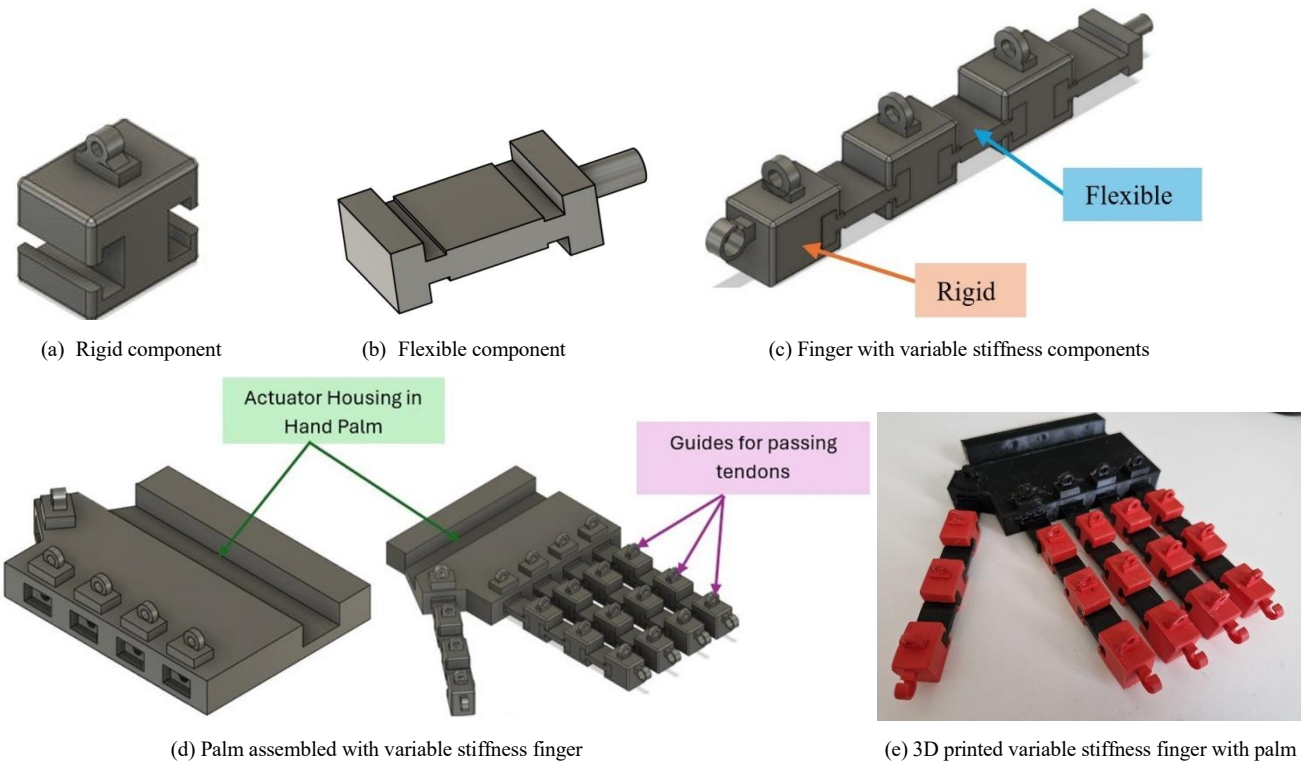
(d) Wearable soft exoskeleton combining rigid link structures with tendon-based mechanisms [7]

Fig. 1. Different types of Soft Robotic Hand/Glove

electromyography (EMG) sensor lacks reliability for handling complex tasks that might benefit from combining data from multiple sensors to achieve more accurate and comprehensive results. Bützer et. al. [7] developed a lightweight, fully wearable, actuated soft exoskeleton named RELab tenoexo to assist hand-impaired patients with grasping tasks in everyday activities. RELab tenoexo features a three-layered spring finger mechanism combining rigid link structures with tendon-based mechanisms (Fig. 1(d)), offering safety, adaptability, and multiple control options. However, it generates a maximum fingertip force of up to 6.4 N per finger, below the target of 10 N, affecting the secure grasping capability. Further advancements have focused on low-friction tendon routing and modular structures. Wang et al. [8] reviewed tendon-based actuators fabricated via additive manufacturing and highlighted the advantages of embedding sensing layers to enable closed-loop feedback. However, their survey primarily addresses component-level innovations and lacks validation in fully integrated systems for rehabilitation tasks. Patel et al. [9] proposed a 3D-printed tendon-driven robotic hand with anatomically inspired actuation and demonstrated improvement in adaptive grip across varied object shapes. Nonetheless, their prototype is limited to actuation bandwidth and does not incorporate real-time sensing or control mechanisms. Moreover, Goh et al. [10] presented a tendon-driven soft gripper with variable stiffness and integrated proprioceptive sensing, implementing multi-material printing for joint flexibility. While promising, their design focuses on open-loop control and is constrained to single-finger grippers, limiting its applicability in full-hand rehabilitation or assistive tasks requiring coordinated multi-finger motion. Recent developments have also focused on improving tendon routing and user comfort in wearable soft exoskeletons. Bagneschi et al. [11] proposed a tendon-driven soft hand exoskeleton featuring a novel lateral tendon layout that enhances glove stability by applying clenching forces during activation which reduces slippage and allows for a compact design. However, the embedded actuator adds bulk to the hand segment, which can reduce dexterity during tasks involving tight spaces or fine manipulation. Considering the current limitations of the existing tendon-driven soft robotic hand/glove, the purpose of this project is to design and develop a simplified variable-stiffness tendon-driven modular soft hand through 3D printing technique. The paper is organized as follows. In Sec. II, design and manufacturing of the developed tendon-driven soft robotic hand are presented. In Sec. III, actuator system and sensor integration are discussed. Sec. IV deals with the experiments performed to evaluate the proposed system, whereas in Sec. V, conclusion and future work are outlined.

II. Design and Manufacture

The tendon-driven soft robotic hand is designed with bio-inspired principles, mimicking the flexibility and dexterity of human hands. The variable stiffness of the robotic hand is achieved through the use of distinct 3D-printed materials: flexible NinjaFlex TPU85A for adaptability and rigid Polylactic Acid (PLA) for structural support. This design utilizes individual sections of harder PLA material for solid links in fingers and gripping surfaces whereas softer TPU sections are for joints. The combination of these materials offers a balance between strength and flexibility, allowing precise control over both grip force and adaptability.



(a) Rigid component (b) Flexible component (c) Finger with variable stiffness components

(d) Palm assembled with variable stiffness finger (e) 3D printed variable stiffness finger with palm

Fig. 2. Structural Framework of the tendon-driven soft robotic hand

A. *Material Properties and 3D Printing Parameters*

NinjaFlex TPU85A, a thermoplastic polyurethane, which provides the required compliance and flexibility [12]. The low elastic modulus (15.2 MPa) of the material allows the flexible parts to undergo significant deformation without breaking when stress is applied, enabling the soft hand to bend and conform to objects of various shapes and sizes. In contrast, the rigid parts of the hand are printed using Polylactic Acid (PLA) is used for segments that require structural support and stability, such as the tendon attachment points [13]. The Shore hardness of NinjaFlex TPU is 85A, ensuring a soft, rubber-like feel, whereas PLA has a Shore hardness of 77D, providing a harder and more durable structure. The material properties and 3D printing parameters are shown in Table I.

TABLE I. TABLE TYPE STYLESMATERIAL AND 3D PRINTING PARAMETERS

Properties	Flexible part	Stiff part
Material type	***Ninjaflex-Thermoplastic polyurethane(TPU).***	***Polylactic acid (PLA)***
Modulus of elasticity (E)	15. 2 MPa.	3500 MPa
Shore Hardness	85A	77 D
3D printing infill density percentage	20%	20%
3D printing layer height	2mm	2mm

The soft robotic hand's components are manufactured using an Ultimaker S5 Fusion Deposition Model (FDM) 3D printer. The chosen 0.2 mm layer height and 20% infill density for both materials provide an optimal balance between flexibility and strength. These parameters ensure that the flexible parts can bend and deform under stress while maintaining durability, and the rigid parts retain sufficient strength to hold their shape under operational loads. The FDM process enables precise control over the printing process, allowing the creation of detailed structures with varying stiffness throughout the robotic hand [14].

B. *Structural Framework of the soft robotic hand*

The structural framework of the modular soft robotic hand, as illustrated in Fig. 2, consists of multiple modular components. The rigid components of the robotic hand are designed to ensure smooth tendon movement and reduced friction. The tendons are guided through a top-mounted hole to minimize friction and wear (Figure 2(a)). Following the bioinspired architecture of the human finger (Fig. 3) [15], all three joints (MCP, PIP and DIP) are replaced with flexible components (Fig. 2(b)) to deliver similar movements.

The flexible components are designed with rectangular ends to simplify the 3D printing process and improve the connection between components. The palm of the 3D-printed gripper is fabricated using 85% TPU with 20% infill to facilitate bending and flexion. One finger is offset at a 23-degree angle to act as a thumb, enhancing overall grip strength. The design also includes 4 mm diameter holes for securing the tendons and maintaining alignment during operation. Additionally, the flexible section

connection points feature 4 mm holes, acting as part of the finger-securing mechanism, which prevents detachment during dynamic movements (Fig. 2(d) and (e)). The detailed dimension of the soft robotic hand is shown in Table II.

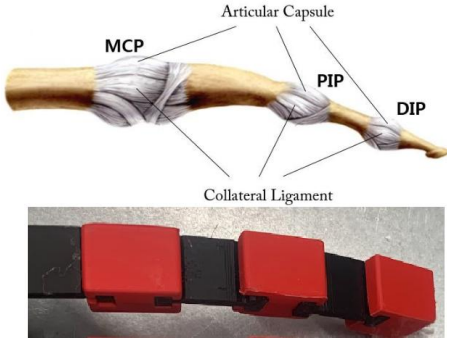


Fig. 3. Replication of human finger architecture

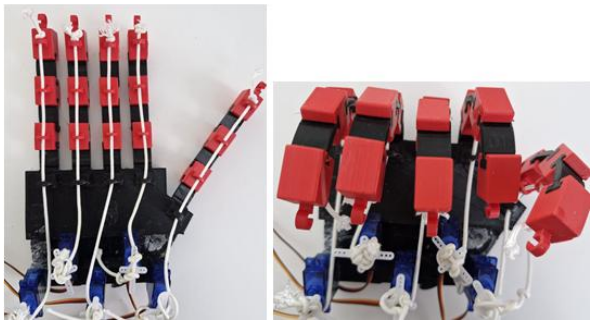
TABLE II. DIMENSIONS OF THE SOFT ROBOTIC HAND

Component	*Material*	*Dimensions (mm)*	*Infill*
Rigid Component	PLA	16 x 20 x 14	20%
Flexible Component	TPU	25 x 8 x 4	20%
Palm	TPU	80 x 105 x 15	20%
Tendon Hole (Palm)	TPU	Diameter 4	20%
Hook Piece (Finger End)	PLA	8 x 4.1	20%

III. ACTUATOR SYSTEM AND SENSOR INTEGRATION

A. Actuator System

The actuation system of the robotic hand is driven by servo motors, with each servo motor controlling the movement of a single finger. The servos are connected to nylon tendons that run through the length of each finger, simulating muscle contraction when pulled by the servo motors. Five servo motors are mounted on the palm of the robotic hand and controlled by an Arduino Uno, as shown in Fig. 4. In this set-up 360-degree continuous servos are used with the control of the pulse width modulation which allows the fingers to either fully bend or extend as shown in Fig. 4.



(a) (b)

Fig. 4. Tendon-driven soft robotic hand actuation system with nylon tendons and servo motor connections: (a) extend; (b) bent.

B. Sensor Integration and Operation

The sensor integration within the actuation system of the tendon-driven soft robotic hand allows for versatile control by utilizing flex sensors and force sensors, as illustrated in the process flow diagram (Fig. 5). These sensors work together to provide feedback on the hand's movement and grip strength, making it adaptable to various tasks. The flex sensor can measure the bending angle while the force sensor detects the amount of pressure applied to objects during gripping. The sensors are connected to an Arduino microcontroller, which processes the sensor signals and determines output commands for the five servo motors. The circuit is also designed to safeguard the function and maintain consistent performance.

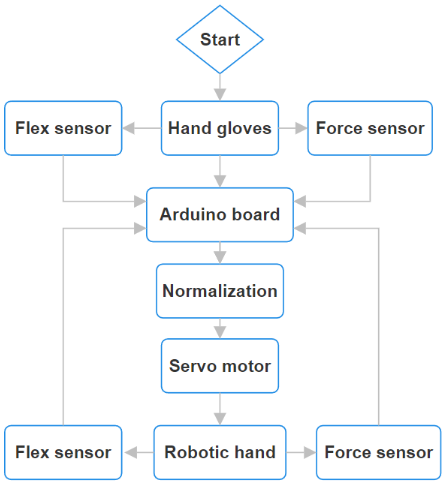


Fig. 5. Process flow diagram

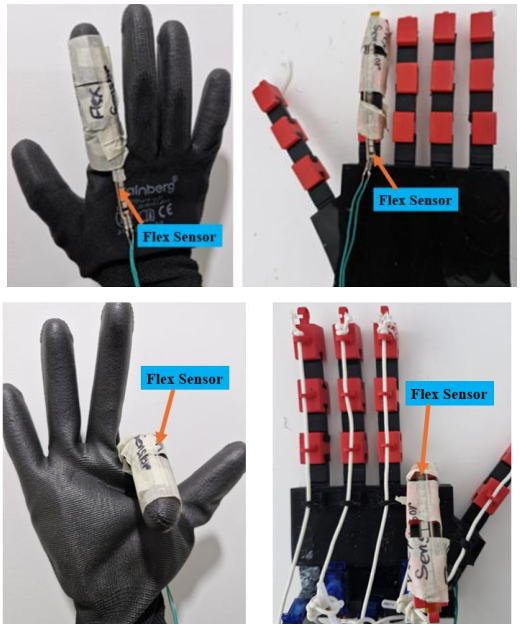


Fig. 6. Bending angle testing of glove and soft robotic hand

IV. EXPERIMENTAL TESTING

A. Performance on bending angle

In this section, experimental testing is set up to evaluate the behaviour of a soft robotic hand when integrated with a glove. The test will show the flex sensor's response attached to the soft robotic hand and compare its performance with that of the glove. The sensor placement is shown in Fig. 6, where it was strategically positioned to capture the bending angle. Both sensor data are recorded through the Arduino board. The comparative analysis between the glove finger and the robotic finger is shown in Fig. 7.

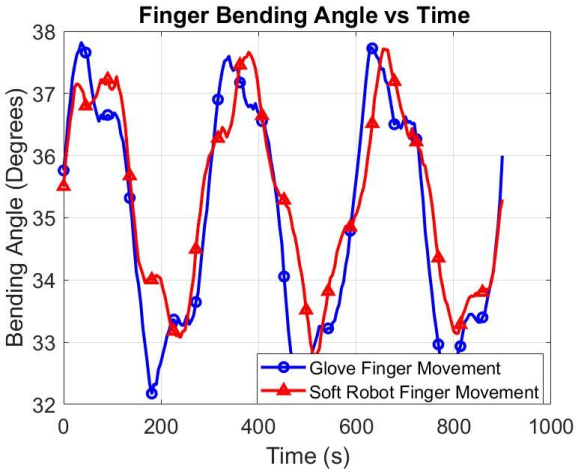


Fig. 7. Comparison between glove finger movement and soft robotic finger

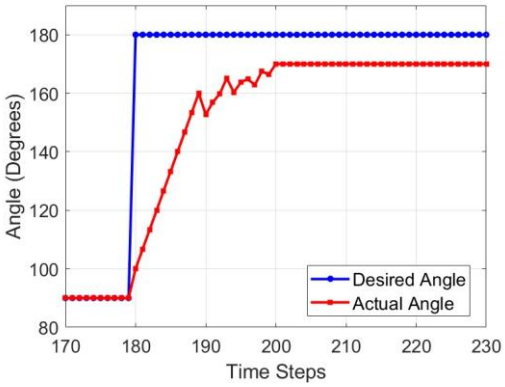
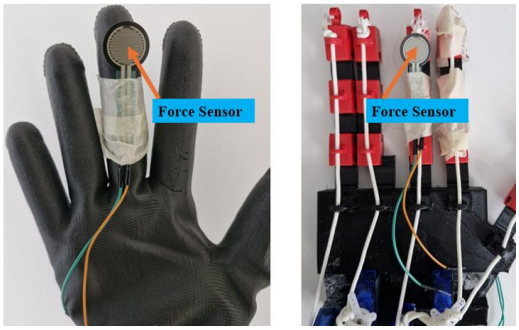


Fig. 8. Comparison between glove finger movement and soft robotic finger

In Fig. 7, the glove finger movement (blue line) demonstrates relatively smooth periodic variations with visible peaks and troughs, capturing the natural dynamics of finger flexion. The peak bending angle of the glove finger reaches approximately 38°, reflecting the full range of motion during flexion. The soft robotic finger (red line) closely tracks this pattern, showing comparable fluctuations in bending angle, with peak values approaching 37.5°. This close alignment highlights the dynamic responsiveness of the soft robotic system in replicating human-like movement. Despite minor deviations due to structural stiffness and mechanical constraints, the overall tracking accuracy supports the system's suitability for assistive and rehabilitative applications. Fig. 8 illustrates the behaviour of the robotic finger's movement demonstrating both the desired and actual angles over time. The desired angle is derived from the flex sensor input and represents the target position for the finger's flexion. The actual angle shows how well the robotic hand follows the desired input. Initially, both angles are stable at 90 degrees, but the desired angle exhibits a sharp increase to 180 degrees, simulating a rapid command for full flexion. The actual angle follows more gradually, with fluctuations as it approaches the desired value due to the lag in the servo motor's inertia and system dynamics. Eventually, the actual angle stabilizes just below the desired value.

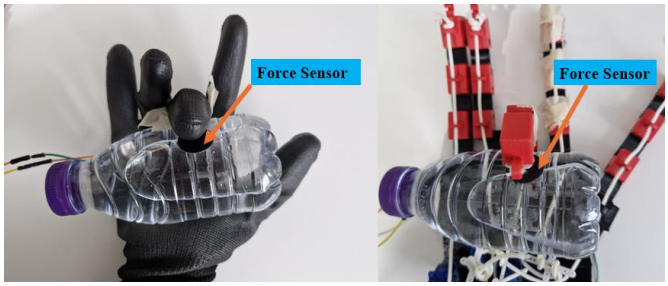
B. Performance on gripping force

In this section, we describe the behaviour of gripping force in the soft robotic hand. The tests were designed to measure the force sensor's response to gripping force for both the glove finger and soft robotic finger. The sensor placement is shown in Fig. 9 (a) and (b) respectively at the fingertip to capture the forces exerted during gripping tasks.



(a) (b)

Fig. 9. Force sensor placement (a) glove finger; and (b) soft robotic finger.



(a) (b)

Fig. 10. Gripping a water bottle (a) glove finger (b) soft robotic finger.

The gripping force exerted by the glove finger and the soft robot finger is plotted in Newtons (N) over time in Fig. 11. Initially, both systems exhibited relatively high force levels that gradually decreased and stabilized. The glove finger movement

demonstrated higher peak forces with subtle oscillations due to the natural compliance and muscle involvement of the human finger. In contrast, the soft robotic finger maintained a slightly lower but more consistent force profile throughout the duration. This comparison underscores the robotic finger's ability to deliver sustained and controlled gripping force, which is essential for repetitive rehabilitation and assistive tasks.

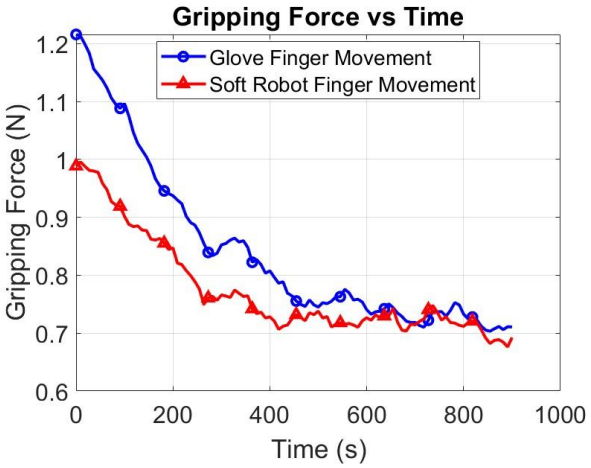


Fig. 11. Comparative analysis of gripping force for glove and soft robot finger.

V. Conclusion

The modular tendon-driven soft robotic hand has provided important insights into the design, control, and performance of soft robotic systems. By using the combination of rigid and flexible material, the hand was able to achieve dynamic movements that closely mimic the dexterity of a human hand. The experiments demonstrated the robotic hand's ability to respond effectively to real-time feedback from integrated flex and force sensors, allowing for precise adjustments in finger movements and grip forces. The joint design and tendon-driven mechanism provided smooth actuation, while the modular structure of the robotic hand allowed adaptability in various configurations. The performance of the prototype was validated through a series of tests that showed its ability to replicate human finger movements and grip pressures, confirming its potential for applications such as prosthetics, rehabilitation, and industrial automation. Several areas for improvement have been identified and will be addressed in future work. First, the thumb angle needs to be adjusted from 23 degrees to 40 degrees to better replicate human hand patterns, improving overall grip performance. Further design improvements will be focused on string tension for reliable actuation and lesser friction. Enhancing advanced sensor fusion techniques including force, flex, EMG (Electromyography) and IMU (Inertial measurement unit) will further refine the hand's adaptability. Moreover, future versions will focus on miniaturizing the actuation system and implementing wireless control to increase portability and suitability for wearable applications.

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