Soft Robotic Manipulation System Capable of Stiffness Variation and Dexterous Operation for Safe Human– Machine Interactions

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Soft robots have attracted great attention in the past decades owing to their unique flexibility and adaptability for accomplishing tasks via simple control strategies, as well as their inherent safety for interactions with humans and environments. Here, a soft robotic manipulation system capable of stiffness variation and dexterous operations through a remotely controlled manner is reported. The smart manipulation system consists of a soft omnidirectional arm, a dexterous multimaterial gripper, and a self-powered human–machine interface (HMI) for teleoperation. The cable-driven soft arm is made of soft elastomers and embedded with low melting point alloy as a stiffness-tuning mechanism. The self-powered HMI patches are designed based on the triboelectric nanogenerator that utilizes a sliding mode of tribo-layers made of copper and polytetrafluoroethylene. The novel soft manipulation system has great potential for soft and remote manipulation and human machine interactions in a variety of applications from elderly care to surgical operation to agriculture harvesting.

1. Introduction

Soft robotics makes full use of the softness, large deformation, and compatibility of various soft materials and actuation principles to achieve unique functionalities as well as safe manipulations.^[1,2] Over the past decades, a variety of soft robotic manipulators, i.e., soft grippers and soft arms, have been studied.^[3] Examples include pneumatically driven grippers,^[4] soft active material-based grippers,^[5] octopus-inspired soft arms,^[6] elephant trunk-inspired arms,^[7] and humanoid

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hands.^[2] Compared with traditional rigid robotic manipulators,^[8] these soft counterparts are more compliant, more adaptable, and easier to control, thereby more suitable for safe machine-human and machine-environment interactions, such as grasping fragile objects, picking apples, and assisting elderly people and children. Moreover, soft manipulators are unique for physical and distributed computations through their compliance feature, reducing the needs for sophisticated algorithms and mechanisms in planning and control for real-world applications.

The inherent compliant feature of the soft robots, on the other hand, poses critical challenges for achieving high structural stability and high loading capacity for specific applications, such as manipulation of heavy objects ^[9] and surgical operations.^[10] To overcome this, one potential

solution is to tune the stiffness of soft robots so that they can sustain external loads (including self-weight) or exert large forces for robust interactions when needed. A variety of methodologies and materials have been proposed to adjust the stiffness of soft materials and structures, including electrorheological (ER) and magnetorheological (MR) fluids,^[11] particle jamming,^[12] thermoplastics,^[13] shape memory polymers (SMPs),^[14] and low melting point alloys (LMPAs).^[15] However, ER/MR fluids generally have limitations of requiring proper leakproof packaging. Although particle jamming is a fast-responsive method for stiffness change, it requires a bulky setup for pumping and vacuum operations. The application of SMP is somewhat difficult for soft robots due to its high modulus in the martensite phase. Thermoplastic materials are based on localized heating to change stiffness, which is difficult for large area/volume materials as they would need many heating elements and complicated control designs. Compared to SMPs and thermoplastics, LMPAs can provide a large stiffness difference between solid and liquid states via Joule heating. Furthermore, self-healing can be intrinsically realized by the recrystallization of alloys.^[15] Therefore, LMPA is a promising candidate for achieving stiffness variation for soft robotics applications.

For many applications involving hazardous or dangerous environments (e.g., factory workspace or deep ocean), remote control of robots (including soft manipulators ^[16]) is desired. Human–machine interface (HMI) can achieve two-way information transmission between human and machines and has



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Figure 1. Soft robotic manipulation system capable of shape morphing and stiffness variation for safe human–machine interactions. A) Schematic illustration of the soft robotic manipulator system under the remote control of human–machine interface (HMI). B) Schematic illustration of a designed soft finger actuator for soft grippers capable of dexterous operations. The soft actuator can be bent bidirectionally driven by a single DC motor, and the flexible hinge structures and soft, porous blocks are utilized for smooth contact and ease of bending. The inset photographs show the casted soft blocks (60% porosity). C) Schematic illustration of the soft manipulator comprised of a soft arm capable of omnidirectional bending and a soft gripper with three soft fingers mounted on a compliant stander. D) Photograph of a soft arm prototype which can bend to an arbitrary direction under the programmable actuation.

been widely used in a broad spectrum of fields, such as smart electronics, robotics, and virtual or augmented reality (VR/ AR).^[17-19] Recently, wearable electronics has been explored for HMI use to collect and interpret physical and/or physiological data of human beings in various situations,^[19,20] such as the soft and conformable electroencephalogram (EEG) recording system for auricle,^[21] epidermal mechano-acoustic sensor for speech recognition,^[22] and stretchable devices for detecting wrist motions.^[23] Existing wearable sensing methods for hand motion detection are mainly based on mechanical motioninduced variations of electrical parameters (resistive/capacitive sensor),^[24,25] optical-based measurement,^[26] visual tracking,^[27] and physiological signal collection.^[28] However, these methods typically suffer from drawbacks such as the requirement for additional camera/lighting devices, poor wearability, poor signal-to-noise ratio (SNR), sophisticated computing algorithms, and the need for external power supplies. Triboelectric nanogenerators (TENGs), which are based on the coupling effects of electrification and electrostatic induction, can effectively convert the ambient mechanical energy into electricity.^[29] TENGs have great potentials for the self-powered sensing and flexible and wearable HMIs for sensing human motions/gestures by converting voltage signals into digital command for

electronic devices.^[30] For instance, a TENG-based VR 3D-control sensor was designed with two opposite touch spheres to detect all the six-axis directions in 3D space,^[31] and a delta-parallel TENG sensing gears with multiple electrodes was proposed to define 512 virtual sensing pixels for robot control.^[32]

Here, we report a remotely operated, soft cable-driven manipulation system consisting of a soft stiffness-tunable arm, a bioinspired gripper, and self-powered HMI controllers (Figure 1A). The soft robotic finger actuator is designed to have semiellipse-shaped hinges on both sides for bidirectional bending (Figure 1B,C). Thanks to the bioinspired design with flexible hinge structures, the soft multimaterial gripper of the manipulator is capable of opening and grasping operations. Foam-like filler blocks are used for filling the cavity/ grooves to prevent the cables from possible entanglement in manipulations without affecting the bending performance. The soft robotic arm is configured with three cables to achieve omnidirectional bending while the embedded LMPA tubes in the arm body enable on-demand stiffness change via Joule heating (Figure 1C,D). A compact, biocompatible, and easyto-use TENG-based HMI patch is proposed as a self-powered finger motion sensor for remote control of the manipulation system (Figure 1A). The soft manipulation system with the

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TENG-based wearable HMI is expected to have great potential in heavy loading applications of soft robotics and offers a new platform for future soft manipulator development.

2. Design and Fabrication of Soft Manipulator System

2.1. Design and Characterization of the Soft Robotic Arm

Figure 1C,D illustrates the bioinspired soft robotic manipulator that can bend omnidirectionally and grasp objects dextrally. The

cable-driven approach is employed for the actuation of the soft arm, in which motors can pull tendon cables embedded in the internal holes of the soft arm body to generate needed deformation/bending. Such an actuation approach is attractive owing to its intuitive shape morphing, simple fabrication process, and easy control designs. The soft robotic arm can bend in any direction via a three-cable configuration as shown in Figure 1C, and its stiffness can be adjusted through the phase changes of LMPA tubes under heating or cooling stimuli.

As shown in Figure 2A–C, the proposed soft arm is moldcast into a bellow profile using Ecoflex 00-30 (Smooth-on Inc.,







USA) to prevent the potential buckling arising from the compression of silicone rubbers. A central hole with diameter of 20 mm in the soft arm facilitates the bending of the arm, and three uniformly distributed smaller holes with a diameter of 8 mm are placed around the center hole for housing LMPA tubes that tune the stiffness of the arm. The 3D-printed cable fixators are used to fix the ends of the cables to the arm's tip. When the DC motors pull or release the cables in a programmable manner, the soft arm will bend to the desired bending direction and bending angle. With the three uniformly distributed cables and the miniature DC motors (130 rpm and 0.66 kg cm) (Pololu Inc., USA), the arm tip can reach any point in the sphere-like workspace as shown in Figure S1 and Movie S1 in the Supporting Information. It is demonstrated that the soft arm can generate a maximum bending angle of $\approx 90^{\circ}$ in any direction.

The soft robotic arm can tune its stiffness through heating or cooling of the LMPA tubes embedded in the arm body (Figure 1C,D). Under Joule heating, the LMPAs in the tubes change from the solid-phase state to the liquid-phase state, thereby varying the total stiffness of the robotic arm. The LMPA tube is fabricated by encapsulating LMPA (nontoxic Field's metal with 16.5 Sn, 32.5 Bi, and 51 wt% In, melting point: 62 °C) within a tube surrounded with heating coils (Figure 2D). Properties of the Field's metal are listed in Table S1 (Supporting Information). Other types of LMPAs (e.g., gallium) can also be selected for this purpose based on the required melting temperatures and mechanical properties needed in specific applications. To avoid the possible separation of the materials, we prestretch the silicone tubes before injection of the LMPA in the fabrication process (Figure 2D). Owning to the equilibrium of the internal stress, ruptured LMPA segments in the solid state can easily be rejoined together upon heating, resulting in its self-healing capability. A larger density of coil turns typically gives rise to more uniform melting of LMPA but consumes higher energy. In our design (Figure 2E), the LMPA core stored in a tube can be fully melted in ≈ 100 s when a constant current of 0.3 A is applied. However, the cooling down of LMPA may take longer time (\approx 160 s) due to the poor heat dissipation and convection between LMPA and its surrounding environment. The mechanical behaviors of the LMPA tube in a complete solid (heat OFF) or liquid (heat ON) state are presented in Movie S2 (Supporting Information).

Figure 2F-H shows the finite element (FE) simulation results of the soft arm segment under the soft and the hard state, respectively, when subjected to concentrated forces. When the soft arm is vertically mounted on the platform and a pulling force of 2 N is applied to a cable in the arm by the DC motor, the solid LMPA tubes (heat off) will prevent it from deflecting (Figure 2F). When the weight of the soft gripper (≈ 160 g) is considered for a precurved arm, the arm will be bent all the way down when the Joule heat is applied to the LMPAs without the cable pulling force. On the contrary, the solid LMPA tubes can maintain the profile of the soft arm without generating large deflections (Figure 2G). The LMPAs in solid state and the cable-pulling effect could further enhance the loading capacity of the soft manipulator, as shown in Figure 2H, an extra 1000 g load is applied on the curved arm. Figure 2I,J shows the FE simulation results and the experimental data about the effects of LMPA tubes on the deflection of the soft arm which is held horizontally under its own weight. It is observed that the soft arm can remain straight with a small tilt angle of 23°, deviating from the original (horizontal) direction when the LMPAs are in the cool (solid) state, while the tilt angle increases to 63° under gravity when the LMPAs are heated to liquid state. The maximum strain of the soft arm is reduced from 57% to 14% when the LMPA in the tubes switches from the liquid state to the solid state.

2.2. Design and Fabrication of the Dexterous Soft Gripper via Mimicking Human Fingers

Stable, robust, and dexterous soft grippers are critically important for soft robots to perform tough tasks successfully. To balance the requirements in material properties and actuation performances, a common solution is to utilize a relatively stiff/ rigid frame together with certain flexible joints for constructing finger actuators. For cable-driven soft grippers, an engineered design with suitable notches or hinges can be a promising option for ease of implementation and adjustment.^[33] In this work, inspired by the phalanx structure and joint motion of a human finger, we design the primary frame for the soft finger with interlaced semiellipse hinges on both sides (one more hinge on the inner side for better inward bending behavior) (Figure 3A). Such hinge structures can produce larger bending displacements than other patterns, like circular and corner-filleted hinges, with the same actuation forces.^[34] The main frame of the soft finger is mold-cast with Dragon Skin 30 (Smoothon Inc., USA) to obtain a relatively high stiffness using a 3D-printed mold (Figure 3A).

To realize bidirectional bending with only one single motor, two arrays of holes are routed through the entire body away from the center axis. In addition, two square grooves are created on the fingertip to accommodate cable fixators. External notches may incur possible entanglements of the driven cables with sharp tips in real applications, for example, interference and entanglement of cables with the contacted or surrounded objects in the working environment (e.g., tree branches in apple harvesting tasks). Therefore, we design soft filler blocks to fill the notches and encapsulate the exposed cables with negligible rigidity increase in bending actuation (Figure 3B). The foamlike filler blocks (porosity ≈60%, Figure 1B) made of Ecoflex 00-30 are integrated onto the semiellipse notches to encapsulate the exposed cables. These blocks can easily be stretched and compressed, and barely constrain the flexion/extension of soft fingers. To reduce the number of motors required, we employ a spindle with two identical grooves for twining threads in the opposite directions (Figure 3C). When the DC motor rotates clockwise, Cable-2 will be pulled up (outward bending of the soft finger) while the prerotated Cable-1 will be released simultaneously without interfering outward bending, and vice versa. Also, a spindle cover with its inner surface matching well with the profile of the spindle may be designed to restrict the moving space of cables to prevent them from jumping out of the groove.

Figure 3D illustrates the bidirectional bending performances of the as-fabricated soft finger actuator. As the actuation



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Figure 3. Design, fabrication, and characterization of a dexterous soft gripper. A) Schematic of the fabrication process of the main frame of the finger actuator made of Dragon Skin 30. Schematic illustration of a soft finger actuator that is cable-driven and capable of bidirectional bending via equipped flexible hinge structures. B) Schematic of the fabrication process for the foam-like soft block fillers made of Ecoflex 00-30. The porosity of the soft block filler can be controlled by salt percentage during mixing. C) The spindle structure designed for two-way cable-pulling in both directions by one DC motor. The spindle cover can facilitate the cable movements in the grooves (marked with red). D) Experimental results for the bidirectional bending of a soft finger actuator with porous filler blocks under different cable-pulling forces. E) Numerical results for the bending profiles and strain distributions in the finger actuator filled with fully elastomeric blocks under the same pulling forces in (D). F) Designed structure of the compliant finger stander for a three-fingered gripper. The stander is made of Dragon Skin 30 and the remained pathways are for driven cables. G,H) Photograph of an assembled soft gripper for opening and grasping manipulations.

motor rotates, the overall length of the inner cable wound on the spindle will be reduced and the tension in the cable will make the soft finger gradually bend along a certain direction by squeezing the soft blocks placed in the semiellipse notches. Soft blocks with a lower modulus are preferred for the bending actuation. Experimental results (Figure 3D) show that the soft finger can produce an inward bending angle of 112° when a cable-pulling force of 5.2 N is applied, and an outward bending angle of 80° under a pulling force of 4.8 N. Figure 3E shows the bidirectional bending profiles and the strain distributions of the actuator under different forces, corresponding to the cases shown in Figure 3D. As the soft filler blocks simulated in normal form (zero porosity) exhibit higher elastic modulus, slightly larger forces are required to bend the soft finger to the same extent, indicating that the porous blocks can facilitate the flexion/extension of finger actuators.

We finally mount three soft finger actuators onto a compliant stand (Figure 3F) to form a fully soft gripper that can freely perform opening and grasping operations (Figure 3G,H). To increase the initial grasping size, in our design each soft finger is configured to have a tilt angle of 30°, and the two cables that are embedded in the soft finger are kept in the precast holes and pathways in the stand to connect with the corresponding DC motors fixed on the bottom base (Figure 3F). The soft finger



actuators can bend in a programmable manner by controlling the rotation direction and retention time of DC motors (Movies S3 and S4, Supporting Information). The soft gripper is able to grasp an object with a weight of ~500 g based on the selected motors and a larger grasping capacity can easily be obtained by replacing the small DC motor with a larger one with higher torque. The workspace of the soft manipulator consisting of a soft arm and a gripper is fitted through the operation testing data (Figure S1, Supporting Information). The touching or gripping points are constrained in an elliptic hemispheroid contour with a maximum radius of 190 mm and a height difference of 132 mm. Larger workspace and more complex bending profiles can be achieved by equipping the soft arm with multiple segments.

2.3. Design and Characterization of the Self-Powered Human-Machine Interface for Remote Operations

Hand motions are the mostly easily captured information via wearable devices for implementing HMI in a variety of applications, such as dactylology, robotic control/guidance, and augmented reality (AR) and virtual reality (VR).^[24,35] Here, we propose a new self-powered HMI design through triboelectric nanogenerator (TENG) technology for simple but robust motion detection so that remote operations of the soft manipulator can be implemented effectively and with low-cost. As illustrated in **Figure 4**A, the flexion and extension of a human finger are based on the rotations of hinge joints located between the phalanges. Proximal interphalangeal (PIP) joint, the joint



Figure 4. Design and working principle of the TENG-based HMI patch for remote control of the soft manipulator. A) Schematic illustration of the structures of an index finger and the corresponding hinge model based on PIP joint. The tensile displacement of the skin around PIP joint is linearly related with the rotation angle of PIP joint. B) Schematic design of the TENG-based HMI patch. Two separate parts are built with PTFE and copper triboelectric layers. C,D) Demonstration of a compliant TENG-based HMI patch worn on a thumb. The rotation of PIP joint will generate a relative slide motion between the two tribo-layers, resulting in a voltage signal. E) Working principle of the HMI patch in slide mode for electricity generation. F) The output voltages of the HMI patch induced by two different bending degrees of human finger (slight and full bending) and the selection of a threshold value for robust control.



located between the proximal and the middle phalanxes, possesses the highest flexibility and motion independence among all joints.^[36] In addition, the tensile displacement of the skin around the PIP joint is linearly related to the joint rotation angle, enabling both quantitative and qualitative measurements.^[37] Therefore, our TENG-based HMI patch is developed based on the simple motion detection of the PIP joint through a sliding working mode and converts finger motions into fast responsive signals for soft manipulator control.

The TENG-based HMI patch consists of two separate components for easily implementing the lateral sliding motions for the tribo-layers to convert mechanical energy of finger motions into electricity (Figure 4B). Part A of the patch contains a PET strip covered with a thin copper film and partially stuck to the adhesive surface of a piece of Kinesio tape. On the other hand, Part B is built as a shallow chamber structure, and a PET strip, first covered with a copper layer and then a polytetrafluoroethylene (PTFE) layer, is sandwiched between two pieces of Kinesio tape. Kinesio tape (SME Inc., USA) is adopted as the substrate layer in the wearable HMI patch owing to its superior flexibility, strong durability, good water resistance and biocompatibility.^[38] Ionized air injection can be utilized to enhance the surface charge density of the PTFE triboelectric layer,^[39] which can improve the output voltage magnitude and thus the control sensitivity. When the TENG patches are attached onto the proximal and middle phalanxes, respectively, the two tribo-layers will slide relatively under the rotation of finger joint, dragging the copper strip out of/into the chamber structure and resulting in voltage signals for control purpose (Figure 4C,D).

Figure 4E describes the working principle of the TENG-based HMI. In the initial state, the two triboelectric layers are in close contact and overlap each other, and there is no electric potential generated due to the electrostatic equilibrium between PTFE and copper layers. Once the finger bends inward, a relative slide is induced between the two tribo-lavers due to the rotation of PIP joint. Then, a potential difference is formed between the two electrodes, resulting from the in-plane charge separation. When the TENG is connected to an external resistor, a transient current will be generated to neutralize the electrons induced by triboelectric effects. Further bending of the human finger will prolong the charging process and the new electrostatic equilibrium state can be achieved once a full separation between the tribolayers is done. On the contrary, when human finger extends, the copper layer in Part A will slide backward and then be stacked together again, resulting in a reverse current. We measure the voltage signals from different bending gestures of fingers (Movie S5, Supporting Information). As can be seen from the real-time monitoring data, the induced voltage varies with the finger flexion angle (PIP joint) and such a triboelectric signal exhibits the merits of rapid response and ultrahigh sensitivity, demonstrating obvious peaks at slight flexion cycles (<30°).

Since the output voltage by the TENG patch has a positive correlation with the bending angle of human finger, a threshold-based control method can be adopted for capturing the intended finger motions with the assistance of a Arduino board and a radio-frequency module (Figure S2, Supporting Information).^[17] To make the HMI patch a stable and robust "controller" for teleoperation of the soft manipulator, voltage signals induced from the involuntary finger movements or from the interferent movements of adjacent fingers should be eliminated through a suitable signal processing method (Figure 4F). It is demonstrated that a maximum peak voltage of 1.5 V is generated with an external resistor load of 500 $M\Omega$ by a slight flexion of thumb ($\approx 30^{\circ}$), while a minimum peak voltage of 3 V is generated when the thumb ($\approx 90^{\circ}$) is fully bent (at a frequency of 1 Hz). Thus, a threshold value in the range of 1.5–3 V, close to the upper limit, can be selected as the threshold value to ensure the sensitivity and robustness of the triggering. In such an approach, when the finger gestures are performed, the filtered signals will be generated for control purpose. The threshold value for each TENG patch may be calibrated after repeated use due to the negative influence of humidity (e.g., sweat) and degradation of the output performance of the tribolayers. This newly designed TENG-based HMI patch is able to detect human hand motions (e.g., finger flexion/extension) more conveniently and effectively than other methods through voice control or computer vision detection.

3. Evaluation and Demonstration of the Soft Robotic Manipulation System for Remote Operations

The soft robotic manipulation system can be remotely controlled by the designed wearable HMIs in an assembled compact design. As shown in Figure 5A, the whole system consists of a soft robotic gripper, a soft tunable arm, a wireless communication module (i.e., receiver and transmitter), and a few wearable TENG-based HMI patches. Triboelectric signals induced by the flexion/extension of human finger joint will be first processed (amplified & rectified) and sent to the analog ports of Arduino board (Figure S2, Supporting Information). Then, the analog-to-digital converters (ADC) converts the analog voltage signals into digital values, which will be wirelessly transmitted to the control board. The central processing unit (CPU) on the board will compare the received signals with the defined thresholds to determine whether and how to actuate the DC motors for operating the soft manipulator. In our prototype, there are totally six miniature DC motors: three of them for the bending actuation of the arm and the other three for the bending control of soft fingers (Figure 1C). Thus, the soft robotic manipulator can be completely controlled by a few HMI patches to achieve different gestures, as necessary. When the TENG-based HMI patches are worn on fingers, induced voltage signals from finger bending will be wirelessly transmitted through multiple channels to different actuation units of the soft robotic manipulator system (Figure 5A). The real-time processed signals generated from the motions of fingers are presented by the serial plotter using the open-source software, Arduino Integrated Development Environment (IDE) (Figure 5B). Each voltage peak above the threshold can be regarded as a bioinspired "button" for executing specific motion commands for the soft robotic manipulator. We can further program the corresponding commands for each TENG-based HMI according to specific preference or requirements.

Figure 5C,D presents the interactions of the soft manipulator and the human fingers via the TENG-based HMI. In the



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Figure 5. System-level integration and evaluation of the soft robotic manipulation system. A) Schematic diagram of the soft robotic manipulator system including a soft gripper, a soft tunable arm, HMI patches, and wireless communication module (receiver and transmitter). CPU, central processing unit; ADC, analog-digital converter. B) Real-time signals triggered by different flexion and extension behaviors of human fingers. Each time a peak voltage signal that exceeds the corresponding threshold value will be translated into a digital command for robotic control. C) Demonstration of the soft robotic manipulation system in a synchronous robotic control scenario. The HMI patches are assigned with different control commands for actuating the motors/cables for desired manipulations. The soft arm is wirelessly remotely controlled to perform omnidirectional bend through the motions of human fingers via the HMI patches. D) Demonstration of the soft manipulator for collaborative operations with human hand under remote control mode via HMI patches.

first case, the three TENG-based HMI patches are designated separately for controlling bending of the soft arm. When a valid trigger signal is applied through finger flexion, the signal will be converted into a command for controlling the rotation of DC motors. As depicted in Figure 5C, the soft arm will bend to the left side when the index finger is bent, and then the flexion of thumb will actuate another motor/cable to turn the arm counterclockwise. If necessary, one can set the reverse commands for HMI patches to achieve a full operation of the soft arm. For a vertically hanged soft manipulator (Figure 5D), the trigger signal by the flexion of thumb can be programmed to control the grasping operation of the gripper. A series of actions are performed sequentially as follow: the soft arm is first bent to approach the object (i.e., a roll of Kinesio tape) by bending the right index finger; the trigger signal induced by the thumb will then drive the soft gripper to grasp and hold the object. A

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secure grasp can be achieved by multiple flexions of the thumb. Finally, the arm restores back to its initial position/gesture by bending the left index finger. The TENG-based HMI can conveniently and robustly control the soft robotic manipulator with satisfied accuracy and precision.

4. Conclusion

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In summary, we have developed a soft robotic manipulation system based on the bioinspired cable-driven soft arm and a soft gripper together with a self-powered HMI patch. The soft robotic arm is bellow-shaped and omnidirectionally bendable while the soft gripper equipped with three fingers is capable of performing dexterous opening and grasping operation. The embedded LMPA tubes in the soft arm can adjust the overall stiffness of the arm body through phase changes of alloys under Joule heating and achieve a self-healing capability. A multimaterial design including a stiffer finger frame and porous hinge filler blocks enables the soft finger actuator to be easier to bend and more robust for interactions and gripping. Additionally, the soft manipulator based on the cable-driven mechanism is scalable for constructing longer and more complex systems in a modular design approach, without losing the flexibility and convenience in controlling and installation. The self-powered TENG-based HMI is a flexible, compact, and biocompatible tool for motion sensing and controlling. The flexion/extension of the human finger leads to a relative sliding motion between the tribo-layers and generates a voltage output correlated with the bending amount. For easy implementation and robustness to interference, a threshold-based control strategy is employed to filter the voltage signals for the potential HMI between the manipulator and human fingers. This research presents a compact, low-cost, and robust design and approach for building advanced soft robotic system and provides a new solution to achieve wireless control of soft robots for safe human-machine interactions.

5. Experimental Section

Fabrication of the Soft Arm: An assembled 3D-printed mold, including reverse sawtooth covers and several cylindrical rods, was first prepared for mold casting with polyvinyl chloride (PVC) tubes as the hole fillers for installing driven cables. Ecoflex 00-30 (weight ratio of Parts A and B = 1:1) was well mixed and then poured through the top opening of the mold, and after curing, the arm segments were demolded with tube filler removed and bonded robustly by a silicone rubber glue, Sil-poxy (Smooth-on Inc., USA). To reduce the friction between the cables and silicone body and avoid cable-induced damage to the soft materials, three short tubes were trimmed and bonded to the junctions of arm segments. Two-terminal disc-shaped silicone ends were cast and connected to the soft arm body for easy installation. Finally, three braided fishing cables (30 LB) were guided through the cable holes in the arm body, and each has one end surrounded around a screw on the cable fixator and the other wound over the motor shaft.

Fabrication of the LMPA Tubes: The as-purchased molten Field's metal (ChemistryCabinet, USA) in hot water (100 °C) was sucked into a silicone tube (Uxcell, China) with an inner diameter of 4 mm using a syringe. Holding the position of the plunger and removing the tube out of water, the liquid LMPA core gradually solidified at room temperature. Then, the tube filled with solid LMPAs was prestretched longitudinally

by pushing it to slide along the core (2–3 mm), and the stretched tube parts were filled by silicone adhesive for encapsulation. Finally, a coil of nichrome (radius of 0.05 mm) was wound around the tube for applying Joule heating.

Fabrication of the Soft Fingers: A 3D-printed mold was prepared with PVC tubes as hole fillers (Figure 3A) and filled up with Dragon skin 30 mixture (a weight ratio of parts A and B = 1:1). The finger frame was demolded after curing process, with the inserted tubes trimmed correspondingly, which can reduce the potential wear and tear arising from the cable pulling. Elastomeric foam-like block fillers were made by mixing elastomers (Ecoflex 00-30 mixture) with salt (Figure 3B) for desired porosities, which can be calculated from Equation (S1) in Text S1 (Supporting Information). A centrifugal mixer (ARE-310, Thinky, US) was utilized to mix the elastomers and salt for achieving a homogenous compound for casting and the ultrasonic bath was used to accelerate dissolution of the remaining salt particles in elastomers. For integration, two fishing lines were routed sequentially along the holes of finger frame and the soft blocks, each with one end twined on a spindle and the other fixed on a cable fixator. Sil-poxy was employed to the contact surfaces for a robust junction of these two components.

Fabrication of Kinesio-Tape-Based TENGs: The PET film (thickness of 0.2 mm) was covered by a thin copper foil (0.05 mm) (EMI Ltd., China), and then multiple pairs of PET-based strips could be cut from it with two sizes (1.5 \times 3.6 and 1.5 \times 5.0 mm²). The PTFE film (0.1 mm) was flattened onto the copper layer of the shorter strips with connected wires. Meanwhile, Kinesio tapes were cut into suitable sizes for serving as substrates. The longer strip was bonded onto the adhesive layer of a slender piece of Kinesio tape, forming Part A, while the shorter one with PTFE was stuck onto the top of the tape by using a doublesided adhesive tape. For electron injection, the PTFE strip was connected to the anode of a high voltage polarimeter (ET2673A), and the needles pointing to PTFE surface were wired to the cathode with a 10 mm vertical distance. A polarization voltage of 6 kV was applied onto the needles and lasted for 4 min for electron injection. Then, a wider Kinesio tape piece with its release liner partially trimmed on both sides was placed and stuck on the shorter strip, forming a free-moving chamber structure, Part B.

Measurement Setup for TENGs: Current preamplifier (Keithley 6514 System Electrometer) was used to measure the output voltage of the TENG-based HMI device. In addition, a real-time signal collection and display system was realized via a programmed LabVIEW interface.

Finite Element Modeling: Finite element (FE) analysis was performed with software package, ABAQUS 6.14. For modeling the LMPA embedded arm, the CAD models of the arm and LMPA cores were discretized by four-node tetrahedral elements. Ogden constitutive model was used to fit the mechanical properties of Ecoflex 00-30: μ 1 = 0.001887; α 1 = -3.848; $\mu^2 = 0.02225; \ \alpha^2 = 0.663; \ \mu^3 = 0.003574; \ \alpha^3 = 4.225; \ D1 = 2.93;$ D2 = 0; D3 = 0,^[40] and the physical property of Field's metal in solid state was selected from Table S1 (Supporting Information). LMPA cores were bonded onto the hole surfaces via a tie constrain, and self-contacts of arm's profile were defined in case of large deformations. In terms of boundary conditions, the bottom end of the arm was constrained in all degrees of freedom (DOFs) and a gravitational force was applied along required direction. Cable-pulling action was simplified by adding a concentrated force on the cable fixation point. As for the simulation of the soft finger, a combined rigid body frame and soft blocks (zero porosity) via a tie constraint were discretized by four-node tetrahedral elements. The mechanical property of Dragon skin 30 was simulated as an incompressible hyper-elastic Mooney-Rivlin model with an elastic modulus of 1 MPa and Poisson ratio of 0.49,^[41] while the soft blocks were modeled by Ogden constitutive model. The pulling forces were directly applied to the fingertip, and all the DOFs of the other end of the finger was fixed. Static FE analysis was used to predict the deformations and strain distributions of soft bodies made of different materials and to investigate the performance of the components along with actuation forces in specific configurations so as to meet the design requirements before prototyping.

Data Process and Wireless Control Setup for the HMI: The analog voltage signals generated by the TENG patch were converted into digital

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signals by an analog-to-digital converter in Arduino Nano. Because the analog port only allows positive voltage less than 5 V, thus, a resistor (500 MΩ) and a Zener diode (5.1 V) were connected in parallel with the TENG-based HMI patch to remove the background noise, adjust the input voltage level, and protect the circuit board. The microprocessor of transmitting board can compare the trigger signals with the thresholds and determine whether or not to transmit the commands to the relevant motors through a radiofrequency (RF) module (nRF24L01), which employs the 2.4 GHz band and works with a transmission rate of 250 kbps to 2 Mbps. For the motion control board of the soft manipulator, an actuation module (L298n) was connected with the Arduino UNO to increase the allowed operating voltage for motors (up to 46 V).

This manuscript involves the application of wearable HMI for wirelessly remote control of soft robotic manipulator. The HMI patches were attached to the finger surface of the subject to detect the bending gesture, and the subject was one of the authors of this manuscript. Therefore, these experiments were carried out with the full, informed consent of the subject, in accordance with all local laws and without relevant ethical issues.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Keywords

grippers, human-machine interfaces, motion sensors, soft arms, soft robotics, triboelectric nanogenerators, variable stiffness

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