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**DESIGN AND PREPARATION OF
EXO-GLOVE WITH TACTILE SENSING**

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Declaration

We, Bekzat Azamatov, Yryskeldi Dinmukhamedov, Adilet Zhumabay, and Ali Oryn, hereby declare that this report entitled “Design and Preparation of Exo-glove with Tactile Sensing” is the result of our own project work except for quotations and citations that have been duly acknowledged. We also declare that it has not been previously or concurrently submitted for any other degree at Nazarbayev University.

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Abstract

Doing simple daily tasks gets difficult for people with hand impairments, and to solve this, many assistive devices have been developed. However, they are too expensive, heavy, complex, and difficult to integrate with reliable tactile sensing. Thus, to address these problems, this project develops a finger flexion and extension assistive exo-glove with integrated tactile sensors based on Triboelectric Nanogenerator (TENG) technology. The glove itself is simple to wear and is 3D-printed from SIL-30 silicone, which has strong mechanical properties, including high elongation and good flexibility during bending. For mechanical assistance, a compact tendon-driven screw-guided mechanism that converts motor rotation into linear displacement of the tendon guide for controlled flexion and extension was developed. In the case of tactile feedback, at the fingertips, a TENG sensor was incorporated, which was fabricated with conductive silver ink electrodes between two layers of silicone. The performance of the sensor was experimented with both manual and machine-controlled loading conditions. Voltage outputs during hand tapping were observed to rise and fall above 20 V and this represented a high response to natural touch interactions. The electrical output was both reliable in tracking applied force and contact frequency under conditions of 1-3 N static forces and during cyclic tests with a frequency of 1-3 Hz. Also, in real-time experiments with the built-in exo-glove system, it was observed that the processed signal of tactile sensation was steady in the no-contact condition and revealed a definite change towards higher values during finger-object contact. The signal consistently exceeded a predefined threshold, enabling reliable detection of grasp events and successful triggering of the motor stopping mechanism. In order to determine the mechanical properties of the silicone material 5 ASTM D12 Standard specimens were tested in a Universal Tensile Machine. The findings were an average of 2.08 MPa tensile strength at maximum and an average of 885% elongation at break meaning that the material is very elastic and flexible. In general, the findings indicate that a soft robotic glove can be effectively used to integrate assistive movement with TENG tactile sensing. The actuation system functioned properly, enabling finger flexion and extension. The glove was fully assembled, and both the glove design and the tactile sensor were found to be functional. These results highlight the potential of the exo-glove for practical and affordable use in the future.

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Chapter 1

Introduction

1.1 Overview of Hand Impairments and Exo-gloves

Hands are believed to be an essential part of human lives because they allow us to create and be independent. Loss or reduction in the hand's mobility significantly impacts a person's independence, which leads to a reduction in the person's quality of life, work abilities, and social life. Hand impairments are a significant global problem. The World Health Organization (WHO) estimates that more than 190 million people globally are impacted by hand impairments, and 2% of the population in Kazakhstan is affected [1]. These disabilities occur due to various causes such as stroke, spinal injuries, other physical traumas, and aging [2]. To address these issues, soft robotic engineers have developed tactile-sensing Exo-Gloves, wearable, lightweight devices designed to assist or restore impaired human hand functions and also provide tactile feedback [3]. In this regard, the goal of this research is to develop a soft Exo-Glove using silicone (SIL 30) with characteristics of being stretchable and highly flexible (can elongate up to 900%). The device also has TENG tactile sensors that provide feedback about the interaction and a linear actuation of the fingers to help their flexion and extension.

1.2 Existing exo-glove devices and limitations

With new developments in robotics, we are starting to think of rehabilitation and assistive technologies in a new way. Exo-Gloves, in particular, are becoming popular for providing hand mobility and independence. New prototypes are made with soft materials and tendon actuators to move fingers. They also have tactile sensors for the glove to sense and respond. For instance, the Exo-Glove Poly II, a wearable, lightweight device that allows people with weak hand muscles to grasp different objects. Users are able to grip and manipulate objects more easily due to its tendon-driven system [4]. And later, the upgraded model of this glove was introduced in the Exo-Glove Poly III, which had an enhanced thumb movement, making it easier to grip [5]. But despite these advances, Exo-Gloves still have some limitations:

- Limitations of Traditional Sensors

In many prototypes of exo-gloves, commercial or stiff sensors that are not designed for flexible robots are used. These sensors can be costly, brittle and are difficult to bend or conform to a moving, curved surface, making them difficult to incorporate into soft gloves that are in constant flux as a user's hand moves [6].

- Expensive and Complex Actuation Systems

Most of the existing exo-gloves adopt a pneumatic system for finger flexion and extension to achieve greater power output. But these types of actuation systems are unsuitable for daily use, as they can be bulky, expensive, and require maintenance.

- Ergonomic and High Production Issues

Although soft exo-gloves are designed to be comfortable, existing systems are often still difficult to manufacture and size, expensive, and difficult to don and doff. Certain systems do not have proper adaptation to different hand sizes and lack sufficient thumb movement to allow for a wide range of grasp types. While Exo-Glove Poly III improved the thumb's mobility, it still required careful placement of the actuators and tendon routing to ensure proper functionality, which increased the complexity and reduced the simplicity required for daily usage [5].

1.3 Triboelectric Nanogenerators (TENG) as tactile sensors

Triboelectric nanogenerators are self-sufficient tactile sensors that use the combination of electrostatic induction and triboelectric charge transfer to produce electrical output from physical contact. When mechanical contact or deformation takes place, this process allows the sensor to generate detectable voltage or current signals. TENGs provide an energy-autonomous option for wearable devices like soft exoskeletons and rehabilitation gloves, as opposed to traditional tactile sensors that need constant power input. The TENG tactile sensors in our project are specifically made with silver inks as the compliant conducting electrode and a soft silicone elastomer as the triboelectric layer [7]. Because of their good stretchability, biocompatibility, and strong electronegativity, silicone materials are the best triboelectric materials for this project. Silver electrodes, on the other hand, have great conductivity and flexibility, also they are conformable to curved hand surfaces, guaranteeing low performance loss while hand motion and finger bending [7]. The pressure during hand to object interaction can be measured and transformed into electrical signals so there will be no need for external power circuitry by incorporating several TENG sensors

into the exo-glove structure. This improves mobility and safety of the using person while also streamlining system integration. Then, TENG technology can detect both dynamic and low-pressure touch inputs, which is the same as the tactile feedback needs of hand rehabilitation applications where user-device coordination and grip monitoring are important [6].

1.4 Significance of the study

This research is especially relevant today, as more people around the world need practical and accessible hand rehabilitation and assistive solutions. Taking into consideration that millions worldwide, including the population of Kazakhstan, face issues related to hand impairments, any cost-effective solution may help to restore independence and promote improvement in the quality of life. Existing devices have a lot of drawbacks, such as being costly, difficult to manufacture, and having complex actuation systems. So, this paper is focused on overcoming these limitations by developing a self power, soft, cost-effective exo-glove made from silicone based on TENG tactile sensor and linear actuator. The proposed glove could therefore be a good fit for rehabilitation purposes and daily help, as it offers tactile feedback, good flexibility, and ease of use. This research can help to enhance the development of wearable robots and paves the way for more accessible, user-friendly assistive technologies for those with damaged hand function.

1.5 Engineering Ethics and Standards

Engineering Ethics

The Exo-Glove with tactile sensing was developed considering key engineering ethics such as user safety, biocompatibility, and reliability of the system.

- Safety and Protection of the user

The Exo-Glove is developed in such a way that it can work safely without causing any injuries, high pressure, or pain. This was realized by focusing on the minimization of forces applied, ergonomic designing, and safe electrical functioning.

- Biocompatibility

Because the device will be in contact with the skin, it is made of non-toxic and skin-safe materials, like silicone (SIL 30) which will not cause any allergic reactions.

- Reliability

The TENG tactile sensor is designed to provide accurate and reliable feedback.

Engineering Standards

The silicone material (SIL 30) used in the Exo-Glove is tested for the mechanical properties according to ASTM D412. This is the standard used in measuring the tensile strength, elongation, and elasticity the material can undergo ductile deformation over time for use.

Chapter 2

Literature review

2.1 Hand Impairments and Rehabilitation Needs

Impairments of hand function are one of the most debilitating outcomes of neurological diseases, especially stroke, and severely impact on the ability to complete everyday tasks. Stroke is one of the major causes of chronic disability globally, with many survivors exhibiting upper-limb deficit, such as reaching, grasping and fine manipulation of the hand [8]. This has a profound effect on activities of daily living (ADLs), affecting independence and quality of life.

Hand motor impairments have been shown to include weakness, coordination and voluntary control of finger movements. Sensory deficits further impact function, and are often present in patients. As recent research has reported, hand impairments following stroke can result from a combination of motor and sensory dysfunction, and can reflect the complex nature of upper-limb dysfunction [9].

Neuroplasticity, which refers to the capacity of the brain to reorganise and develop new connections following injury, is crucial to recovery of hand function. Current rehabilitation strategies seek to activate these mechanisms with task-specific repetitive training. As shown in *Figure 1a* [10], neuroplasticity encompasses structural and functional reorganisation on various levels, such as synaptic changes, axonal sprouting and cortical network reorganisation. These mechanisms allow for limited recovery of motor function through compensation for injury.

But spontaneous improvement is not complete. Even after rehabilitation, many people still have severe hand dysfunction, including difficulties with fine motor skills and grasping. The main constraint of current rehabilitation approaches is that they focus only on motor training, ignoring sensory feedback. Recent research indicates that sensory feedback, particularly tactile feedback, is vital for motor recovery through its role in supporting sensorimotor integration and activating areas in the brain responsible for motor control [9].

The role of sensory feedback is also underlined by experimental studies that report an increased cortical activity together with functional connectivity in patients after stroke when using tactile feedback. *Figure 1b* [9] illustrates the experimental approach, where tactile feedback is used in grasping tasks and results in changes in brain activation in the motor and prefrontal cortex areas. This finding confirms that motor recovery is not only related to motor repetition but also to sensory integration.

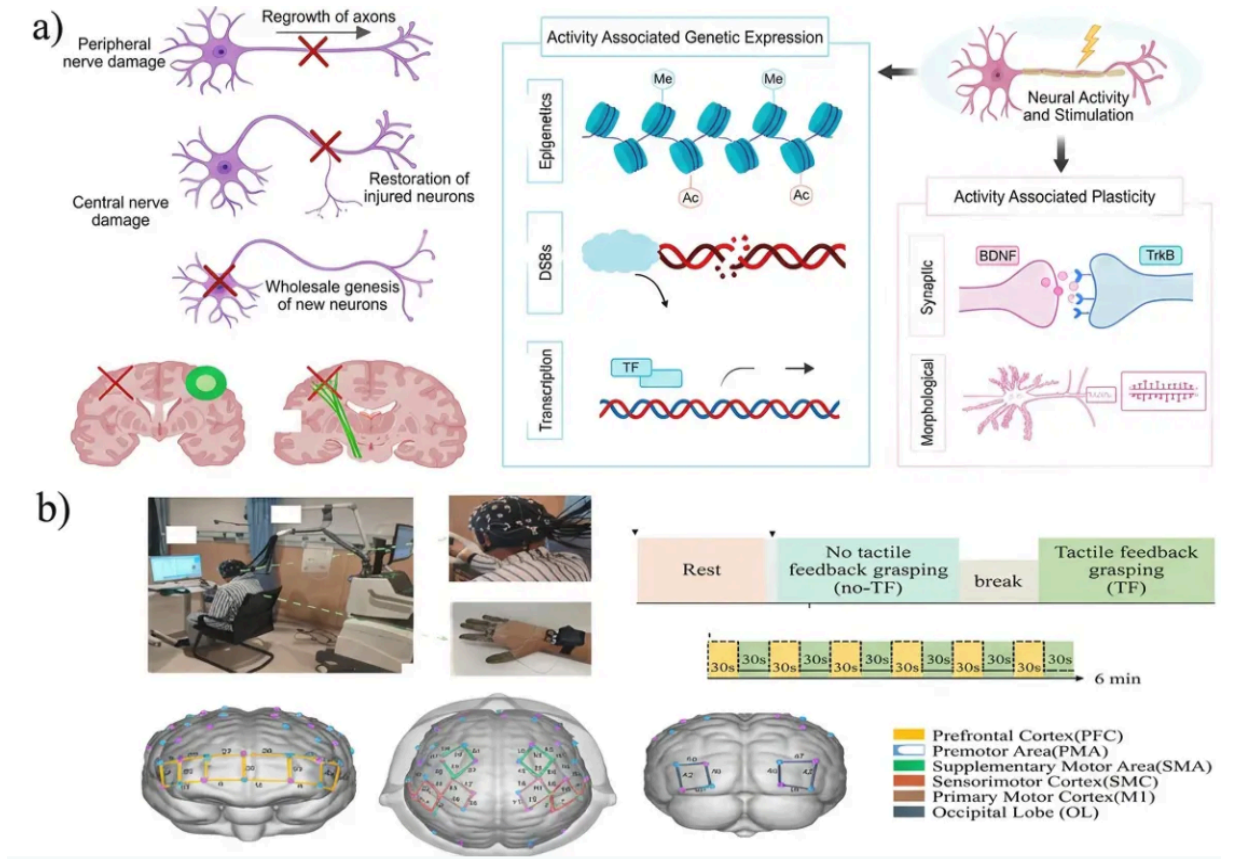


Figure 1. (a) Mechanisms of neuroplasticity following neural injury; (b) Experimental setup and brain activity measurement during tactile feedback-based hand rehabilitation.

A further key issue in rehabilitation is the efficiency of the therapy. Current rehabilitation therapy involves intensive, therapist-supervised training, and is time-consuming and costly. Recent studies have stressed the need for technologies that facilitate continuous, intensive, and task-specific training, while being affordable and reducing the overall cost of health care [Ritz]. Wearable and robotic rehabilitation technologies have been suggested as a way to overcome these challenges and deliver training and feedback.

Moreover, existing rehabilitation technologies still lack the capability to provide natural and informative sensory feedback. As highlighted in [8], many robotic devices do not provide sufficient somatosensory feedback to effectively simulate natural hand interactions. This is highly significant since normal (motor) hand function involves an ongoing interaction between sensory and motor processes.

Overall, motor and sensory dysfunctions, which both need to be improved to restore hand function, work together to produce hand impairment following stroke. Current rehabilitation methods offer limited benefit, but recent studies have shown that motor and sensory feedback are both required for successful rehabilitation. This requirement has spurred recent advances in

assistive technologies, including soft robotic exo-gloves and tactile sensing devices, to improve motor skills and interactions.

2.2 Exo-Gloves as Rehabilitation Devices

Robotic hand exoskeletons and exo-gloves have been proposed to assist repetitive and controlled finger movements to overcome existing limitations of traditional rehabilitation. Such systems allow for prolonged training, which is critical for motor rehabilitation, and minimise the need for therapist-led training [11].

The initial hand exoskeleton designs were mainly rigid devices that required joint alignment with the human hand. As shown in *Figure 2* [11], various mechanical designs including linkages, tendon-driven mechanisms and joint-aligned structures have been developed to replicate human finger movements. But these rigid structures can result in discomfort, misalignment, and limited natural motion, which can be problematic for wearable devices.

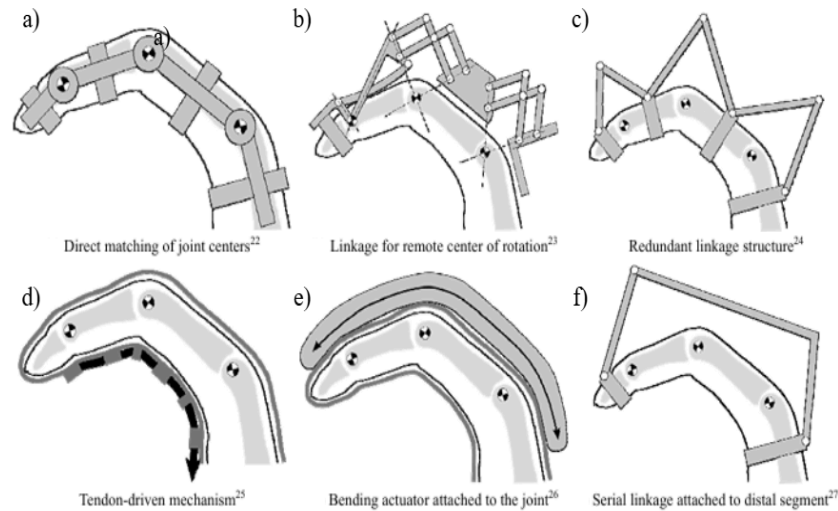


Figure 2. (a–f) Different mechanisms for reproducing finger joint motion in hand exoskeleton devices.

To address these issues, soft robotic exo-gloves have been developed. A prominent concept in wearable robots is tendon-driven mechanisms. This allows light weight design, and to transmit the forces to the user's hand remotely, which decreases the effort of the human hand. Baik et al. developed the tendon-driven haptic gloves that can deliver the kinesthetic and cutaneous feedback. They showed that the combination of the types of feedback enhances human perception over using kinesthetic feedback only [12].

Similarly, Gerez et al. also worked on tendon-driven exo-gloves to enhance the grasping performance. They emphasise the importance of underactuated and compliant systems which can simplify the system yet keep its functionality. They demonstrated that the low cost and low complexity solutions can also help to increase the grasping force.

Another major direction in the field of soft-robotic gloves is the elastomeric materials based actuation systems. These types of devices employ soft actuators and compliant structures to help move the fingers. The design of the soft robotic glove in [13] uses fluid-actuated fiber-reinforced elastomeric actuators to produce bending. As depicted in *Figure 3b* [13], the actuator design uses elastomeric structures and reinforcement layers to regulate deformation, allowing programmable movements (e.g. bending and twisting). This enables the actuator to replicate human finger motion while being safe to interact with and having a low stiffness.

Moreover, the system design of soft exo-gloves prioritises portability and user-friendliness. As shown in *Figure 3a* in [13], the actuators are placed on the back of the hand, allowing the user to interact with the object from the palm. Sensors and control units are also integrated in a portable set up, allowing for assistive and rehabilitation at home.

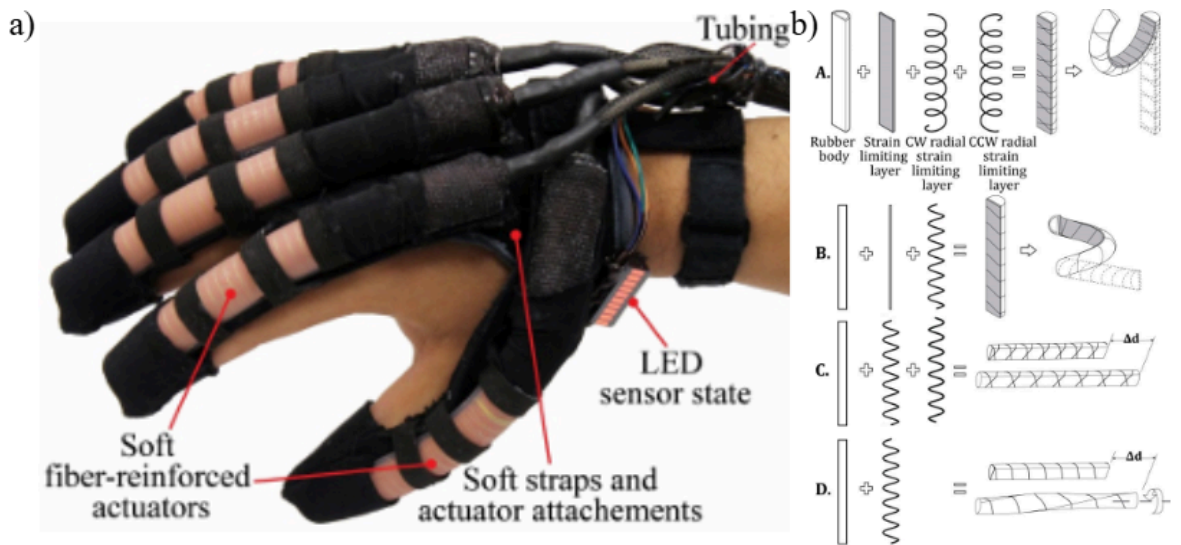


Figure 3. (a) Soft robotic exo-glove with fiber-reinforced actuators; (b) Structural configurations of soft pneumatic actuators.

The other key innovation is variable-stiffness soft pneumatic exoskeletons. In the device shown in [14], the stiffness of the actuator can be varied along the finger. As you can see in *Figure 4* [14], adjustable stiffness along the actuator enables it to better conform with the finger's natural joint bending during movement. It allows the device to assist with various

rehabilitation tasks, such as full fist, hook fist and pinch grasp, as shown in *Figure 4* of the paper. This flexibility is essential for individualised rehabilitation and enhanced accuracy.

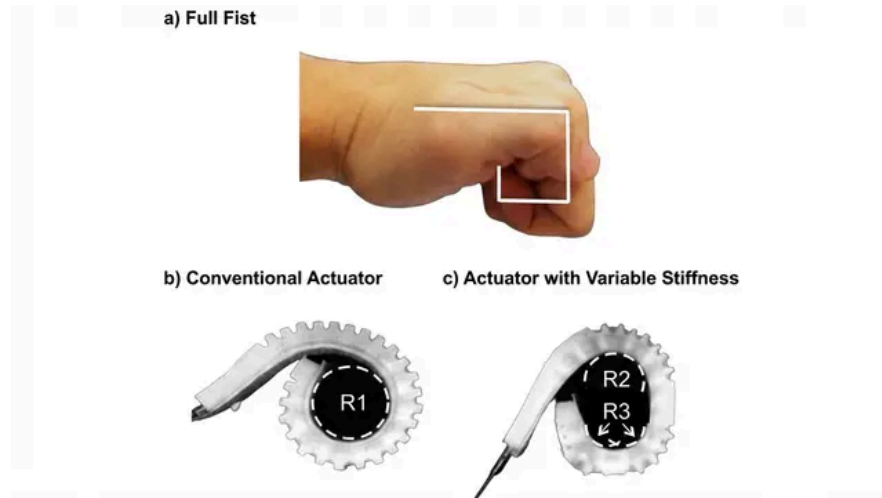


Figure 4. (a) Full fist motion; (b) conventional actuator bending profile; (c) actuator with variable stiffness.

However, there are still some issues. Although soft exo-gloves enhance safety, comfort and wearability, current systems largely concentrate on motion assistance, neglecting the importance of sensory feedback. This prevents users from perceiving contact force, and adjusting grasping force during tasks. This limits the effectiveness of rehabilitation tasks because the human hand has to combine both motor control and tactile feedback for natural hand function.

Thus, while exo-gloves offer an effective means of providing assistance for hand motion and performing repetitive rehabilitation, it is necessary to supplement these systems with tactile sensing. This makes the integration of new types of sensors, such as triboelectric nanogenerators (TENGs), an important development, which will be explored next.

2.3 TENG Sensors as Sensing Elements

TENGs are a new type of self-powered sensor, capable of converting mechanical energy into electricity. TENG sensors are different from traditional sensors that rely on an external power source: they are based on the combination of contact electrification and electrostatic induction, and can serve as both energy harvesters and sensors [15] . This makes them

well-suited for wearable and rehabilitation devices where energy efficiency and continuous operation are crucial.

The operation principle of TENGs is shown in *Figure 5* [16]. Contact electrification occurs when two materials with different triboelectric characteristics are brought together, resulting in opposite charges on their surfaces. When they are separated, an electrical potential difference is generated, resulting in electron transfer through an external circuitry. This allows for the conversion of mechanical energy (like pressure or strain) into electrical energy. In *Figure 5* (c-d) [16] the device generates different outputs under open- and short-circuit conditions, which can be employed for sensing applications.

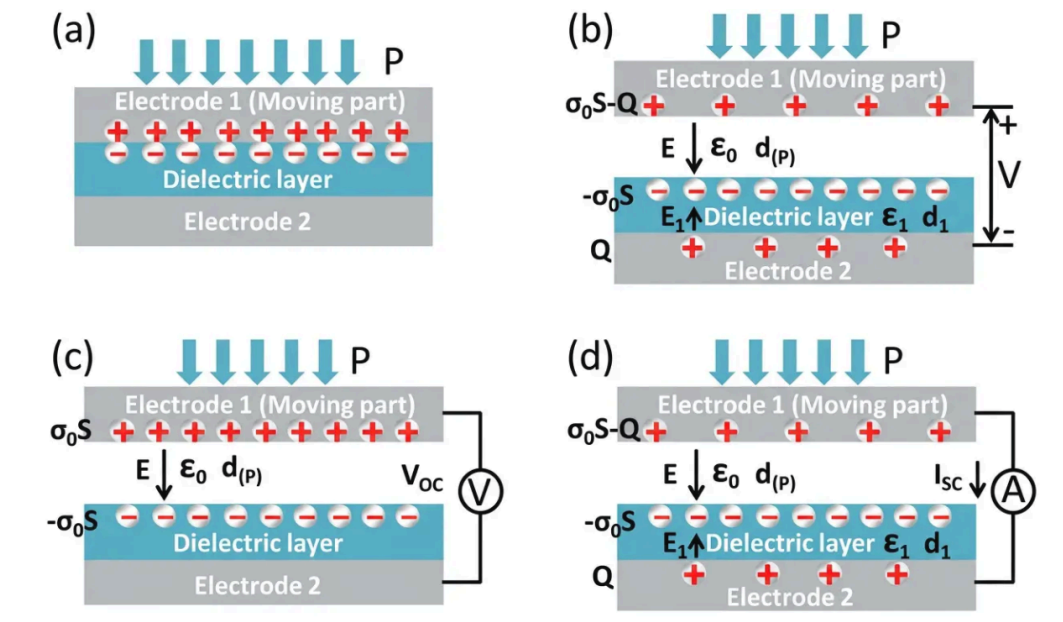


Figure 5 (a–d). Working mechanism of a triboelectric nanogenerator showing charge generation, potential difference, and electrical output under contact and separation.

Theoretically, TENGs can be viewed as a capacitive system where the output is dependent on the transferred charge, capacitance and gap distance. As explained in [17], the electrical performance of TENGs can be described by a voltage-charge-displacement (V - Q - x) relationship, which shows the electrical response is affected by the mechanical input. This dynamic connection between mechanical strain and electrical output allows TENGs to be used as pressure, motion and tactile sensors.

Apart from their operation principle, there are also several merits of using TENGs as sensors in wearable systems. As depicted in *Figure 6* of [18], flexible triboelectric sensors can be used for wearable devices to track human movement and bio-signals. They are often

lightweight, flexible and compatible with soft materials, allowing for their integration into wearable systems like exo-gloves. Also, they are sensitive to small displacements and can produce different electrical output signals for various motion patterns, making it possible to monitor hand movements.

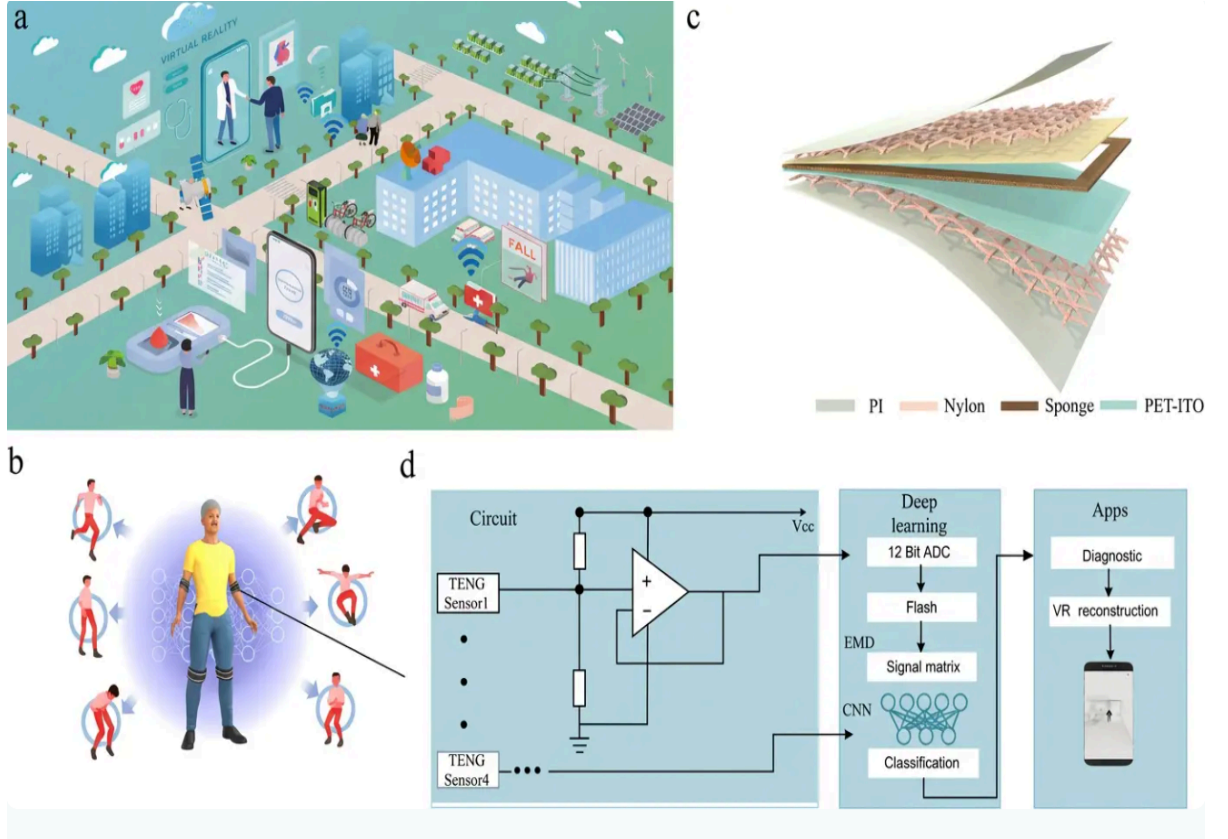


Figure 6. (a–d) Architecture of a triboelectric sensor-based system for human motion monitoring and healthcare applications.

TENG pressure sensors also have high sensitivity and large sensing ranges, essential for tactile sensors. In [16], it's reported that the sensing performance of TENGs can be improved by fine-tuning material properties, microstructures and device structures. The device design is crucial for enhancing sensitivity and output signal quality, leading to the detection of low pressures.

However, TENG sensors also have some limitations, including unstable signals under different environmental conditions and high output impedance. But recent efforts have been directed towards material development, structure design and signal processing to address these issues.

In summary, TENG sensors offer a unique combination of self-powered, high sensitivity and flexible characteristics, which make them an ideal candidate for wearable rehabilitation systems. Their capability to directly generate electrical signals from mechanical interaction makes them a promising choice for incorporating into exo-gloves to provide real-time tactile feedback and improved interaction.

Chapter 3

Methodology

3.1 System Overview

This paper focuses on the design, manufacturing and testing of the soft-assistive device with TENG-based sensors for tactile sensing. The system has two major tasks: (1) assisting finger motion and (2) sensing the interactions with the environment.

The glove system is made up of three main subsystems: (1) a soft silicone glove to mimic the motion of the fingers, (2) a mechanical actuation system for converting the rotation of the motor into the linear movement of the nut which pulls the tendon, and (3) TENG-based tactile sensors embedded in the fingertips of the glove. The subsystems are integrated to work as a soft wearable system that assists the closing of the hand and senses the interactions.

Figure 7 shows the integrated design of the exo-glove system, featuring the main components. The wearable silicone glove fits the user's hand, assisting with natural finger movements, and tendon-driven structures are embedded along the fingers to receive actuation. The actuation unit on the forearm translates motor motion to tendon movement, facilitating finger flexion. Furthermore, TENG sensors are incorporated at the fingertips to offer tactile sensing through contact and interaction forces. This setup enables the system to assist hand movements and sense the interactions with the environment simultaneously.

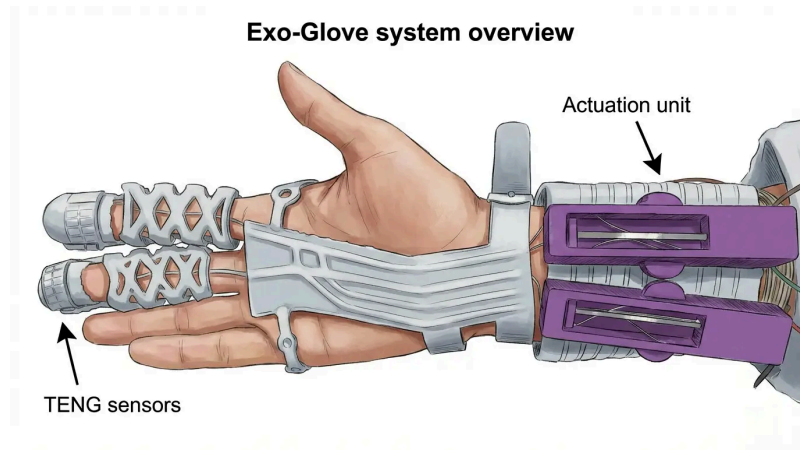


Figure 7. Exo-Glove system overview.

3.2 Exo-Glove Design and Development

3.2.1 Exo-Glove Designing Process

In order to design the assistive glove, first we have studied the literature. Soft assistive gloves can be designed with several different types: pneumatic gloves, tendon-driven gloves and electroactive gloves. Here, a tendon-driven mechanism has been used for the actuation of the assistive glove. The tendon-driven mechanism has several advantages: it allows the natural finger movement, allows for effective force transmission [19], and allows for compactness [20]. These features make the tendon-driven approach very popular in the area of wearable robotic gloves and rehabilitation [21].

The CAD design (SolidWorks) is used for the geometry design of the glove. Throughout the research, it has been decided that the glove will have the index and middle parts as well as the possible installation of the thumb part, since the grasping movement is only needed for the index and middle fingers. The finger part is the most critical and complex design among all of the parts because the finger part is the most active part. The finger part has been designed using an iterative process (*Figure 8*). In the first version (*Figure 8a*), the finger module was designed as a segmented structure with equal segments along the finger. In the next design (*Figure 8b*), the diamond pattern was incorporated into the top part of the design to enhance wearability of the glove. The inner and outer diameters of the tunnels for tendons have been increased to avoid problems during the printing.

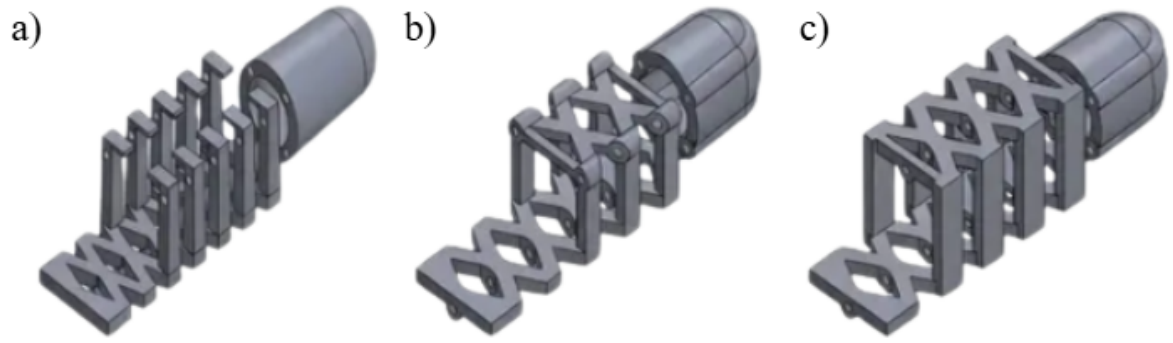


Figure 8. Finger design development a) Initial finger design; b) Improved finger design; c) Final finger design.

The final design (*Figure 8c*) consists of a diamond-shaped pattern, which gives better stretching and bending for fingers. That type of pattern repeated from the top and bottom sides of the design. This structure replicates the natural human finger arc and can bend smoothly under the tendon-driven system work. Also, the diamond-shaped pattern allows to decrease the mass of the glove, to improve airflow [20], and it is effective in minimizing hand sweating. That open-cell design gives good structural strength while remaining comfortable to wear. In soft robotic systems, the flexible patterns that are capable of bending and maintaining its structural integrity are a common approach [21].

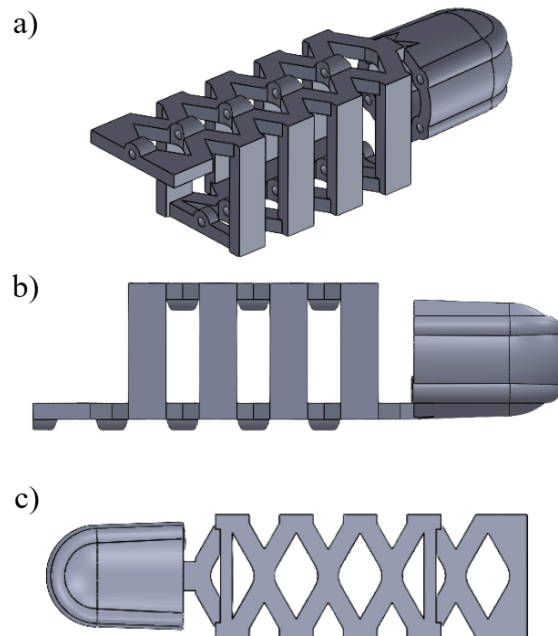


Figure 9. a) Isometric view of finger design; b) Side view of finger design; c) Top view of finger design.

Following the finger design, the design of the glove, including the palm parts, has been completed. Glove architecture is focused on manufacturability, wearability, and compatibility with actuation systems. As shown in *Figure 10a*, the glove is divided into 4 parts, which are assembled together in one glove capable of flexion and extension. Due to the elongated geometry of the glove and the size limitations of the 3D silicon printer, the glove design has been divided into multiple segments. That not only avoids scaling the design down, but it can also be beneficial to change the specific part of the glove if one of the parts is damaged. Easy maintenance and part replacement are very important for our exo-glove design [22].

The glove structure consists of the index finger, the middle finger, the outside part top, the outside part bottom, the inside part top, and the inside part bottom. The finger parts are connected to the outside top part, in that way, the tendon routing for extension can be assembled in the right way, as demonstrated in *Figure 10a*. Each top component connects perfectly with its bottom component through alignment slots and bonding surfaces. In addition, the glove design has places for magnet implantation. Magnets are used to easily secure the glove around the palm. That type of rapidly wearable mechanism is often used in the assistive gloves [23]. For the fixation of the exo-glove around the wrist, a watch straps like structure has been designed. *Figure 10a* clearly shows how separate segments interlock into one complete structure.

The tendon routing is one of the essential parts in the glove design, the previous studies have shown that the tendon configuration significantly impacts the motion accuracy and system performance [24]. Inspired by biomechanics of the human hand, the tendons were placed

along the glove in order to create the controlled movement, as shown in *Figure 10b*

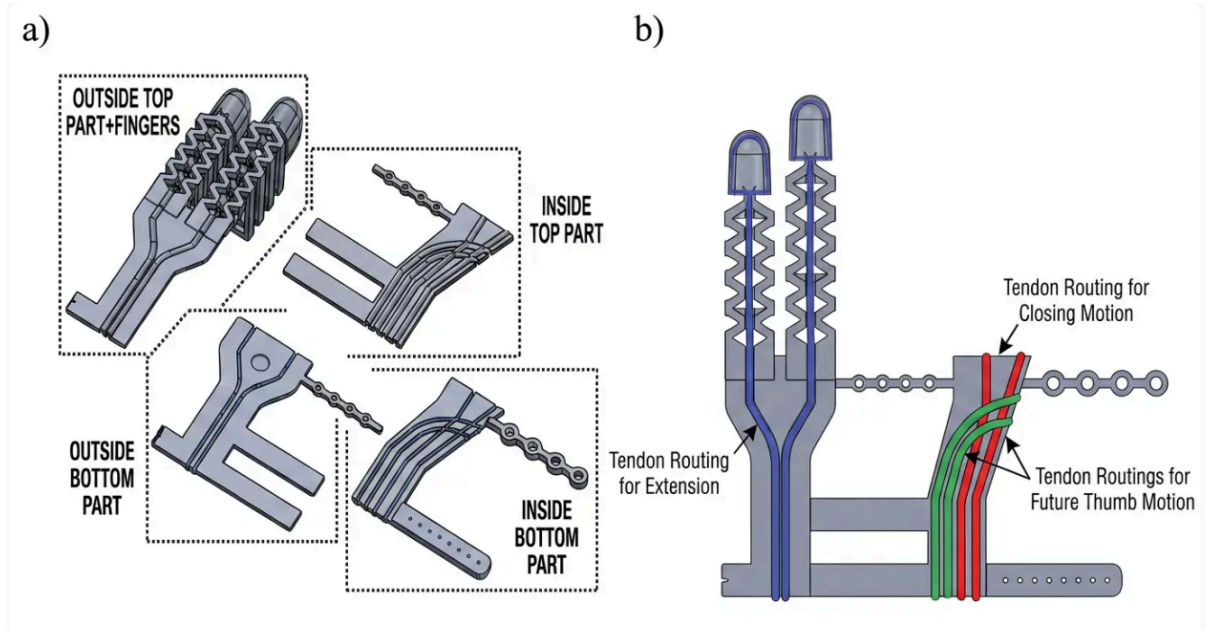


Figure 10. a) Exploded view of the glove main body assembly, b) Glove main body design.

3.2.2 Fabrication of Exo-glove

Silicone was selected as the primary material for Exo-Glove due to its stretchability, durability, and tactile transmission properties. Silicone is a widely used material in soft robotics applications because it can deform easily while maintaining structural integrity [25]. In this project, silicone provides a safe and comfortable interaction with the human hand, allowing natural finger movement and long-term use. Additionally, the ability of silicone to resist environmental factors (temperature and moisture) makes it suitable for biomedical applications [26]. Silicone is an effective material for accurate pressure and contact forces detection during interaction with objects [27].

To fabricate the Exo-glove, the S300 Silicone 3D Printer was used, which is shown in *Figure 11b*. This printer operates based on fluid additive manufacturing. It has two nozzles. One nozzle prints the overall design of the object, while the second one prints the support for that object. They move independently, which prevents their collision.

As shown in *Figure 11a*, the process starts from the calibration of nozzles to ensure accurate material flow and later proper curing. At first, the finger part of the glove was 3D printed, as the sensors are first integrated onto the fingertips. After calibration, the design is sliced, converting the 3D model into layer-by-layer instructions. Following the slicing, the flow rate of the silicone is adjusted to properly print the design, as it directly affects the quality of the

printed design. At first, some printed designs failed. To solve this issue, the configurations were changed in the slicing process. Then, it is printed for approximately 6-7 hours. Finally, it is cured 3 times in a Drying Oven, which is shown in *Figure 11c*, at 50°C, 80°C, and 130°C for 4, 2, and 2 hours, respectively. The support is removed by washing the printed object.

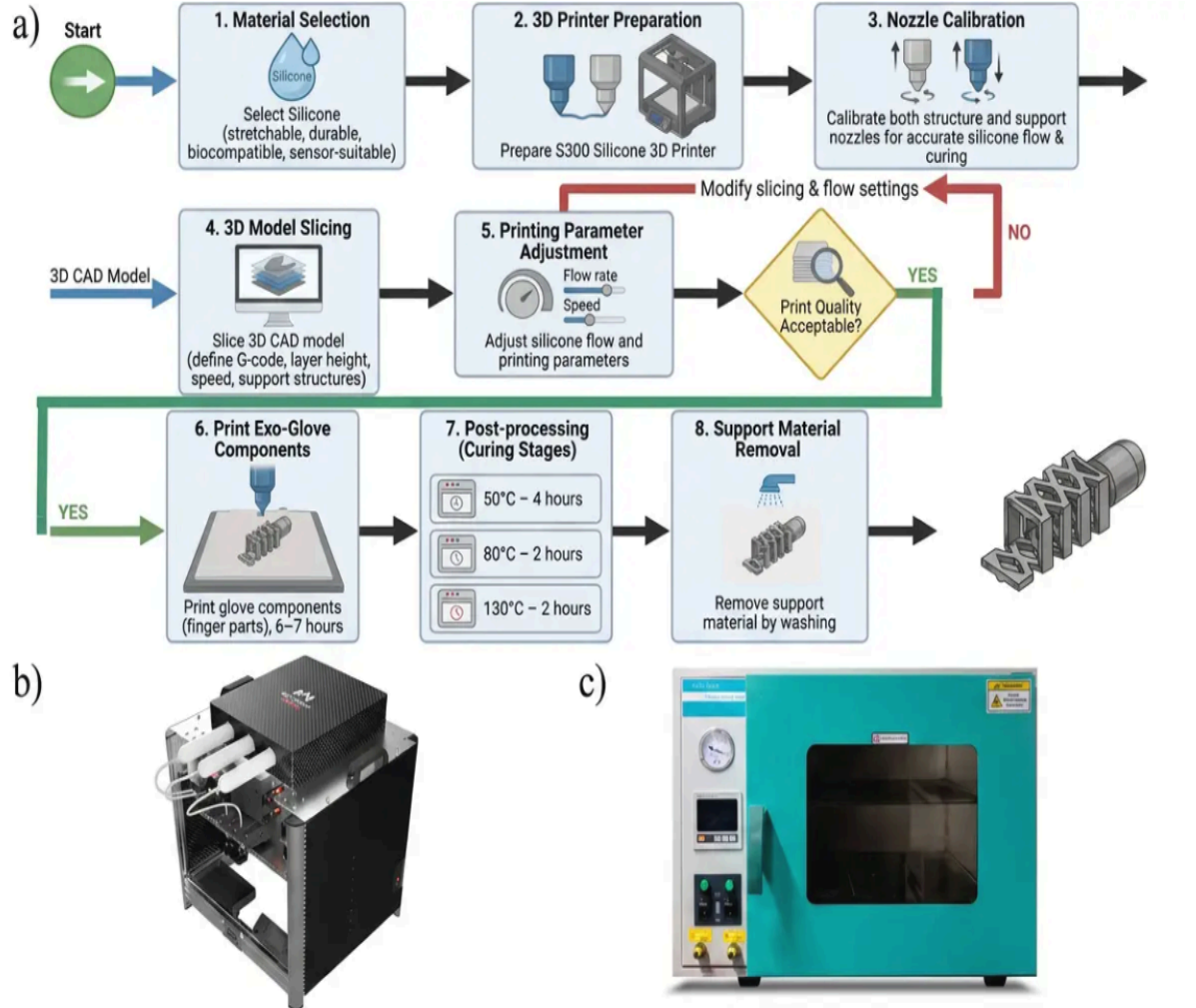


Figure 11. Fabrication Process and Equipment for Silicone-Based Exo-Glove Production: a) Process Workflow, b) Silicone 3D Printer, c) Curing Oven.

3.3 Actuating System Design

3.3.1 Design Overview

Aiding finger flexion and extension is one of the main functions of our exo-glove. To implement this, a screw-guided twisted tendon mechanism was developed, which is shown in *Figure 12* below. To make the system cost-effective and compact, fewer components are used. As shown in *Figure 12*, it consists of a motor with a screw, a nut with its casing, a

bearing with a bearing collar, a motor case, and tendons. Each component is vital and has its own purpose. The tendons are passed through the holes of the nut and are tied. The action starts from the motor. As the motor rotates the screw, it will generate the linear motion of the nut, and eventually, the tendons are flexed or extended. Here, the motor casing consists of the upper casing and the bottom casing. They are fastened together, and their inner surfaces constrain the nut casing from its coupled rotation with the screw. The bearing is used for supporting the screw and its smooth rotation by reducing friction. The bearing collar is used to lock the bearing on the screw. The motor's rated load torque is 0.1 kg/cm, and its speed is 2400 rpm, so they should be sufficient to linearly displace the nut. Our system will have 2 of these actuation units. They will be placed vertically on the forearm using the armband. In this actuation system, the motor with the screw, the bearing, and the tendon are purchased. The motor casing, the bearing collar, and the tendon guide are manufactured using a 3D printer with PLA filament. The bearing is inserted by a press fit, and all components are assembled into the printed motor casing.

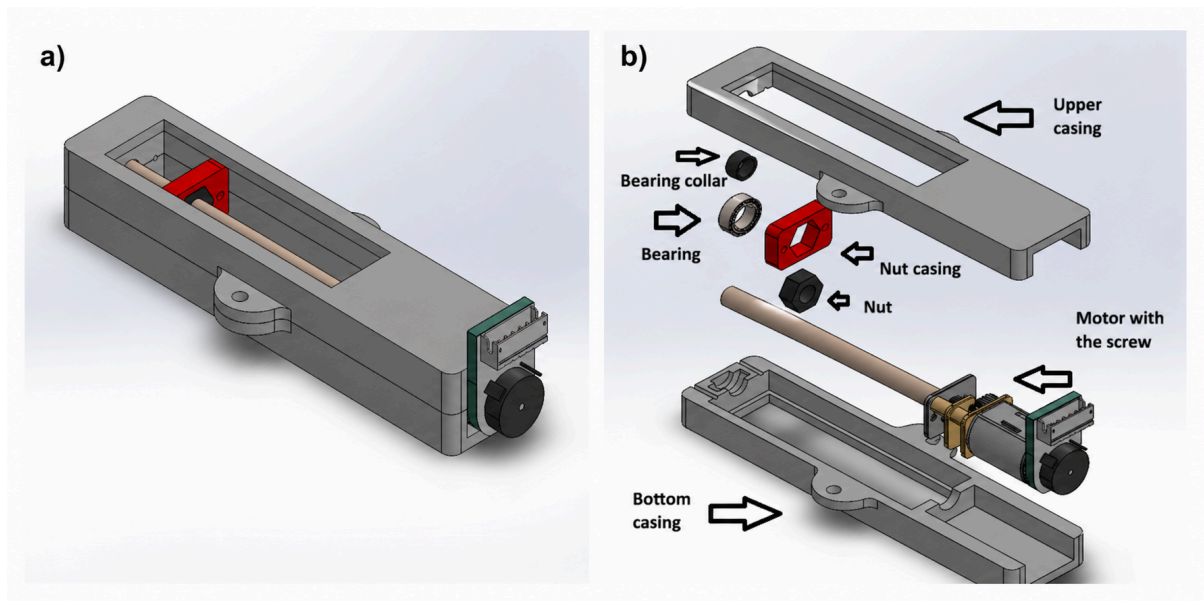


Figure 12. a) Actuating unit assembly, b) Exploded view of actuating unit assembly.

3.3.2 Hardware Setup

A simple control system will be used to drive the motor. As shown in *Figure 13*, this system will consist of an Arduino Mega 2560 microcontroller, one motor driver L298N, a power supply, two motors, one button, a mini breadboard, and a tactile sensor. The motor driver will be used to control the motor by delivering the proper voltage and regulating its speed via

PWM signals. The battery will power the motor driver and the Arduino. All components share a common ground, ensuring stable operation and proper signal referencing.

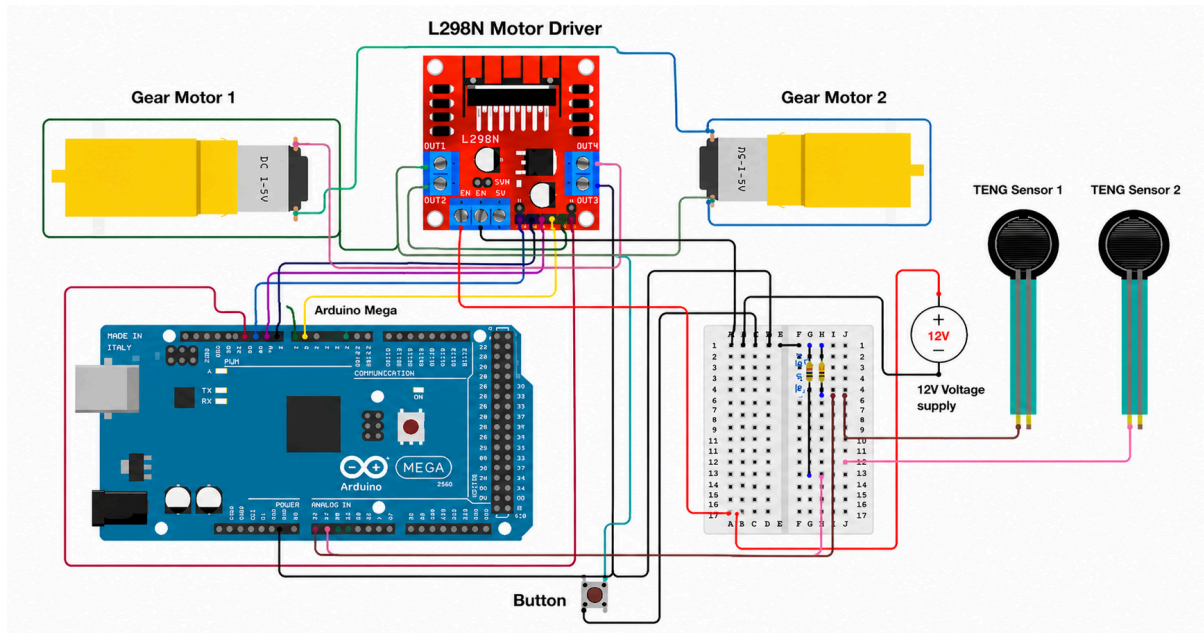


Figure 13. Hardware setup.

3.3.3 Tactile Sensor Integration and Grasp Detection Mechanism

To provide real time contact and interaction detection during the movement of the fingers, the exo-glove has the tactile sensing system embedded into the actuation system. A tactile sensor based on a TENG is used to make it happen, as opposed to a traditional force sensor. The TENG sensor produces an electrical signal when in contact as opposed to the traditional sensor that measures the amount of force in the air, and is especially applicable in measuring interactions in wearable soft devices.

The TENG sensors are interconnected with the arduino Mega by using the analog input pins (A0 and A1). The triboelectric effects cause the electrical signal recorded as changing voltage (0-5V) to be measured by the Arduino built-in analog-to-digital converter (ADC). This translates the analog signal into a digital value within 0-1023 and then they are processed further.

The actuation system has the tactile sensor embedded in its control loop. Once a push button is pressed, the motors start rotating the shaft and move the tendon mechanism that flexes the fingers. The fingers close gradually as the tendons are pulled by the motors. The signal value is continuously monitored in this motion of the system.

The primary function of the tactile sensor in this system is grasp detection. As shown in *Figure 14*, as the fingers close upon pressing the push button, and eventually come into contact with an object, the TENG sensor produces a noticeable increase in signal due to the interaction between surfaces. A grasp is confirmed only when a sensor records 15 distinct hits above a predetermined threshold of 15.0. Here the motors are switched off and it means that further movement is not necessary. At this point, by switching off motors, the system is in effect changing a motion phase to a holding phase that enables the exo-glove to hold on to the object without over-reacting. Besides grasp detection, the system has a time based stopping condition to restrict unnecessary movement. This is to make sure that the system does not run forever without contact. The maximum travel time is programmed through measuring the distance required to move the tendons and trying it in the longest time possible. The system is tested by its performance using a high-speed Serial logging method (115200 baud). The Arduino sends the important parameters in a comma-separated format to enable real-time analysis and post processing: Time (ms), Sensor value, Threshold, Motor state. The data obtained were subsequently plotted (Sensor value Vs time) to determine the characteristics of the signal and confirm the usefulness of the grasp detection technique. The Arduino code of signal processing and actuator control is detailed and is provided in the Appendix.

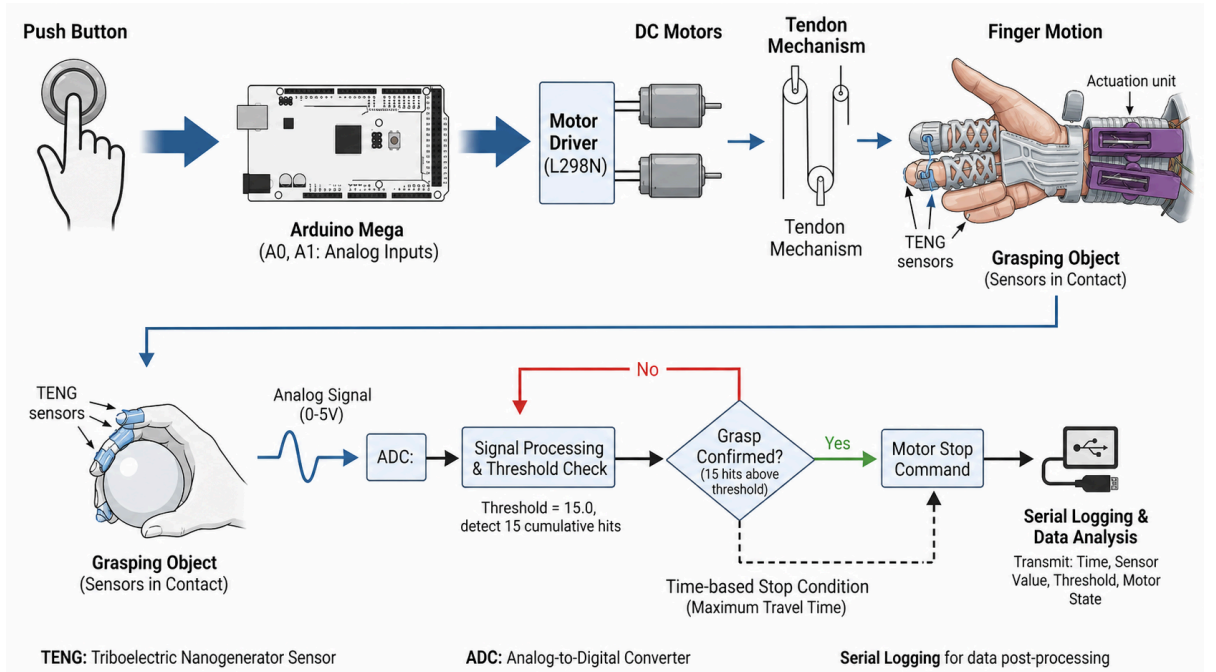


Figure 14. Grasp Detection Control Scheme of the TENG-Based Exo-Glove.

3.4 TENG Sensor Development

3.4.1 TENG working principle

The TENG applied in the current study works on the principle of the coupling of contact electrification and electrostatic induction, and it allows converting mechanical deformation into electrical signals. During the physical contact of two substances with varying propensity to lose or gain electrons, charge transfer at the interface takes place because of variances in triboelectric characteristics. When separated, opposing charges are left on the surfaces producing an electric potential difference between the electrodes. This potential causes electrons to flow through an external circuit giving an electrical response that can be linked to mechanical stimuli applied like pressure or force or deformation. In the soft wearable devices, the TENG devices are normally used in contact separation mode wherein compressions and releases are repeated to produce alternating voltage waveforms. The more force applied the more the contact area and surface charge density, and the higher the output voltage. Likewise, the rate of charge transfer is influenced by the frequency of mechanical excitation, which determines the signal amplitude and waveform properties. These attributes render TENGs especially well suited to applications in tactile sensing as they offer high sensitivity, self-powered capabilities and the ability to work with flexible substrates. Polymer-based materials also increase the stretchability and conformability, which is critical in incorporation of soft robotic gloves and wearable assistive devices. Moreover, TENG sensors have high response rates and low power consumption, which means that this type of sensor can detect human-object interaction in real-time, without external power supply. The mechanism is extensively documented in wearable sensing systems and soft robotics, and has been shown to reliably detect pressure, motion, and tactile feedback in flexible electronics. The resulting voltage output is directly proportional to the mechanical input, thus making it possible to quantitatively sense the forces of interaction in the exo-glove design introduced in this study [28].

3.4.2 TENG sensor design

The tactile sensor in this project is based on a TENG structure, which converts mechanical pressing into electrical signals through the coupling of contact-induced charge transfer and electrostatic induction. The selected triboelectric material is a soft silicone elastomer (Ecoflex-00-30), chosen due to its strong electronegativity in the triboelectric series, biocompatibility, flexibility, and excellent surface conformity with the human hand. As a compliant electrode layer, a silver ink conductive pattern is screen-printed onto a silicone

substrate, as shown in *Figure 15*. silver provides high electrical conductivity while maintaining elasticity under repeated bending and stretching, making them suitable for wearable tactile interfaces [6]. A base silicone sheet puts the silver electrode, while an additional thin silicone triboelectric film is attached to the patterned surface using liquid Ecoflex. This structure is cured in an oven at 130 °C for one hour to ensure a strong and uniform interface. When an external force is applied to the sensor, such as fingertip tapping or grasping, mechanical deformation causes the top silicone layer to make intimate contact with the silver electrode [29]. Upon release, separation occurs. The difference in triboelectric charge affinity generates a potential difference across the electrode. The system operates in a single-electrode mode, enabling simplified wiring and more convenience for wearable use. Since only one electrode is needed, the human body or the surrounding ground serves as the reference potential. This reduces complexity and improves compatibility for integration on curved glove surfaces without restricting finger mobility. Under applied pressure, the sensor is expected to produce increasing voltage peaks as the contact area and degree of compression rise. Stronger tapping or higher applied force results in larger charge transfer and so higher signal output. During repetitive motion, the positive and negative voltage peaks show continuous contact–separation cycles and confirm stable TENG performance.

3.4.3 TENG Sensor fabrication process

The production of the TENG tactile sensor has started with the printing of a pattern of conductive silver ink on a polyvinyl chloride (PVC) layer. PVC was chosen as the first printing surface due to its smoothness, dimensional stability, and compatibility with the conductive inks deposition. These features assist in preserving continuity of the conductive traces and minimize chances of cracking during the handling. The sample was then dried thoroughly after printing to make sure that the silver ink stuck well to the surface of PVC. Drying should be done properly to avoid delamination of the conductive layer, and to ensure stable electrical performance.

After the printed layer was completely dry, the electrical conductivity of the conductive layer was measured with a multimeter. This measure was necessary to provide continuity in the conductive path that was able to conduct electrical signals produced in the triboelectric contact. Once conductivity had been established, a fine conductive wire was connected on the lower part of the silver pattern. A solid electrical connection between the external measurement circuit and the silver electrode was achieved by tin soldering. Tin was chosen

due to formation of stable metallic bond, low contact resistance, which is significant to reduce signal loss during data acquisition. The position of the wire towards the bottom of the design was to prevent interference with the contact area, as well as to minimize mechanical stress during bending.

To improve the mechanical durability of the conductive layer, the printed silver pattern and the soldered connection were covered with a thin layer of Ecoflex silicone elastomer. Ecoflex has been chosen because it is very flexible, soft and biocompatible, and can thus deform with the sensor without rupturing the conductive network. The protective Ecoflex coating has two primary functions: it enables the avoidance of the rapid mechanical fatigue of the silver ink structure when repeatedly bending it, and it functions as a triboelectric layer that allows the generation of charges by means of contacts. Although the extra coating made the sensor less sensitive to external contact, the compressible nature of the Ecoflex layer allowed the detection of voltage signals.

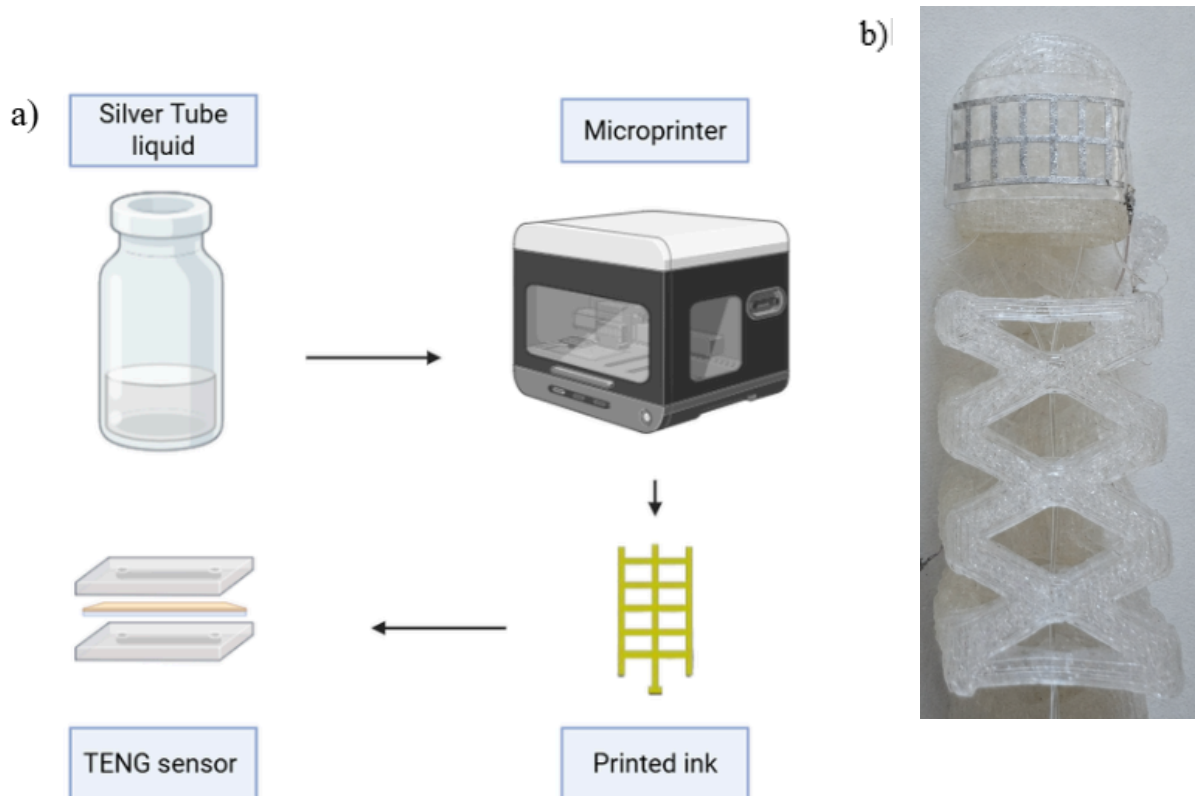


Figure 15. a) TENG sensor preparation step by step. b) Printed version example.

Once the encapsulated sensor had been prepared it was fitted to the fingertip area of the main exo-glove. The point of finger was chosen since this is the point of interaction that has the

greatest force of the interaction during grasping and tapping. At first, the bonding agent between the sensor and the silicone glove surface was liquid Ecoflex. In this step, ecoflex has been selected, which allows keeping the overall flexibility, and compatibility of the soft materials. Nonetheless, the surface quality of both the silicone glove and the sensor made of PVC varied; thus, it was not easy to hold the position steady in the curing process. The liquid Ecoflex failed to offer adequate initial fixation which led to possible misalignment.

To counter this problem, a drop of super glue was used to obtain initial fixation. Super glue was utilized merely as a sticky material since it allows quick assembly and keeps the sensor attached as the sensor proceeds with the processing. By successfully aligning, another coating of Ecoflex was applied towards the edges of the sensors to form a flexible and strong bond. This last Ecoflex coating was necessary to make the sensor firmly attached yet also to maintain the gentle mechanical properties of the glove. The Ecoflex adhesive was allowed to dry at room temperature and the drying time was about six hours. This method of attachment offered stable mechanical fixation, shielded the conductive elements, and ensured flexibility to wearable tactile sensing devices.

3.5 Testing procedures

3.5.1 TENG sensor testing

The performance of the fabricated TENG tactile sensors was measured through a series of experimental tests. It was designed to assess voltage response under hand-like interaction conditions. The aim of these tests were to detect signals from hand tapping as well as from applying constant forces and frequencies. The triboelectric working principle anticipates a dynamic, alternating voltage output during contact and release, therefore measurement apparatus must correctly record transient electrical responses, in line with the written TENG characterization methods in flexible e-skin research by Song X et al [7]. As shown in *Figure 16a*, to record the electrical output, the sensor was connected to an oscilloscope capable of measuring rapid signal fluctuations due to contacting and releasing behavior. Lead wires from the silver electrode were routed to the oscilloscope input, while the others served as the reference ground, as required for single-electrode TENG operation. As shown in *Figure 16b*, a linear motor testing machine was used to apply controlled pressing frequencies during automated tests, while simple fingertip tapping was employed for realistic human interaction evaluation. The equipment setup allowed real-time visualization of output waveforms to

quantify sensor responsiveness, similar to procedures mentioned in the literature for stretchable triboelectric electronic skin. Static force application was first performed by pressing the fingertip sensor with forces of 1 N, 2 N, 3 N. Each force level was applied to the sensor with a frequency of 1Hz to record voltage peaks and show the consistency of the output amplitude. The purpose of this test was to establish a clear relationship between applied force and generated voltage values. As it was shown in triboelectric theory [30], higher compression increased the effective contact area, resulting in greater charge transfer and stronger voltage signals. This behavior demonstrates the ability of the sensor to realize varying force intensities, a key requirement for monitoring safe gripping levels during rehabilitation tasks.

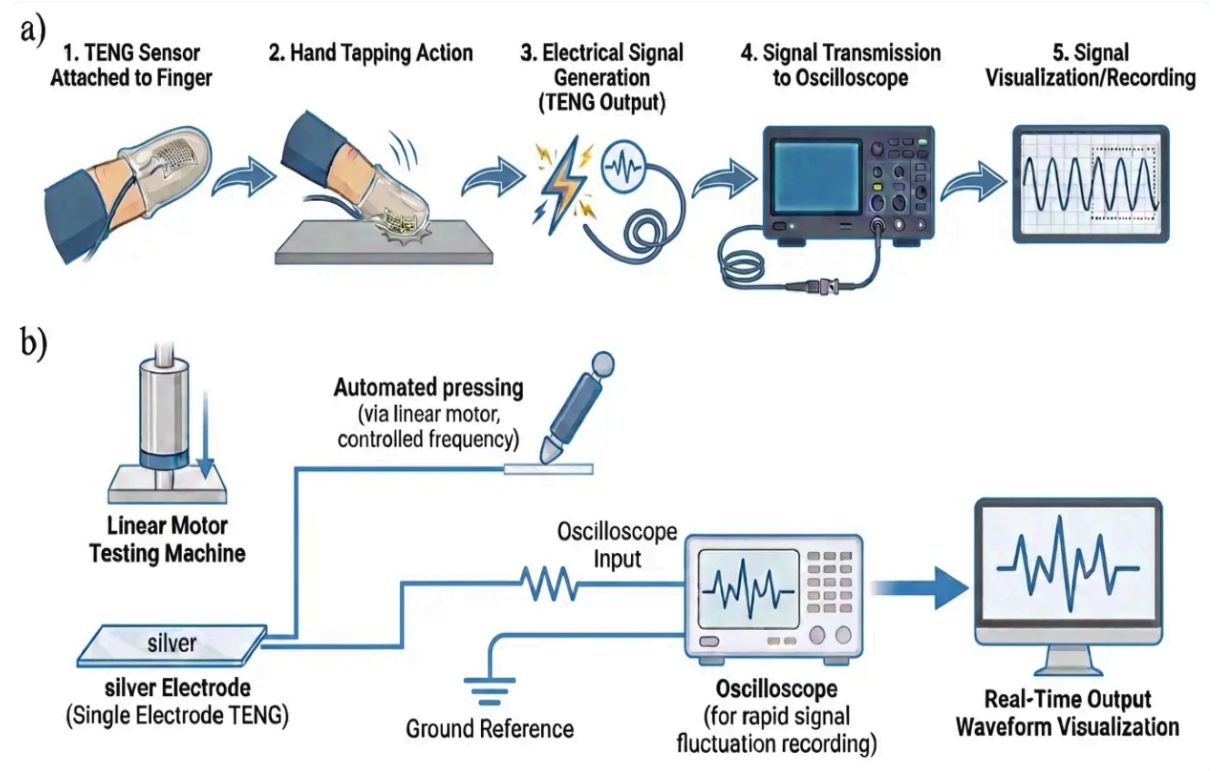


Figure 16. Schematic Illustration of (a) Manual Finger-Tapping and (b) Automated Linear Motor Testing Methods for TENG Signal Generation and Oscilloscope Measurement.

A dynamic test was set to simulate repetitive hand motions. A linear motor applied periodic contact and separation cycles at frequencies of 1 Hz, 2 Hz, and 3 Hz while applying a constant force of 2N. Voltage waveforms showed a wide range between peaks, even though the machine applied only 2N. Additional experiments involved hand tapping on the sensor while it was mounted on a glove fingertip. These realistic interaction tests confirmed that the

sensor outputs recognizable and repeatable tactile signals during basic human movements, consistent with functional requirements for wearable sensing systems.

3.5.2 Silicone Material Testing

5 ASTM D12 Standard specimens were tested using a Universal Tensile Machine, as shown in *Figure 17*, to get the mechanical properties of SIL-30 material. For the input value, the gauge length, width, and thickness of the specimens were 33, 6, and 3 mm, respectively. As a result, the specimens were torn variously, as shown in *Figure 17*, since there were some minor differences in printing the specimens and placing them in their positions in the Universal Tensile Machine.

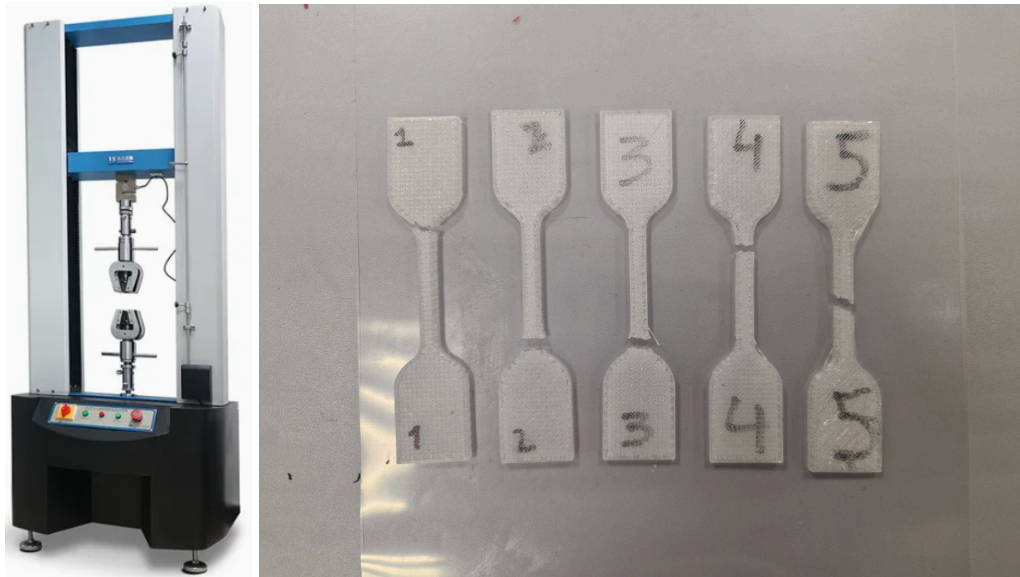


Figure 17. Universal Tensile Machine & Tested Specimens.

Chapter 4

Results and Discussion

4.1 Fabrication Results

The printed part of the finger has been successfully printed, as presented in *Figure 18a*. The finger part is in a cylindrical shape which facilitates comfortable wear and the integration of a microprinted tactile sensor. The printed sample has great stretchability and bendability due to its material and diamond pattern. The sample successfully mimics the finger's curve. The embedded tactile sensor has a spiral conductive pattern, which is wrapped with soft material. The visual inspection, presented in *Figure 18a*, confirms the possibility of maintaining its structure while being stretched. The general view that is also presented in *Figure 18a*, shows that the sample can be easily worn, to be comfortable for the interaction with human fingers. These preliminary fabrication results suggest that soft, tendon-driven exo-skeletons can be successfully fabricated.

The final prototype of the glove was successfully assembled and fabricated, as shown in *Figure 18b*. The system of the glove consists of the three main components: 3D printed silicon module (finger, palm, belt structures), the forearm mounted actuation units and the integrated TENG sensors on the finger tips.

The designed gloves display a light and reconfigurable structure. The palm and wrist parts ensure the stability and fitting of the glove on the hand, respectively, as shown in *Figure 18b*. Moreover, the adjustable straps and fasteners provide the secure fixation during the operations, and the possibility to fit different wrist sizes. The design of the glove allows the easy replacement of the different parts, enhancing maintainability and production.

The tendon-driven actuation system is effectively incorporated into the system. The cables are attached to the fingers and the actuation unit is attached to the forearm. It enables the transmission of the force from the actuators to the fingers, which results in the motion of fingers.

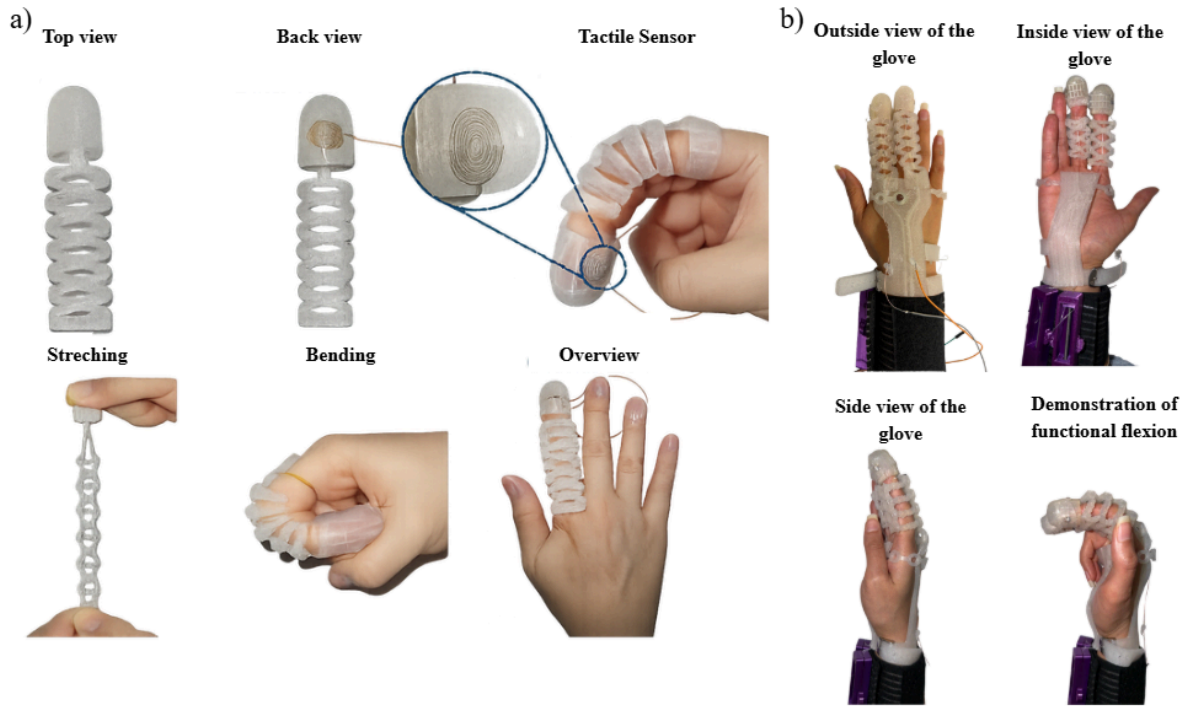


Figure 18. a) Printed index finger part overview, b) Overview of the Fabricated Exo-Glove prototype.

The visual results show that the glove is able to move the fingers. The glove can also grasp the various shapes, as shown in *Figure 18b*. The index and middle fingers are flexed by the movement of tendons and the desired kinematics is maintained.

The design is feasible as shown in the fabricated result. The system shows the correct integration of the mechanical design, tendon actuation and wearable structure, and provide a functional platform for future experimentation and improvement

4.2 Mechanical Testing Results

The results summarized in *Table 1* indicate that the average maximum tensile strength is 2.08 MPa, and an elongation at break is 884.85%. *Figure 19* shows the stress–strain curves of the silicone samples obtained from tensile testing. This graph demonstrates the nonlinear elastic behavior and high stretchability before failure. As shown in the stress–strain curve, all 5 tests follow similar trends, indicating good repeatability and consistent mechanical performance. These characteristics suggest that the material used is very suitable for producing a soft exo-glove.

Table 1. Force, Stress, and Strain values.

Samp les	Maximum force, N	Maximum tensile strength, MPa	Elongation at break %
1	38.136	2.12	986.67
2	37.647	2.09	901.52
3	37.484	2.08	823.33
4	39.113	2.17	924.85
5	35.039	1.95	787.88

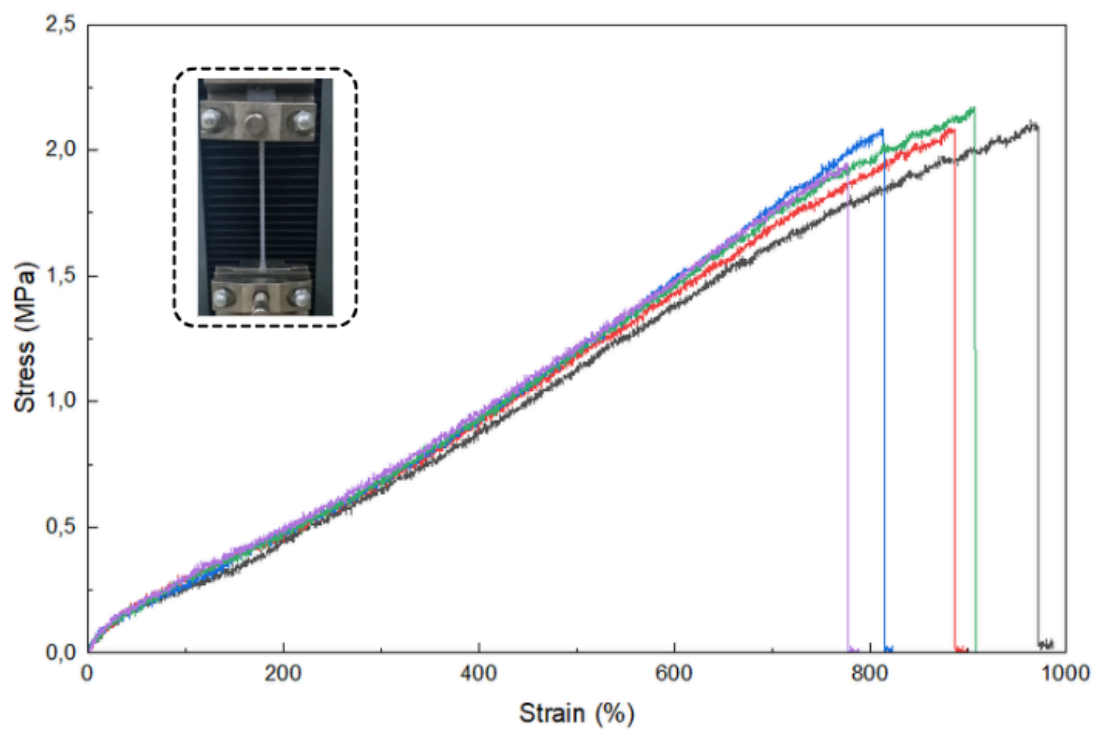


Figure 19. Stress-strain curves.

4.3 Sensor Output Results

The fabricated TENG tactile sensor successfully generated measurable voltage signals under both static and dynamic loading conditions. During manual hand-tapping while mounted on

the fingertip of the glove, the oscilloscope recorded alternating positive and negative voltage peaks, confirming the effective contact–separation operation mode of the single-electrode TENG. As shown in *Figure 20*, the average peak amplitudes during hand interaction reached values exceeding 20 V, demonstrating that the sensor is capable of detecting natural touch inputs without requiring any external power source.

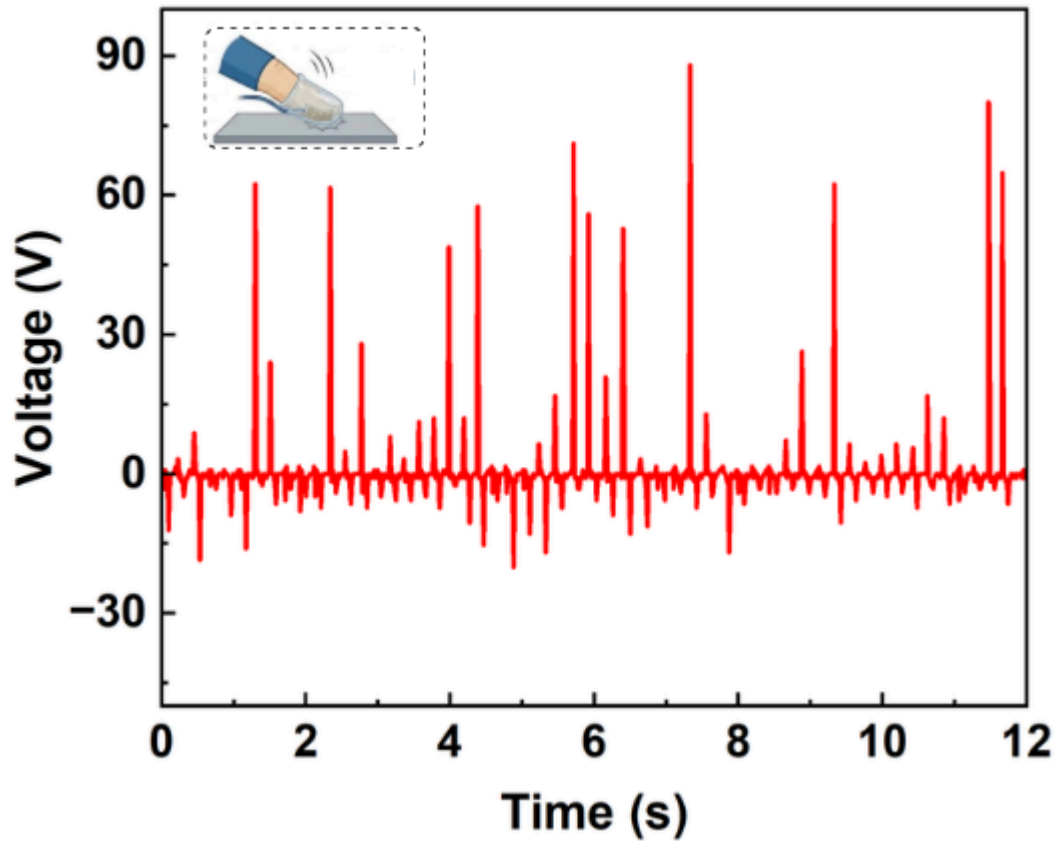


Figure 20. Voltage data of hand tapping.

As shown in *Figure 21a*, to quantify sensor performance, controlled forces of 1 N, 2 N, 3 N, 4 N, and 5 N were applied using a linear actuator. The resulting output signals showed a clear and expected correlation between applied pressure and voltage magnitude, where higher forces produced more pronounced peaks due to increased contact area and triboelectric charge transfer. Across multiple trials, voltage levels ranged from approximately 3–4.5 V for light pressing to more than 35–40 V for higher pressures. These values align with reported output characteristics in soft TENG-based tactile sensors for electronic skin applications, confirming successful material and structural design.

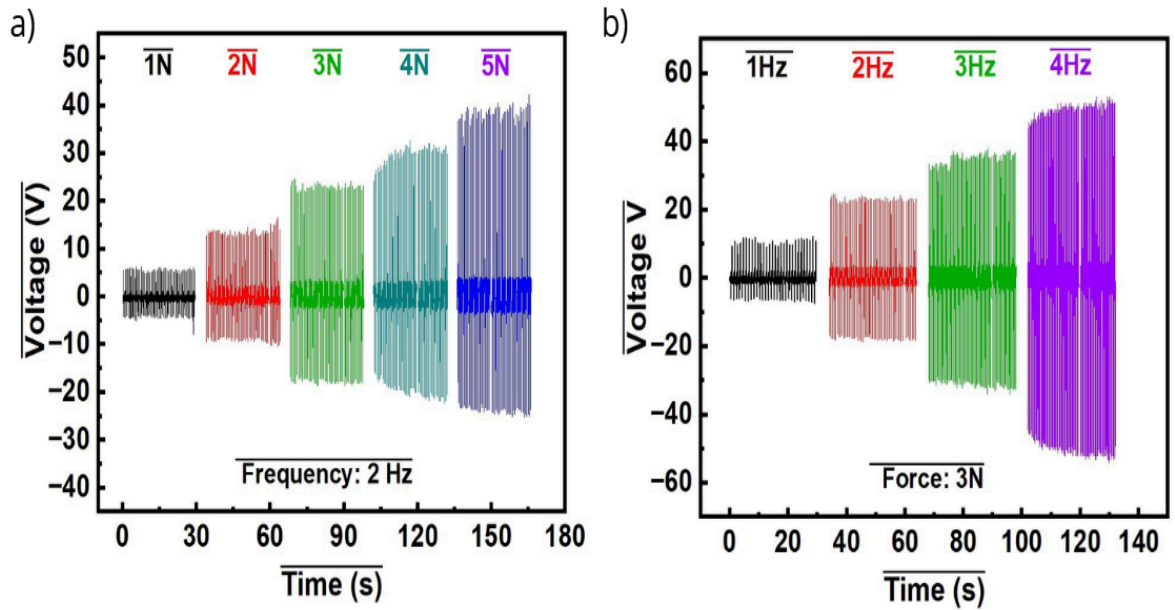


Figure 21. a) Testing setup Linear Motor System with Oscilloscope, b) Voltage data at a constant frequency of 2 Hz, c) Voltage data by a constant force of 3N.

Dynamic testing further demonstrated the frequency-dependence of the output (*Figure 21b*). When repeated contact cycles were applied at 1 Hz, 2 Hz, 3 Hz, and 4 Hz, the voltage waveforms maintained consistent alternating profiles, while peak-to-peak amplitude and signal density increased with frequency. This response matches the theoretical behavior of triboelectric nanogenerators, where faster contact–separation cycles enhance charge generation per unit time. Importantly, the sensor retained stable output after multiple cycles, indicating durability suitable for repetitive use in rehabilitation scenarios where frequent hand motion occurs.

Overall, the results validate that the TENG sensor provides a reliable and meaningful electrical representation of tactile interaction forces. The measurable gradients in voltage with both force and frequency demonstrate its capability to act as a self-powered feedback element within an assistive exo-glove system. The consistent signal patterns confirm suitability for future integration with real-time monitoring electronics or closed-loop grip-control algorithms.

The TENG sensor, which is implemented in the finger, showed acceptable voltage values for linear motor machine testing and also for tapping test. But in the linear motor machine test, when a constant supply of force has been applied to the sensor, the obtained graphs showed no constant voltages. Also, during the changes of frequency with remaining force, the graph

fluctuates significantly. These test results demonstrate that even during small contact forces, the sensor can detect it.

The main difficulty of the design is the placement of the TENG on the fingertip. The fingertip is the place where the sensor is subjected to mechanical forces, which can significantly wear out the sensor due to different causes, such as consistent bending. Despite these limitations, that type of configuration opens opportunities for hand rehabilitation exo-gloves with tactile systems, soft robotic systems, and tactile technologies, hence enhancing real-world applicability. Overall, the design shows promise, but performance must be confirmed through testing, calibration, and long-term durability assessment.

4.4 TENG Sensor Signal Results

In *Figure 22*, the typical signal of the TENG-based tactile sensor in a grasping process is shown. The graph is a representation of sensor value versus time, with a threshold of 15 set to indicate the contact events. During the early phase of the operation (between 0 and 2.7 seconds), the value of the sensor varies at low levels and stays below the threshold. This corresponds to the non-contact phase and noise.

When the fingers come into contact with the object, the signal shows a series of peaks. In contrast to conventional sensors that typically produce a DC signal, TENG sensors naturally generate a transient, AC-like signal due to the contact-separation nature of the charge generation in the TENG sensors. This means that the output is not sustained at a high value, but it spikes rapidly when in contact, and returns to zero when the contact is broken. The spiky nature of the signal is also evident in *Figure 22*, where each interaction results in a voltage spike.

The multiple peaks represent the "on-off" cycles that happen during the grasping process. The underlying physics is due to tiny adjustments of the fingers and slips between the glove and the object. During the finger closure, there is a micro-vibration phase, in which the object and the sensor surface are engaged. This stage involves frequent and brief contact, which results in multiple short peaks in the signal.

In practical applications, TENG sensors are sensitive to both contact and irrelevant vibrations and disturbances. Consequently, one threshold crossing is insufficient to identify whether a grasp has taken place as a single peak can be because of vibration or noise. In

order to overcome this problem, a hit counting approach is taken. This logic basically recalls the existence of multiple peaks, instead of reloading its memory after each peak, so that this system can judge the stability of the interaction. A total of 15 peaks in a row are chosen as the grasp detection threshold in the present work.

It can be observed that the signal between 2.7 and 3.0 seconds is varying with the peak value increasing significantly and exceeding the threshold. Specifically, the heights of the peaks are only marginally greater than the threshold (approximately 17), which is more realistic to real-world contact scenarios. This indicates that the micro-vibration stage has been achieved and that the sensor and object have been in and have been in solid contact. At this point, when the 15th pulse is detected, the control system evaluates the signal as an established grasp, and transmits a signal to the motors to stop.

The repeatability of the grasp detection system was evaluated over five trials, as shown in *Table 2*. These findings show reliable operation with grasp confirmation within a relatively short time window (2.84-3.11 seconds). Across all repetitions, the system detected precisely 15 hits, validating the cumulative hit approach. Additionally, all trials were successful in detecting grasp, demonstrating the system's reliability across trials. The slight differences in detection time are due to variations in finger movement and contact between trials. The findings confirm the stability and consistency of the proposed TENG-based grasp detection system.

To sum up, the signal behavior demonstrates that the suggested sensing system, which is based on TENG, provides a powerful and relevant grasp recognition method. The cumulative hit approach and the hybrid quality of the signal of the system enable the stable contact detection without the use of signal processing techniques involved. It is noteworthy that accuracy of the system depends on the threshold and hits. The differences in the stiffness of objects, surface finish, and other parameters can influence the amplitude of the signal and contact behavior. Therefore, future studies could take into account adaptive thresholding or feature extraction to achieve more robust system functioning across various applications.

Table 2. Repeatability of Grasp Detection.

Trial	Grasp confirmation time (s)	Threshold hits recorded	Detection Result
1	2.97	15	Success
2	2.84	15	Success
3	3.03	15	Success
4	3.11	15	Success
5	2.91	15	Success

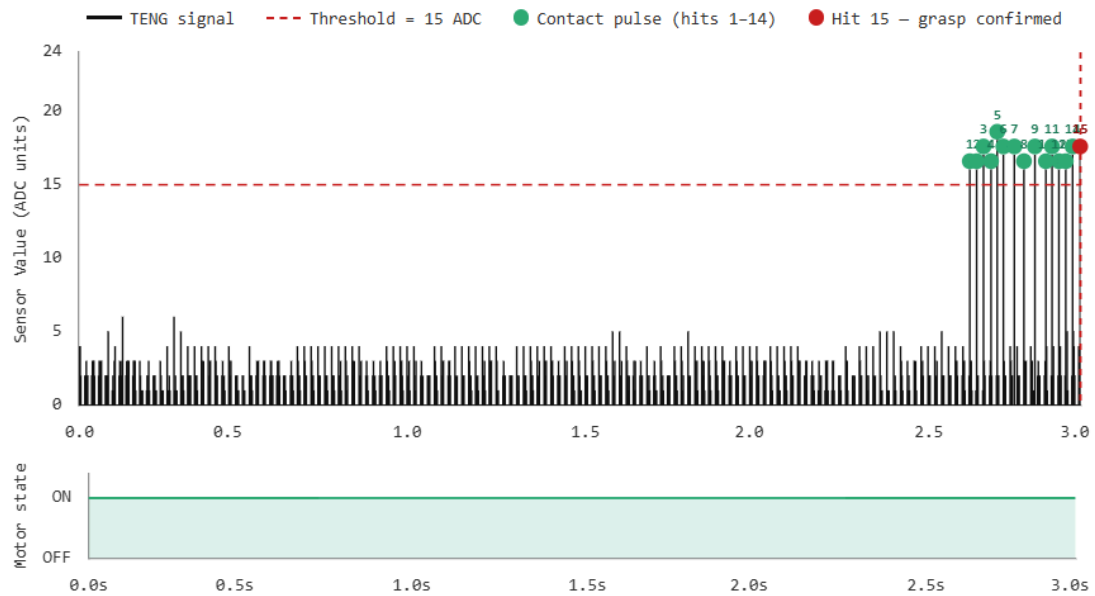


Figure 22. Grasp detection using TENG sensor - Sensor value vs. Time.

Chapter 5

Conclusion and Future Work

The work that has been undertaken in this project begins with the analysis of the already available solutions to people with a hand impairment and ends with the creation of our alternative solution. It entails the design, fabrication, and experimentation of a soft exo-glove coupled with tactile sensing. The successful formation of a workable TENG tactile sensor was one of the most crucial outcomes and it was able to generate consistent voltage results when subjected to both a static and a dynamic test. Silver ink printing on a microprinter made the sensor fabricated by this process significant in that it obtained properties like conductivity and flexibility of the sensor. The design came about due to an enormous number of experiments. In the experiments, it was found out that the TENG sensor signal has the potential to respond to the interaction of fingers and objects and provides discrete peaks when the objects are touched. These signals were large enough to exceed the threshold value set, and it was possible to identify grasp events in the correct and reliable way, and activate the motor stopping system. The actuation system was successfully designed, manufactured, and assembled, enabling finger flexion. The exo-glove was successfully designed and fabricated using a Silicone 3D printer. This printer successfully printed small holes of glove components for wires in high resolution. The 3D-printed finger and glove structures feel very soft, stretchable, and easy to bend. The silicone material that is used for 3D printing showed high flexibility and elongation at break, approximately 885%, while testing it using the Universal Tensile Machine. Overall, the developed system demonstrates the feasibility of integrating soft actuation and tactile sensing in a wearable exo-glove for assistive hand rehabilitation.

5.1 Limitations and Future Work

The fabrication process has several limitations. Printing the silicone glove components takes a long time – approximately 8-9 hours per part, followed by an additional 8 hours of curing. The silicone printer also requires continuous human monitoring, as issues such as inconsistent flow rate or partial clogging could occur during printing. These interruptions often affected print quality and occasionally required restarting the process. As a result, the overall 3D printing process was time-consuming and required constant monitoring. To solve

this problem, in future, new types of silicon, such as SIL-18 and SIL-50, could be used for printing glove components.

An exciting area for potential further developments would be using FMG sensing technology for detecting force on the forearms. Pressure changes, as a result of muscle contraction, cause changes in pressure within the skin surface; therefore, they provide a continuous, static value in relation to a user's intention to hold or grasp. For example, an FMG sensor would be able to give an indication of what type of grasping is intended and how much force is required on the fingers before they contact an object. After the fingers have made contact, a TENG-based sensor would register the occurrence of contact and stop the movement of the motor in the hand. Using an FMG sensor on the forearm together with an existing TENG sensor on the fingertips would allow for the implementation of a two-stage sensing system, therefore moving from a reactive control mode to a proactive control method. This transition would be particularly useful for individuals with some partial hand function, whereby they have muscle activity left in the hand. Furthermore, the current system uses fixed threshold and hit counts (15 and 15). These were adjusted through trial and error for a particular object and contact. For future work, adaptive thresholding algorithms via machine learning should be explored that adapt based on the signal statistics of the detected object to ensure consistent object recognition across different stiffnesses, textures and materials without requiring recalibration. In addition, the current design is for the index and middle fingers. Adding a thumb actuation unit will provide a complete cylindrical and pinch grasp, allowing for greater assistance in daily tasks. The current glove design has been prepared for the routing of tendons to activate the thumb, which can be easily implemented in the future. Lastly, the "gold standard" test for any assistive device is with target users. Therefore, future research should include controlled testing with stroke patients or people with hand impairment, using measures such as grasp success, time and comfort according to established metrics.

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Appendix

Calendar plan

	September	October	November	December	January	February	March	April	May
Research and Training Review the papers Training to use the Microprinter and Silicon printer Divide the tasks									
Designing and Modeling Finalize the CAD model of glove Printing the glove Printing different designs silver nanowires (ink). Optimizing pattern									
Fabrication and Assembly Assemble tendon routing Integrate sensors into the glove fabric Wire motors and sensors into a functional prototype									
Testing Run TENG tests Run Mechanical tests									
Report Write a report									

Responsibility distribution

Task	Team member responsible	Team member assisting	Details
Designing	Bekzat Azamatov		CAD modeling of glove parts, tendon routing
3D Printing	Adilet Zhumabay	Bekzat Azamatov, Ali Oryn	Slicing models, printing parts, post-processing
Sensors Integration and Microprinting	Yrskeldi Dinmukhamedov		Embedding on glove fingertips / palm
Testing for TENG	Yrskeldi Dinmukhamedov		Output electrical performance test, Force and Pressure response test, Response time test.
Signal processing for TENG	Ali Oryn		Signal processing, data logging, and experimental analysis of TENG signals
Mechanical testing	Ali Oryn	Bekzat Azamatov	Tensile testing on printed silicone samples to get stress-strain curve
Tendon Actuation Mechanism	Ali Oryn	Bekzat Azamatov, Adilet Zhumabay	Designing and assembling lead-screw actuator
Documentation	All members		Write a report

Arduino Code

```

// ===== PINS =====
const int IN1 = 8; const int IN2 = 9; const int ENA = 10; // Index
const int IN3 = 6; const int IN4 = 7; const int ENB = 11; // Middle
const int buttonPin = 2;
const int sensorIndexPin = A0;
const int sensorMiddlePin = A1;

// ===== PARAMETERS =====
const int motorSpeed = 150;
const int contactThreshold = 15;
const int requiredHits = 15;
const unsigned long maxTravelTime = 3500;

// ===== STATE VARIABLES =====
bool motorsRunning = false;
bool indexGrasped = false;
bool middleGrasped = false;
int indexHits = 0;
int middleHits = 0;
unsigned long motionStartTime = 0;

void setup() {
  pinMode(IN1, OUTPUT); pinMode(IN2, OUTPUT); pinMode(ENA, OUTPUT);
  pinMode(IN3, OUTPUT); pinMode(IN4, OUTPUT); pinMode(ENB, OUTPUT);
  pinMode(buttonPin, INPUT_PULLUP);

  Serial.begin(115200);
  Serial.println("Time_ms,Index_Raw,Middle_Raw,Threshold,Motor_State");
}

void loop() {
  unsigned long now = millis();

  // 2. Read Sensors
  int valIndex = analogRead(sensorIndexPin);
  int valMiddle = analogRead(sensorMiddlePin);

  // 3. LOGGING DATA (The missing part)
  // Format: Time, IndexRaw, MiddleRaw, Threshold, State
  Serial.print(now); Serial.print(",");
  Serial.print(valIndex); Serial.print(",");
  Serial.print(valMiddle); Serial.print(",");
  Serial.print(contactThreshold); Serial.print(",");
  Serial.println(motorsRunning ? 1 : 0);

  // 4. Index Logic
  if (!indexGrasped) {
    if (valIndex >= contactThreshold) indexHits++;
    if (indexHits >= requiredHits) {
      brakeMotorA();
      indexGrasped = true;
    }
  }

  // 5. Middle Logic
  if (!middleGrasped) {
    if (valMiddle >= contactThreshold) middleHits++;
    if (middleHits >= requiredHits) {
      brakeMotorB();
      middleGrasped = true;
    }
  }
}

```

```

    if (digitalRead(buttonPin) == LOW) {
        delay(200);
        if (!motorsRunning) startGrasp(now);
        else stopAll();
    }

    if (motorsRunning) {
        monitorSensors(now);
    }
}

void startGrasp(unsigned long now) {
    motorsRunning = true;
    indexGrasped = false;
    middleGrasped = false;
    indexHits = 0;
    middleHits = 0;
    motionStartTime = now;

    digitalWrite(IN1, HIGH); digitalWrite(IN2, LOW); analogWrite(ENA, motorSpeed);
    digitalWrite(IN3, HIGH); digitalWrite(IN4, LOW); analogWrite(ENB, motorSpeed);
}

void monitorSensors(unsigned long now) {
    // 1. Check for Timeout
    if (now - motionStartTime >= maxTravelTime) {
        stopAll();
        return;
    }

    if (indexGrasped && middleGrasped) {
        motorsRunning = false;
    }
}

void brakeMotorA() {
    digitalWrite(IN1, HIGH); digitalWrite(IN2, HIGH); analogWrite(ENA, 255);
    delay(100);
    digitalWrite(IN1, LOW); digitalWrite(IN2, LOW); analogWrite(ENA, 0);
}

void brakeMotorB() {
    digitalWrite(IN3, HIGH); digitalWrite(IN4, HIGH); analogWrite(ENB, 255);
    delay(100);
    digitalWrite(IN3, LOW); digitalWrite(IN4, LOW); analogWrite(ENB, 0);
}

void stopAll() {
    motorsRunning = false;
    analogWrite(ENA, 0); analogWrite(ENB, 0);
    digitalWrite(IN1, LOW); digitalWrite(IN2, LOW);
    digitalWrite(IN3, LOW); digitalWrite(IN4, LOW);
}

```