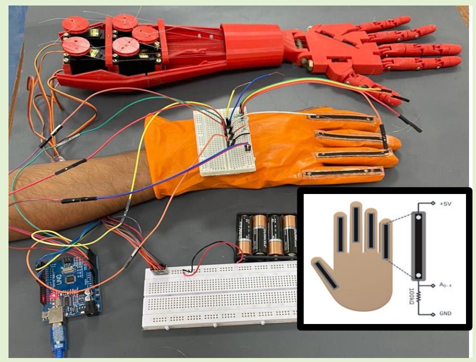
Development of SWCNTs/PDMS Composite Strain Sensors Integrated Smart Glove for Human–Machine Interface Applications

Suraj Baloda, Sashank Krishna Sriram, Puneet Sharma, Sumitra Singh, and Navneet Gupta, *Senior Member, IEEE*

***Abstract*—Smart gloves with their multifunctional sensing capabilities, hold a promising in human–machine interface (HMI) applications. In this work, we present a smart glove based on single-walled carbon nanotubes (SWCNTs) incorporated within a polydimethylsiloxane (PDMS) matrix integrated flexible strain sensor. The flexible strain sensor is designed and fabricated to serve as a crucial sensing component for the smart glove. The integration of SWCNTs with PDMS offers a unique combination of mechanical flexibility and electrical sensitivity, making it an ideal candidate for real-time monitoring and feedback in HMI applications. The fabricated SWCNTs/PDMS strain exhibits a high sensing range, covering up to a strain range of 70%, along with high sensitivity, characterized by a gauge factor (GF) of 73. Additionally, the strain sensor demonstrates excellent linearity, reliability, and durability, enduring repeated loading and unloading for 3000 cycles under a 50% strain. Furthermore, the developed smart glove successfully extends sensing functionality, enabling real time-tasks such as finger motion detection, controlling robotic fingers and can be used in the field of smart wearable electronics and HMI applications.**



***Index Terms*—Flexible strain sensor, gesture recognition, human–machine interface (HMI), polydimethylsiloxane (PDMS), single-walled carbon nanotubes (SWCNTs), smart gloves, wearable electronics.**

I. Introduction

THE development of wearable electronics has brought a revolutionary change in human–machine interface (HMI) in recent years. Among the various wearable devices, smart electronic gloves have emerged as a highly promising and versatile tool for HMI applications [1], [2]. These gloves, equipped with an array of sensors and electronic components enable seamless interaction between humans and machines through intuitive hand gestures, vital sign signals monitoring, and touch-sensitive interfaces, thereby revolutionizing both daily life and scientific experiments [3], [4], [5]. Flexible strain sensors hold significant potential in smart gloves, particularly for hand gesture detection and HMI applications [6]. The development of advanced strain sensors has emerged as a promising candidate to enhance the sensitivity, flexibility, and reliability of HMI devices. These sensors are strategically designed to demonstrate significant deformability, guaranteeing their ability to replicate the wearer's fingers intricate deformations accurately. Traditional strain sensors based on metal foils, wire gauges, and semiconductor-based materials have high sensitivity but a limited strain range, which falls short of meeting the sensing demands of wearable biomonitoring devices [7], [8]. Moreover, they face challenges when mounting on curved surfaces, irregular shapes, and are often incompatible with accommodating finger deformations. Flexible sensors are typically constructed using flexible and

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stretchable materials such as polymers, textiles, elastomers, and nanomaterial-based composites [9], [10], [11], [12]. The flexibility and stretchability allow them to conform to curved surfaces, irregular shapes, and deformations without affecting their performance for continuous strain data detection. Flexible strain sensors are remarkably interesting and potentially useful in a broad range of applications such as health monitoring, human motion detection, human–machine interaction, human–robot interaction and electronic-skin (E-Skin) due to their excellent flexibility and adaptability [13], [14], [15], [16]. The strain sensors based on carbon nanomaterials such as carbon nanotubes, graphene, carbon black, and carbon-based conductive polymers are compatible with finger deformations and interact with irregular surfaces as well as embedded on smart gloves [17], [18]. These sensors are easy to fabricate and cost-effective, making them ideal for human gesture detection and HMI applications in wearable electronics. Among the various carbon nanomaterials, single-walled carbon nanotubes (SWCNTs) have gained considerable attention in recent years because of their outstanding electrical, mechanical, and thermal properties [19], [20], [21]. These remarkable attributes, along with their high aspect ratio, make SWCNTs highly suitable for strain-sensing applications [22]. SWCNT-based strain sensors effectively leverage the piezoresistive effect, allowing them to accurately convert mechanical deformations into electrical signals. This capability facilitates precise and real-time monitoring of human movements, making SWCNTs an excellent choice for advanced sensing applications. Mostly reported flexible strain sensors are mainly fabricated with flexible substrates such as polydimethylsiloxane (PDMS) [23], [24], polyethylene terephthalate (PET) [25], polyurethane [26], polyvinylidene fluoride (PVDF) [27], silicone rubber [28], and rubber foam nanocomposites [29]. Among these flexible materials, PDMS is widely used elastomer due to high flexibility, chemical and thermal stability, good transparency, ease of manufacturing, and nontoxicity [30], [31], [32]. In addition, it complements the advantageous properties of SWCNTs, providing mechanical flexibility and robustness to the strain sensor. PDMS not only serves as an excellent substrate for embedding SWCNTs but also enhances the conformability of the sensor to various surfaces, including smart gloves. The combination of SWCNTs and PDMS offers a synergistic effect, resulting in a highly sensitive and durable strain sensor for HMI applications. Their ability to accurately detect and quantify various types of strains such as bending, stretching, and twisting enables a wide range of applications, including motion tracking, gesture recognition, and body motion analysis [33], [34], [35]. This work presents a simple approach to utilizing SWCNTs/PDMS-based strain sensors in a smart glove-based controller for controlling a robotic hand. The conductive SWCNTs/PDMS composite-based resistive strain sensors are fabricated and integrated with the glove. Furthermore, the robotic hand was developed using a 3-D printer and assembled both mechanically and electrically. Through systematic characterization and calibration of the smart glove and robotic hand, the mimicry of hand gestures is then attempted. The developed smart glove has the potential for hand gesture recognition, advancement of in-depth HMI research, and its broader applications in wearable electronics.

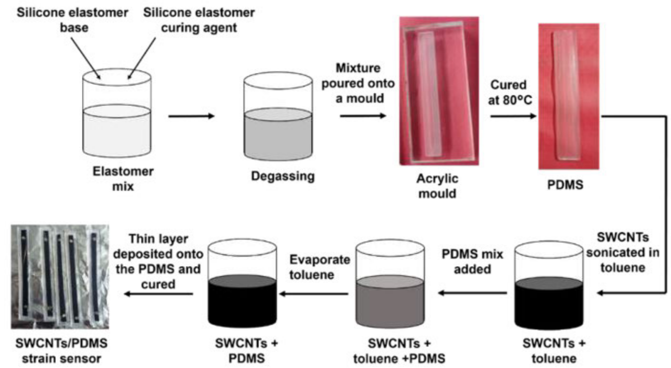

Fig. 1. Schematic illustrating the fabrication process of SWCNTs/PDMS composite strain sensors.

II. Experimental Details

A. Materials and Equipment Used

In this work, SWCNTs/PDMS piezoresistive strain sensors were designed, fabricated, and integrated onto a latex glove. SWCNTs were purchased from Alfa-Aser with 98% purity with an average diameter 40 nm and PDMS sylgard 184 kit from Dow Corning. The morphology of the SWCNTs strain sensor was characterized by a scanning electron microscope (Nova Nano SEM 450). Raman spectra were obtained using a HORIBA Raman microscope with the laser excitation wavelength of 633 nm at room temperature. Robotic hand was printed using Ulti maker S5 3-D-printer in which polylactic acid (PLA) and polyvinyl alcohol (PVA) material from ultimate were used. MG946R servo motors and nylon string were used for electrical and mechanical assembling the robotic hand. The finger motion detection using smart gloves was recorded using an Arduino and analyzed using MATLAB.

B. Fabrication of SWCNTs/PDMS Strain Sensor

In Fig. 1, schematic representation of the fabrication process for strain sensors. Thin layer of SWCNTs/PDMS composite was directly deposited onto a PDMS substrate to form the flexible strain sensor. First, a PDMS mixture was prepared by mixing the silicone elastomer base and curing agent in a 10:1 ratio. Air bubbles were removed from the mixture using a desiccator. After that, the PDMS mixture was poured onto a rectangular acrylic mold and cured the PDMS in an oven at 80 °C for half an hour. The PDMS substrate has dimensions of 78 mm in length, 10 mm in width, and 2 mm in thickness. The SWCNTs were sonicated in toluene solvent for 5 h to achieve a well-dispersed SWCNTs solution. Here, toluene acts as a dispersant, breaking down the agglomerates of SWCNTs and promoting their dispersion. The obtained SWCNTs/toluene solution was combined with a freshly prepared PDMS mixture in a 10:1 ratio and stirred gently to disperse the SWCNTs uniformly in the PDMS matrix. After that, the composite was placed in a hot drier to allow the toluene to evaporate because the absence of toluene is crucial for obtaining reliable and stable strain sensor's performance. Thereafter, the thin

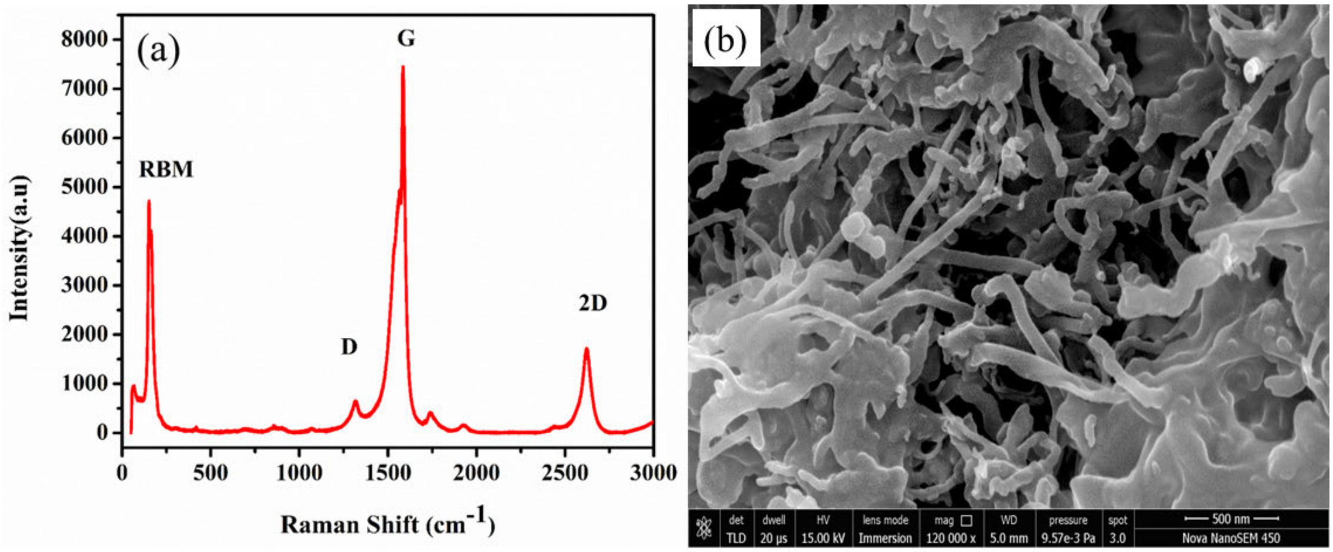

Fig. 2. (a) Raman spectra of SWCNTs. (b) SEM image of SWCNTs/PDMS strain sensor at 500 nm scale bars.

composite layer was deposited onto the cured PDMS substrate and again cured at 80 °C, enhancing composite adhesion on PDMS. The thin layer of the SWCNTs/PDMS film is 70 mm in length, 4 mm in width, and about 0.10 mm in thickness. At the final stage, electrical contacts were applied using conductive silver paste and copper wires.

In order to study detailed information about chemical structure, the Raman characterization is performed. Fig. 2(a) shows the recorded Raman spectra for SWCNTs. There are four major Raman bands observed for the CNTs: radial-breathing mode (RBM) bands around 150 cm^{-1}, D-band at 1325 cm^{-1}, G-band at 1594 cm^{-1}, and 2D-band at 2621 cm^{-1}. These four major Raman bands in the recorded spectra confirm the presence of SWCNTs.

C. Preparation of Smart Glove

The fabricated SWCNTs/PDMS strain sensors were integrated onto the latex glove. However, a challenge arises due to the incompatibility of PDMS and latex gloves with adhesives such as cyanoacrylate-based superglues. To overcome this issue, we opted for a different approach to integrating sensors on the glove.

We used an acrylic adhesive double-sided tape onto the latex glove, and then placed a thin copper tape on top. The next step involved placing a small amount of PDMS mix onto the copper tape and the fabricated sensor carefully placed on the PDMS mix. The sensors as a whole are shown in Fig. 3. Finally, the glove with sensors was cured using the hot oven, ensuring a stable and secure integration of the sensors onto the glove. This process was controlled and repeatable, ensuring consistency of sensor integration on the glove.

D. Development of Robotic Hand

First, the Standard Tessellation Language (STL) files were sliced using Ultimaker Cura 5.1.0 and 3-D-printed using an Ultimaker S5 with 0.2 mm precision and 60% infill. The hand was printed using PLA in the AA 0.4 mm core and

Fig. 3. Photographs of the smart glove fabrication process. (a) Acrylic adhesive double-sided tape onto the latex glove. (b) Thin copper tape with liquid PDMS on the acrylic tape. (c) Latex glove with SWCNTs/PDMS flexible strain sensors.

its support structures with PVA in the BB 0.4 mm core. The process required 80.3 m of PLA, 12.3 m of PVA, and 58 h of printing time. The PVA was dissolved in warm water, and the parts were smoothened with 220-grit sandpaper. The overall assembly process is described in Fig. 4. Appropriate bolts and screws were fixed at all the design joints.

The joints were glued together and 0.3 mm diameter high-strength Nylon strings were passed through each of the fingers and were fixed to the tip of each of the fingers from inside. One string was used per finger, and the two ends of each string were tied to MG946R servo motors. The motor was rotated to its 45° position when attaching the wrist end, with the finger resting position. Now, the motor is rotated to the 135 position, and the other end of the string is pulled till the hand reaches its gripping position. The string is then tied firmly to the motor. This assembling methodology ensures the controllability of the fingers by the motors with sufficient margins. Further mechanical deviations can be accommodated at the software level. This process is repeated for all five fingers. The robotic hand was assembled mechanically and electrically, and the resting and gripping positions of the motors were calibrated and fine-tuned.

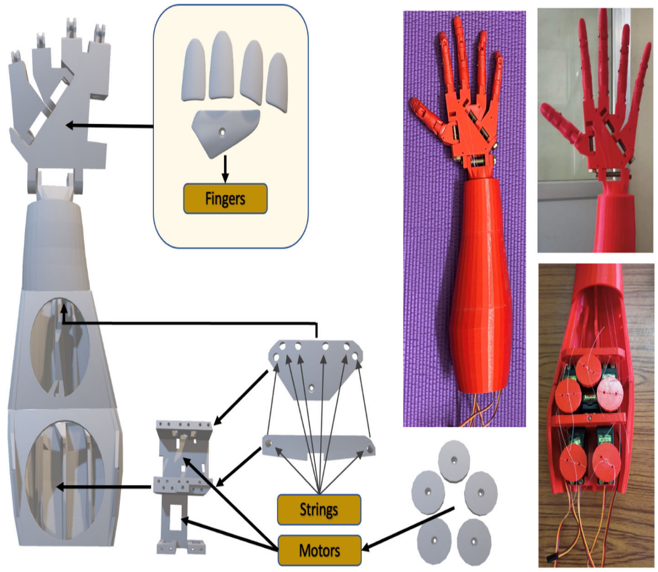

Fig. 4. Procedure followed for assembling the robotic hand.

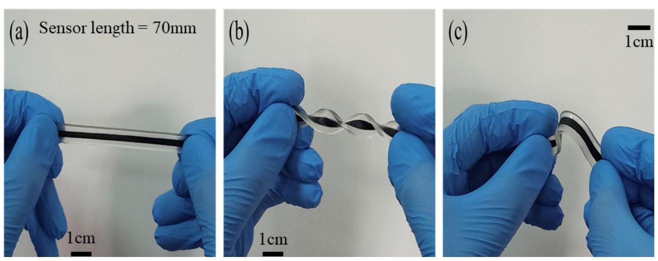

Fig. 5. Optical photographs of fabricated SWCNTs/PDMS-based flexible strain sensor: (a) stretchable, (b) twistable, and (c) foldable.

III. Result and Discussion

A. Electrical Performance of SWCNTs/PDMS Strain Sensor

The surface morphology of the SWCNTs strain sensor has been investigated by SEM, and it is noted that SWCNTs appear smooth, clean, long, straight, well aligned, and uniformly distributed, indicating a less defective wall of SWCNTs. Fig. 5 shows optical photographs of a fabricated SWCNTs/PDMS-based flexible strain sensor that is stretchable and twistable. These properties of the fabricated sensor make it a suitable candidate for integration onto gloves for HMI applications.

The electrical characteristics of SWCNTs/PDMS nanocomposites play a vital role in determining the performance of flexible and stretchable sensors, impacting their sensitivity and stability. The fatigue analysis and electrical performance of the flexible SWCNTs/PDMS strain sensor were evaluated under 3000 cycles of 50% strain, as shown in Fig. 6(a) and (b). The maximum strain values remained consistent, with a standard deviation (σ) of 0.33% in $\Delta R/R_0$ indicating high reliability and repeatability. Furthermore, in the enlarged images as depicted in Fig. 6(c) and (d), constant $\Delta R/R_0$ of about 13.2 was observed after 1000 and 2000 cycles, confirming the sensor's stability and reliability under continuous cyclic loading. As illustrated in Fig. 7(a), the variable resistance value of the strain sensor has a linear relationship with the applied strain. It is seen that the variable resistance value is increased with the increasing strain. Sensitivity is often quantified using the gauge factor (GF), which can be expressed as GF $= \Delta R/ (\varepsilon \times R_0)$ for piezoresistive-type sensors [36]. A higher sensitivity indicates that the sensor can detect smaller variations in the applied strain. Here, ΔR represents the change in resistance, R_0 is the initial resistance, and ε is the strain. The GF of the SWCNTs/PDMS strain sensor is 73 and exhibits remarkable sensitivity, making it highly suitable for detecting finger gestures.

B. Human Robotic Hand Interaction and Glove-Based Controllers

HMI devices facilitate effective communication and interaction between humans and machines. The importance of HMI devices lies in their ability to enhance user experience, increase productivity, and enable seamless control and monitoring of complex systems. Gestures are considered a linguistic communication technique that is intuitive, easy to use, and can be used as a special language to communicate with computers or robots. For this purpose, glove-based controllers are utmost important. These controllers provide the users with an intuitive means of controlling the robotic hands. Additionally, they play a crucial role in building extensive databases used to train models that can eventually replace human users. For example, these controllers may utilize pressure or strain sensors to convert finger motions into electrical signals. In disordered SWCNT networks, conduction is governed by the percolation model, treating the network as a random arrangement of resistors [37]. When tensile stress is applied to the sensor, nanoscale contacts are disrupted, increasing resistance. Conversely, compressive stress forms new contacts, creating additional conductive paths and decreasing resistance. The sensitivity of the sensor to strain is influenced by tube-to-tube coupling coefficients, which describe the "making and breaking" of contacts. This piezoresistive effect is central to the sensor's functionality and is integrated into latex gloves as previously detailed. The primary sensing element of the SWCNTs/PDMS strain sensor is a variable resistance. When it is stretched, the resistance changes. A generic voltage divider circuit was employed to measure the unknown resistance. The circuit transduces the resistance changes into voltage changes. Mathematically, the circuit can be described by the following equation:

$$V_{\text{out}} = V_{\text{in}} \frac{R_2}{R_1 + R_2} \tag{1}$$

where V_{out} is the output voltage, R_2 is the unknown resistance of the SWCNTs/PDMS strain sensor, R_1 is the known resistance, and V_{in} is a 5 V input voltage. V_{out} was recorded using Arduino's 10-bit ADC. Hence, using (1), the resistance of the flexible sensors can be calculated from the ADC's readings. The 16-point averaging is applied to handle any spurious readings, such as loose contacts or accidental shorting due to external metallic objects. Similar steps are also implemented to protect the robotic hand from any danger as well. The

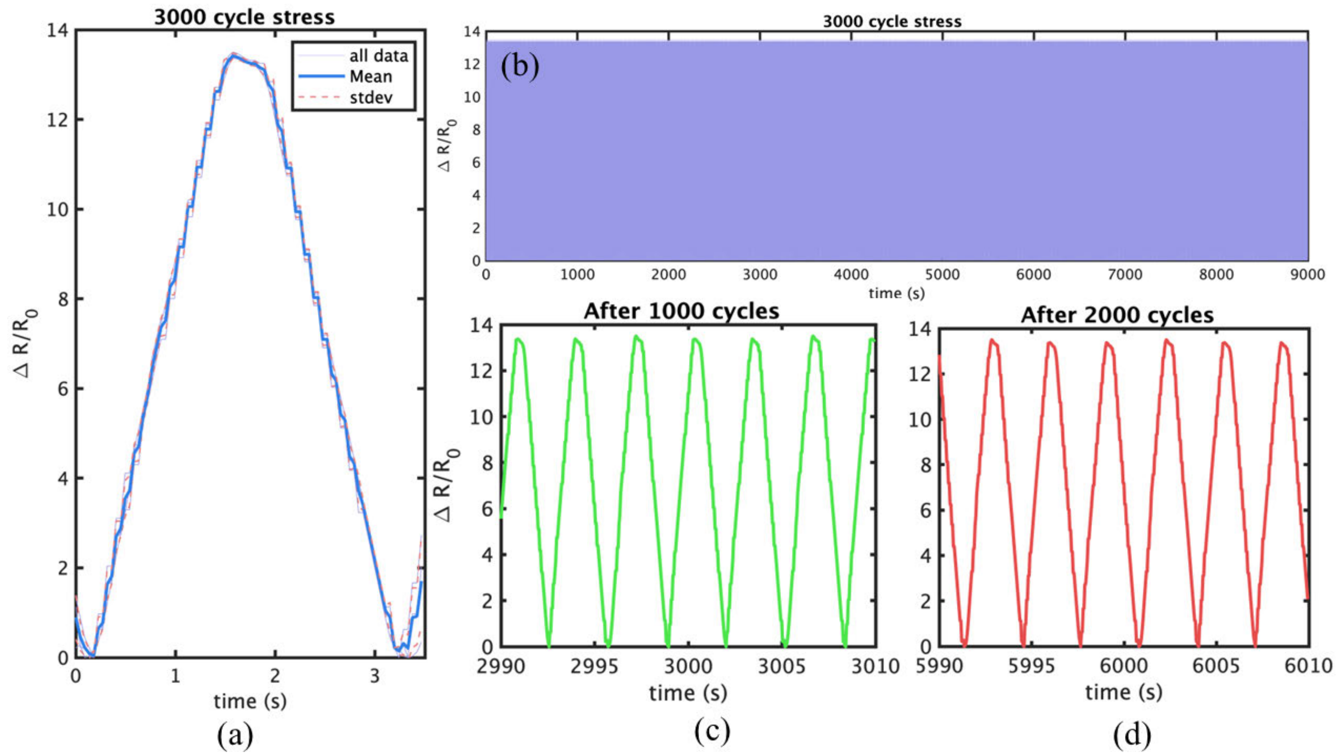

Fig. 6. (a) and (b) Variation of the electric resistance $\Delta R/R_0$ with time for the SWCNTs/PDMS strain sensor for repeated loading and unloading cycles. (c) and (d) Enlarged views after 1000 and 2000 cycles, showing a constant relative change in resistance.

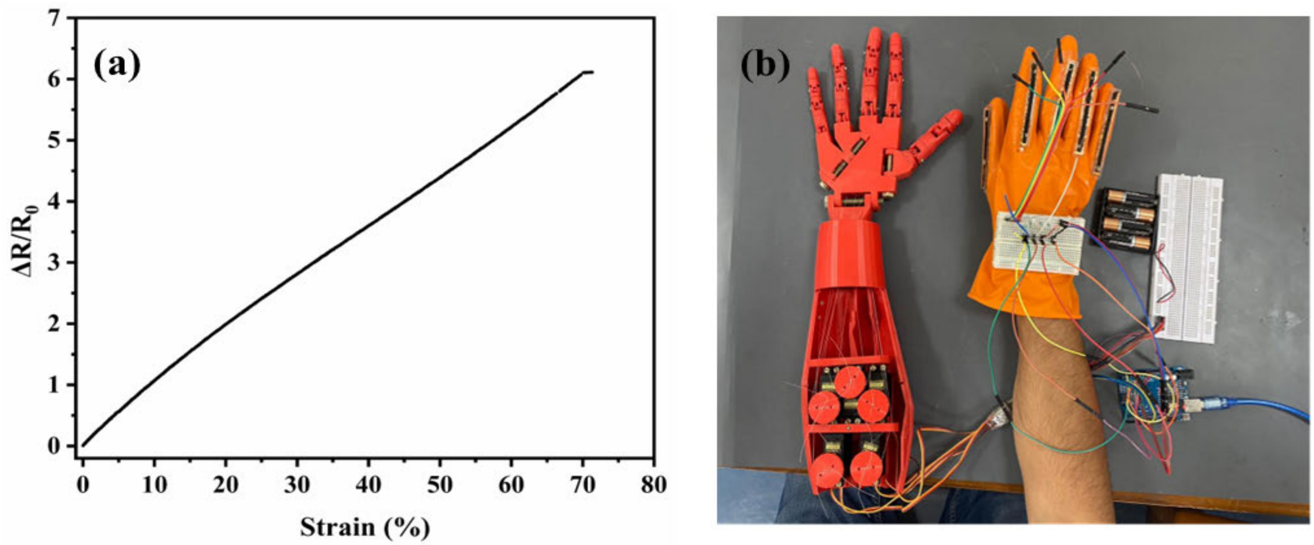

Fig. 7. (a) Sensitivity response of the fabricated SWCNTs/PDMS strain sensor. (b) Electrical assembly of the glove-controlled robotic hand.

voltage-converted resistance values of all sensors are sampled over 5 s at 100 Hz, and the average reading is set to be the baseline voltage of the glove. This value is subtracted from all future readings and mapping the resting position value to the 0 position is attempted. Next, the glove state visualizer tool is utilized. The interface utilizes a pair of scripts based on MATLAB and Arduino. These scripts sample the hand's state at a rate of 100 Hz and communicate the measurements to the MATLAB program through the serial interface. The program then plots the baseline-shifted voltages. This way, each finger can be tested and calibrated individually. The fingers are gripped one by one, and the peaks of the baseline-shifted voltage plots are noted. The gripping positions of all the fingers are assigned to be the corresponding peak values observed, establishing the baseline voltage and maximum deviation through calibration steps. The next step involves mapping these calibrated voltages to the observed motor positions. This mapping is inherently nonlinear due to the nonlinear variations in resistance and voltage as the fingers are slowly clenched.

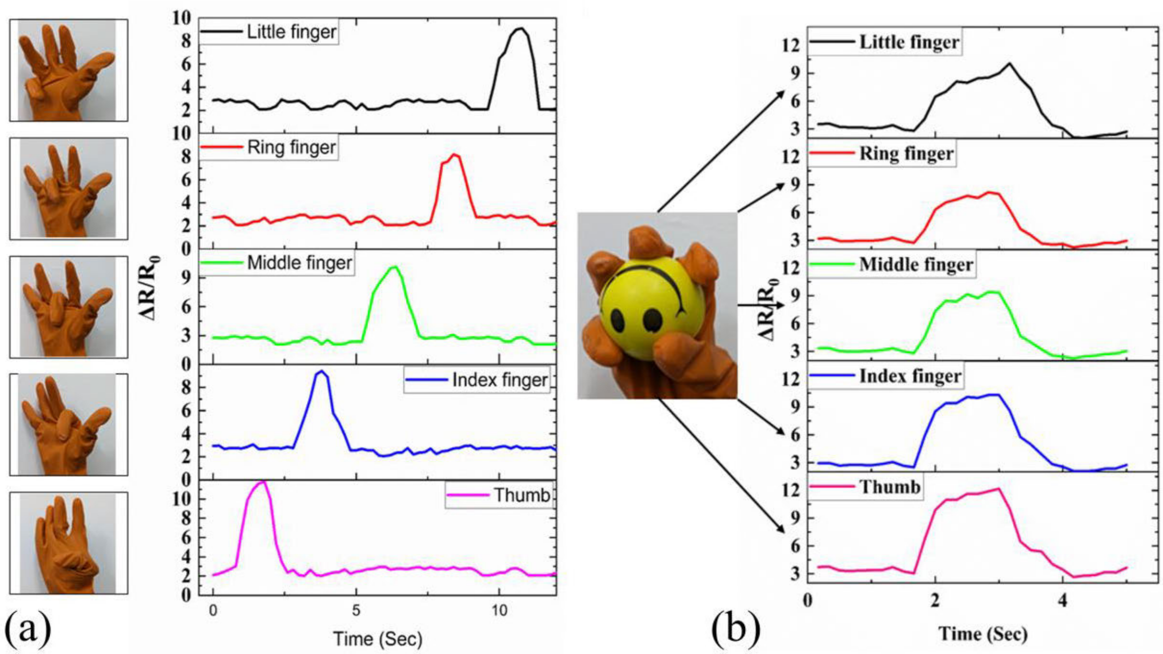

Fig. 8. (a) Strain data from the smart glove with different fingers bending. (b) Resistance variation while holding and releasing the smiley face squeeze ball placed within the fingers of the glove.

The glove-controlled robotic hand's electrical connections are shown in Fig. 7(b). Using five PWM pins, we use an Arduino Uno to read the glove's status and control the hand's servo motors. When the Arduino is powered via USB, it can only provide up to 500 mA, which is not enough for all five servo motors. However, if the 9–12 V barrel jack powers the Arduino, it can give 800 mA, but it is still close to the limit. Therefore, to meet power requirements, we have used a 6 V external battery and the servo motors were connected to a 6 V battery pack with AAA batteries arranged in a 4S configuration. The electrical assembly involves two breadboards designated for the glove and the robotic hand, as shown in Fig. 7(b). The wires from the smart glove are connected with the known resistance and Arduino. The wires from the robotic hand were neatly packaged into a 3 × 5 grid and taped in place. The 6 V battery's supply and ground are connected to the rails of the breadboard. Then, two arrays of five wires corresponding to supply and ground are taped together and connected into the slots in the 3 × 5 grid previously made. At last, another array is connected to the 3 × 5 grid, which branches into the PWM pins of the Arduino on the other side. This modular approach ensures a well-organized and efficient wiring setup for controlling the robotic hand.

C. Finger Motion Detection Using Smart Glove

Finger motion detection measurements were performed to verify the smart glove's suitability for HMI applications. The smart glove is equipped with five SWCNTs/PDMS strain sensors, which track the deformation of finger bending actions to record strain data for each of the five fingers. In Fig. 8(a), the strain response to various finger-bending actions is depicted as captured by the smart glove. Initially, one finger was bent and returned to its original position, repeating this process for all fingers. The recorded strain data corresponds to the thumb, index finger, middle finger, ring finger, and little finger. The smart glove and the SWCNTs/PDMS strain sensor can stretch and deform in response to finger movements. There is a noticeable variation in resistance linked to the bending of each finger.

This phenomenon results from the sensor stretching as the finger bends, reducing the conduction pathway and increasing resistance. When returning to its original state, the sensor underwent compression, which expanded the conduction pathway and consequently led to a decrease in resistance. Fig. 8(b) illustrates the smart glove's resistance changes, stemming from the SWCNTs/PDMS strain sensor's capability to detect and respond to the user's grip on the smiley face squeeze ball. When the glove wearer squeezes the ball, the strain sensor undergoes deformation, resulting in alterations in the electrical resistance within the SWCNT network. The resistance changes are measured through an electrical circuit integrated into the smart glove. Increasing strain (while holding the ball) results in a noticeable rise in resistance while decreasing strain (when releasing the ball) reduces resistance. The strain data for each finger correlates with the bending radius of curvature of the strain sensors. Around 1.7 s, the strain data rises as all five fingers exert pressure on the ball. The strain distribution across the fingers is uneven due to the varying pressures applied by different fingers to the ball. At 4 s, the strain data decrease as the external pressure from all five fingers is released from the ball. These observations indicate that the smart glove based on SWCNTs/PDMS strain sensors can be used in soft robotics to provide real-time feedback and control for soft robots, making them more adaptive, responsive, and capable of handling a wide range of applications such as HMI.

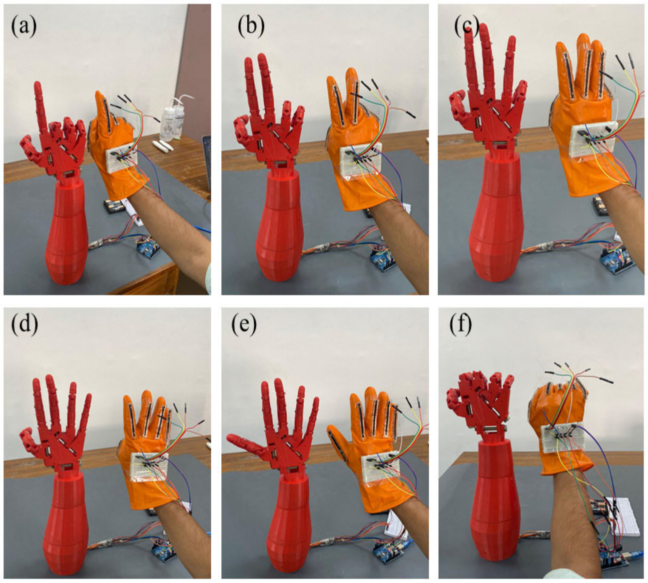

Fig. 9. (a)–(f) Photographs were taken while showcasing real-time human–machine interactions of a robotic hand using an SWCNTs/PDMS-based electronic glove-controlled opening and closing of a human finger.

D. SWCNTs/PDMS Strain Sensor for HMI Application

The fabricated smart glove is worn on the right hand to record finger gesture via SWCNTs/PDMS-based strain sensor. It is shown in Fig. 9(a)–(f) that the hand gestures successfully control the robot fingers. The successful dynamic control of the robot hand through human finger gestures demonstrates the practicality and potential of the smart glove that we have developed for human–machine interactions.

IV. Conclusion

In conclusion, this work presents a SWCNTs/PDMS composite-based flexible strain sensors integrated smart glove for HMI applications. The fabrication process of smart gloves is straightforward, rapid, and cost-effective, making it highly suitable for wearable electronic applications. The SWCNT/PDMS-based strain sensor demonstrates high sensitivity, long-term stability, reproducibility, and durability. To provide real-time examples, we show how the smart glove can be used to detect finger bending, holding, and releasing the smiley face squeeze ball placed within the fingers of the glove. The developed smart glove holds significant promise for advancing the field of HMI technology, enabling seamless and intuitive interactions between humans and machines. Moving forward, the smart glove could be improved with suitable packaging plan. Additionally, the electrical signal can be wirelessly transmitted to mobile devices in future for real time applications.

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