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A Novel All-in-one Manufacturing Process for a Soft Sensor System and its Application to a Soft Sensing Glove

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***Abstract*— A sensing glove is an attractive application of wearable devices. Soft sensors are emerging to replace rigid sensing units, especially for wearable sensor systems, due to its inherent softness, flexibility, and stretchability. However, the fabrication process for the soft sensors is usually complex, time-consuming, labor-intensive, and has low production rate. To integrate a sensor system, an assembly process is essential, which may make the system bulky. Moreover, a solution for the electrode parts has rarely been suggested, although a bulky electrode part may obstruct the user's movement and degrade performance of the sensor. Thus, in this study, a novel fabrication process is suggested based on direct ink writing (DIW) of eutectic gallium-indium (EGaIn), which forms all the items in the sensor system from the sensing units, wiring, and the electrode part. A sensing glove for 2D finger motions was fabricated, and its performance was verified in terms of linearity, dynamic response, and accuracy. The sensing glove can be used as an easily-wearable and an intuitive interface to the virtual reality environment.**

I. INTRODUCTION

Measuring finger motions has been one of attractive topics, because human interacts with the environment and manipulates an object using their hands [1]. Researchers captured finger motions to analyze grasping motion [2], understand the in-depth anatomical structure of the fingers [3], control a robot in the remote region [4], [5], evaluate and improve the efficacy of rehabilitation process [6], [7], and provide an interface to a virtual environment [8], [9]. However, it has been a challenging task to capture finger motions without interrupting the user's motions, due to limited space on the fingers and complexity of finger motions. In case of a camera-based motion capture system, multiple cameras and complicated calibration process are required, and the occlusion problem is especially severe for the hand [10], [11].

To deal with this challenge, various sensing gloves have been developed to reduce cost, space requirement, and weight, improve compactness and mobility of the system, and provide comfort, flexibility, and convenience of wearing, while satisfying a certain level of resolution and accuracy [6], [7], [12], [13]. Many sensing gloves consisted of multiple sensing units assembled into a system, using Flexpoint sensors [14], optic fibers [15], linear encoders or potentiometers with flexible wires [16], [17], and soft sensors [2], [18], [19]. Such an assembly process requires sophisticated and time-consuming handwork to sew or bond the individual sensors,

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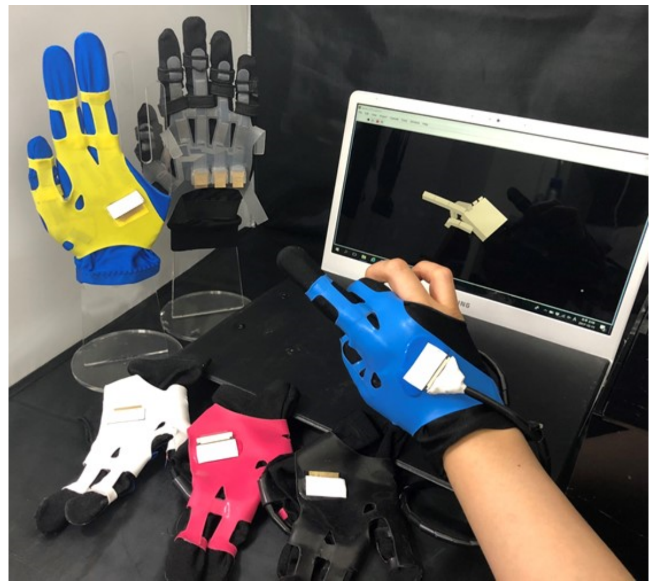

Fig. 1: Soft sensing gloves with various forms and colors fabricated by DIW of EGaIn

which increases the size and cost of the system and makes it difficult to modify alignments of the sensors. However, most of the commercialized sensing gloves even require the assembly process, e.g. CyberGlove [20], Data Gloves [21], Synertial IGS cobra glove [22], and perception neuron [23]. Therefore, a novel solution is required to fabricate a sensing glove without an assembly process.

Another mainstream in the field of sensing gloves is to replace the sensing units with soft and stretchable sensors. Highly stretchable sensors allow minimal discomfort to the user, moderate durability, bio-compatibility, and light weight [7]. Although soft sensing gloves have been developed in various forms, the fabrication process requires high dexterity and extra care with low production rate [2], [18], [19], [24]–[27]. This problem can be alleviated through mask deposition [28], 3D printing [29], embedded 3D printing [30], and hybrid 3D printing [31]. However, the response of the sensors showed time-dependent variation against step excitation due to relatively high viscosity and low homogeneity of the functional materials, which may cause undesirable time-dependent response of the sensor signal [28]–[31]. In addition, the matrix material had relatively high tensile modulus ($> 1\ MPa$), which is not a preferred property for a soft sensor.

In the field of stretchable electronics, eutectic gallium-indium (EGaIn), which is readily available, has drawn much attention due to its attractive properties [32]–[36]. Using the highly flexible and conductive nature of the liquid metal, various types of soft sensors have been developed without severe time-dependent response such as relaxation [2], [19], [25], [37]. Nevertheless, the fabrication process includes casting, bonding, and injection, which requires high dexterity, resulting in low production rate and inaccurate shape of the microchannel containing EGaIn [12]. Also, the size of the sensor system cannot be reduced further, because the assembly process is required inevitably [2], [19].

The fabrication issue can be solved by the direct ink writing (DIW) technique, recently reported by many researchers [38]–[43]. It was found that EGaIn had writable characteristics on surfaces with different levels of roughness [38], and even a free standing 3D structure can be printed, achieving 100 times larger values than the Rayleigh stability limit [39], [41]. Due to its superior structural stability from the spontaneously formed oxide layer, an arbitrary shape of the microchannel can be written directly with EGaIn in a stable manner by adjusting the flow rate of EGaIn and the feed rate of the syringe [42].

In the previous studies, the phenomena related to DIW of EGaIn were investigated and discussed well, but the system-level application, such as a sensing glove, has rarely been reported. In addition, none of them suggested an appropriate solution for the electrical connection from the microchannel to the interface for signal acquisition, which may obstruct free movements of the user and degrade performance of the sensors due to bulky and unstable electrical connection [14].

Thus, in this study, a novel fabrication process for a soft sensor system is introduced, which produces a monolithic structure including all the required items from sensing units to the electrode parts. The signals from the fabricated sensor system can be acquired through commercialized connectors and flexible flat cables (FFC) with the compact and stable structure of the electrode. In addition, the fabrication process minimally requires intervention of the skilled hands, provides extreme flexibility to modify the sensor design, and enables manufacturing a large-area sensor system, resulting in high production rate of the sensing gloves with various forms and colors (Fig. 1). Based on the suggested fabrication technique, a soft sensing glove was manufactured and its performance was tested in terms of linearity, step and relaxation response, and accuracy.

The remainder of this paper is organized as follows. Section II covers anatomical structure of the fingers and kinematic model of it. In Section III, fabrication process is described in detail. In Section IV, experimental verification of the sensing glove is presented. Finally, conclusion and future work is given in Section V.

II. Design of a Sensing Glove Based on a Kinematic Model of the Fingers

Attached on the epidermal side of the hand, a soft sensing unit estimates the joint angle by measuring strain generated on the skin (Fig. 2 (a), (b)). For this, each sensor was located on the target joint at the longitudinal direction of the fingers (Fig. 2 (c)). In this study, a sensing glove was composed with the ten sensing units, attached on the upper side of the fingers to measure flexion and extension (FE) of the proximal interphalangeal (PIP) and metacarpal (MCP) joints of the four fingers, and the interphalangeal (IP) and MCP of the thumb. The serpentine microchannel (radius of curvature $= 350\ \mu m$) was placed on the articular surface of each joint, to maximize difference of resistance change between the sensing part and the wiring part. The center of the serpentine patterns were placed on the center of the joints. All the sensing units are connected to the electrode part through the wiring parts, which has $1\ mm$ pitch at the end.

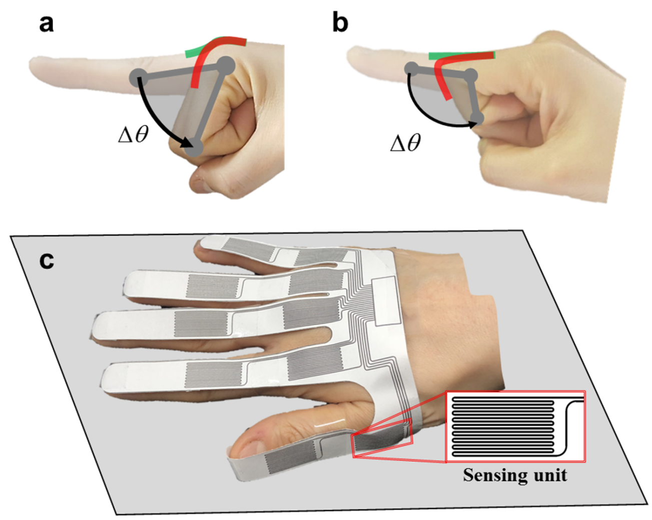

Fig. 2: Design process of a sensing glove: (a) measuring FE of the PIP joint and (b) the MCP joint, and (c) design of a sensing glove for 2D finger motions.

III. Fabrication of a Soft Sensing Glove

A. Fabrication steps

Fig. 3 illustrates detailed steps to manufacture a soft sensing glove through DIW of EGaIn. First, a silicone layer was coated onto a flat circular wafer through spin-coating process (Fig. 3 (a)). Dragon Skin 30 was used as a elastomer matrix [44]. The desired pattern of sensing units and wirings were directly written by EGaIn (Fig. 3 (b)). The custom board was placed at the end of the wiring parts, and the electrode parts were connected by writing EGaIn (Fig. 3 (c)). The written traces were covered by uncured silicone material through squeezing (Fig. 3 (d)). The cured part was trimmed by a laser cutter (Fig. 3 (e)). The workpiece was bonded onto a fabric glove by applying uncured silicone material (Fig. 3 (f)). The electrodes within the custom board were connected by a assembling the contact-type connector module, which was combination of a contact connector and a FFC connector (Fig. 3 (g)). Finally, the sensing glove can be used by connecting a commercial FFC.

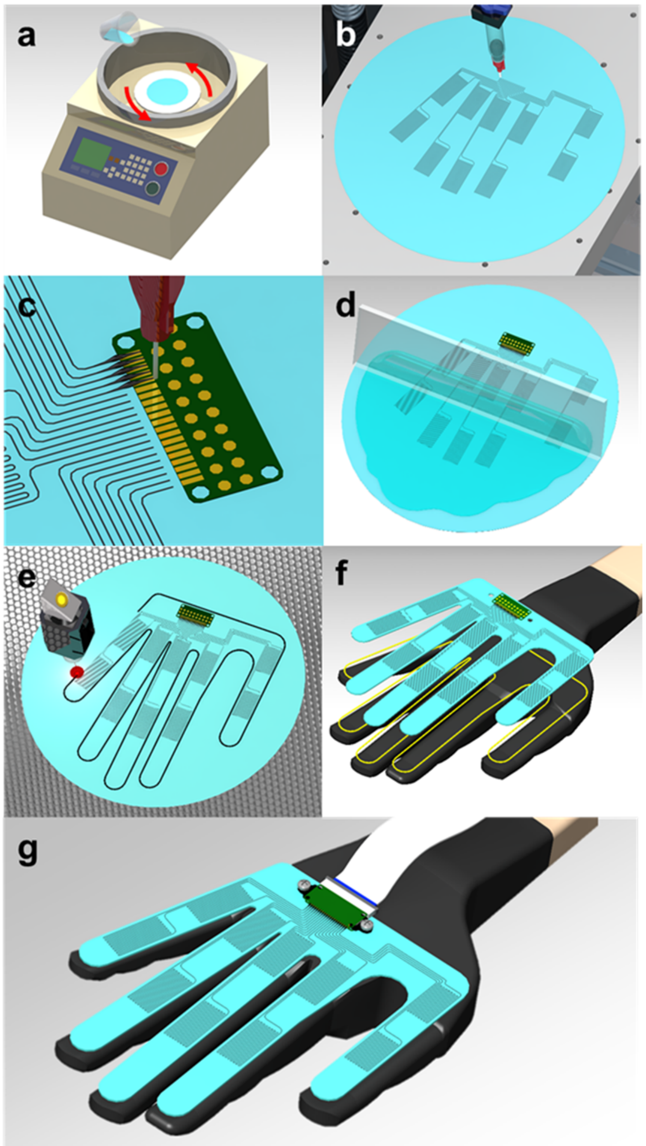

Fig. 3: DIW-based fabrication for a soft sensing glove: (a) spin-coating, (b) DIW of EGaIn, (c) writing the electrode part, (d) silicone squeezing, (e) laser cutting, (f) bonding, (g) a completed sensing glove connected with a FFC with the contact connector module assembled.

B. Equipment setup

Fig. 4 (a) describes the equipment for DIW of EGaIn, which consists of a triaxial precision stage with a syringe motorized by a pneumatic dispenser. For more accurate calibration of the height, a highly sensitive loadcell (Nano 17, ATI Industrial Automation [45]) was attached at the end effector. The printed feature can be characterized by width (W) and height (H) of the cross-sectional area of the microchannel as shown in Fig. 4 (b). To adjust the printed features, the related process variables (Fig. 4 (c)) can be controlled, such as dispensing pressure (DP) from the dispenser, feed rate (FR), inner diameter (ID) of the syringe, and stand-off distance (SOD) between the syringe tip and the substrate. The effect of each process variable is well-explained in [43]. In this study, the process variables were set as follows: DP = 0.1 kPa, FR = 500 mm/min, ID = 410 μ m, and SOD = 50 μm.

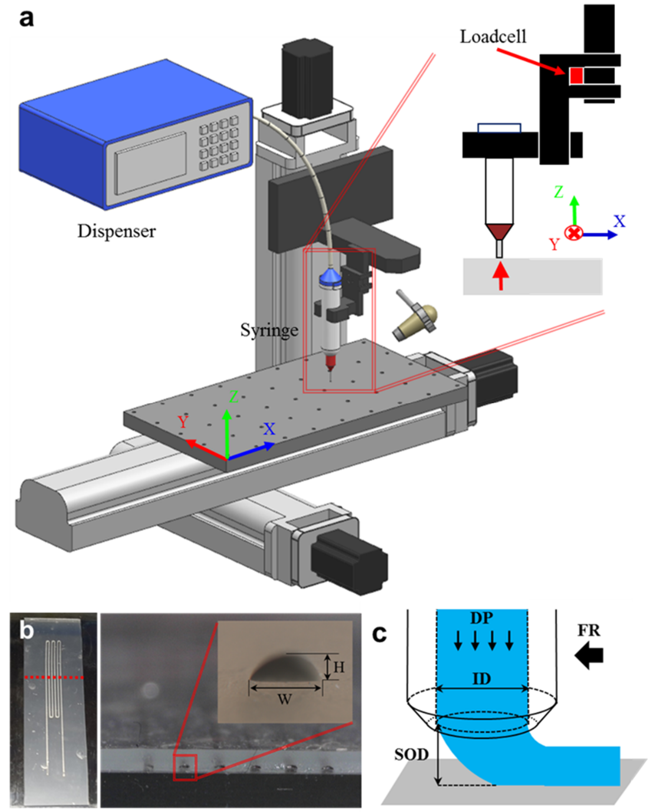

Fig. 4: (a) Equipment for DIW, (b) features of the soft sensor, and (c) process variables of DIW of EGaIn.

C. Direct ink writing of sensing units and electrodes

As shown in Fig. 5 (a), the sensing glove was successfully written along a large area (200 mm diameter circular wafer), including sensing units, wirings, and the electrode part. The custom board (thickness=0.3 mm) was designed to widen the pitches between the wires from 1 mm to 2.54 mm. All the items were written within 15 minutes. The written EGaIn traces of the electrode part were highly consistent as shown in Fig. 5 (b).

IV. Verification of a Sensing Glove

Fig. 6 (a) shows the developed soft sensing glove worn by a user with a FFC connected. The sensing glove can be worn and removed within 15 seconds, providing the same feeling of a fabric glove. To verify performance of the soft sensing units, a rotary potentiometer was placed on a target joint with rigid links attached on each phalanx (Fig. 6 (b)). In this experiment, the MCP and PIP joints of the index fingers were selected, which can be easily accessed through the lateral surface of the hand. The experimental results are shown in Fig. 7.

Relationships between the joint angles estimated by the rotary potentiometer and sensor signal were acquired with

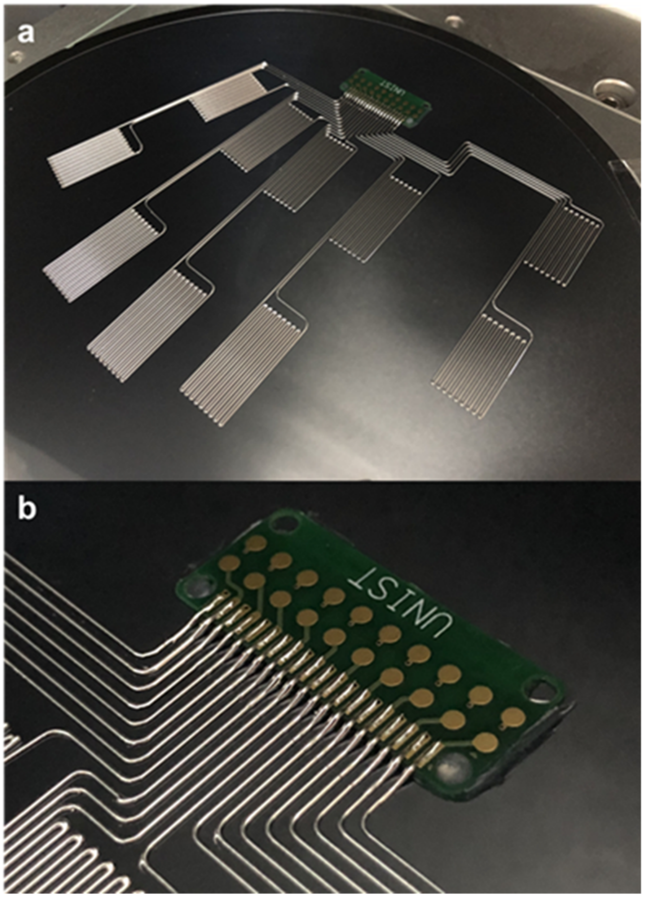

Fig. 5: (a) Written traces of EGaIn for a sensing glove, (b) a detailed snapshot of the electrode part.

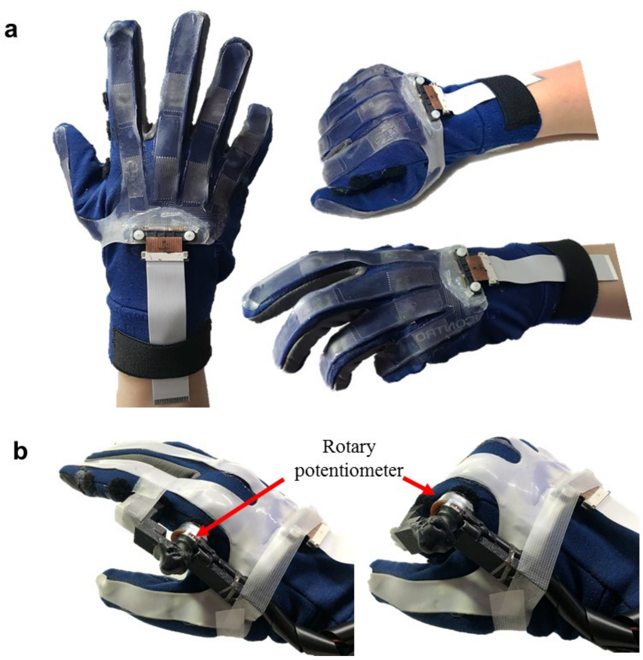

Fig. 6: (a) Soft sensing glove worn by a user, (b) rotary potentiometer attached on the lateral surface of the MCP joint.

different angular speeds, 60 deg/s, 90 deg/s and 120 deg/s (Fig. 7 (a), (d)). As shown in the results, the sensor response hardly varied with loading speeds. Slight hysteresis was observed in the both joints, which was attributed to viscoelastic property of the silicone material and fabric. The R^2 values of each linear model were 0.985 and 0.982 for the MCP and PIP joints, respectively.

To test step and relaxation of the sensor, the subjects were instructed to flex and extend their finger as fast as possible. The experimental results are presented in Fig. 7 (b), (e). In the previous reports, severe time-dependent responses were occasionally observed in soft sensors [2], [19], [25], [37]. Using the highly homogeneous, conductive, and flowable EGaIn, the sensor signals were settled in 0.4 s for both step and relaxation interval, without a time-dependent response. Thus, it can be claimed that the suggested sensor system is appropriate to measure dynamic motions of the fingers.

The arbitrary finger motions were estimated by soft sensors and compared with the joint angles measured by the potentiometer (Fig. 7 (c), (f)). As shown in the results, the errors were within ± 5 deg and ± 10 deg and the root-mean-square errors were 4 deg and 2.5 deg for the MCP and PIP joints, respectively. The captured finger motions can be simultaneously reconstructed by the 3D animation (Fig. 8) using a gaming interface (Unity [46]). Verified in the experiments, the soft sensors successfully estimated both static and dynamic motions of the fingers.

V. Conclusion

To meet the increasing demands of the sensing gloves, the important issues are reliable fabrication and stable and compact electrical connections of soft sensors. In this study, the two issues were resolved by direct ink writing (DIW) of conductive liquid, so-called eutectic gallium-indium (EGaIn). The suggested fabrication process rarely requires the intervention of the skilled hands, because the important parts, such as the sensing units, wiring, and electrode parts, were directly written by EGaIn using the automated equipment. That is, the suggested fabrication process is highly flexible and programmable (thus, easy to modify the designs), and efficient (all the writing was done in 15 minutes, from printing the sensing units to connecting the electrode parts). Using the suggested fabrication technique, the sensing gloves can be manufactured with different forms and colors. In addition, wearing the sensing glove, the users cannot feel significant difference between a normal glove and the sensing glove. In this paper, the detailed steps of the fabrication process was presented and the performance of the sensing glove was experimentally verified. The sensing glove measured joint angles with root-mean-square error smaller than 5 deg.

As future work, the accuracy of the sensing glove will be improved by selecting an appropriate fabric of the glove, and attaching the sensing units properly and firmly. In addition, the additional sensor will be added to capture 3D finger motions. Also, sensing gloves will be applied for wide purposes, such as sign language recognition and a

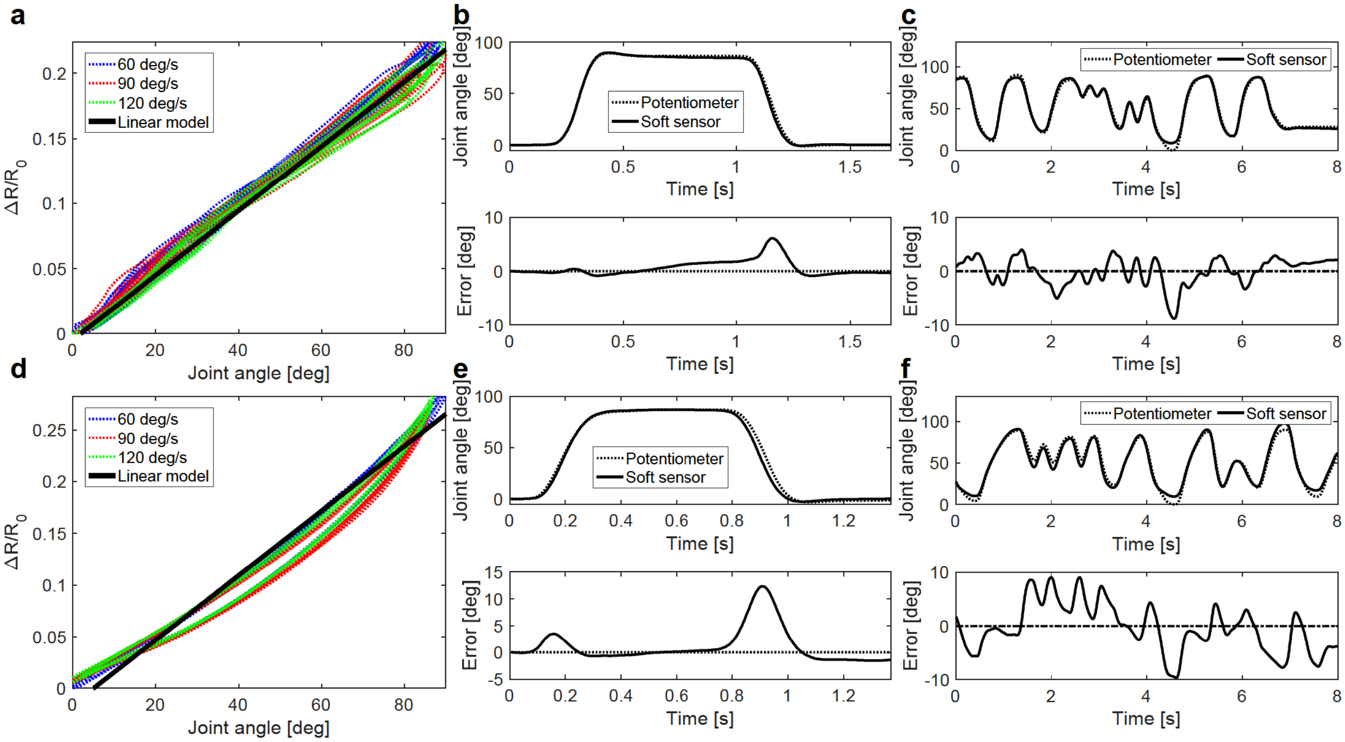

Fig. 7: Experimental results for the MCP joint: (a) joint angle versus sensor response, (b) step response, (c) estimation of joint angles during arbitrary motions, and the PIP joint: (d) joint angle versus sensor response, (e) step response, (f) estimation of joint angles during arbitrary motions.

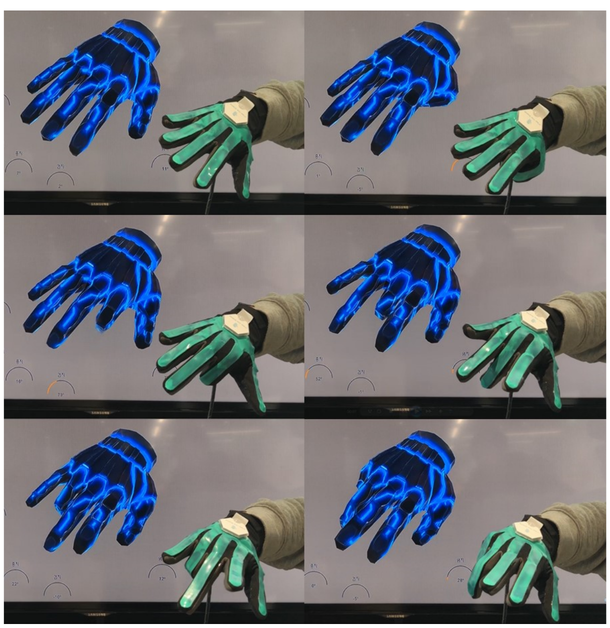

Fig. 8: The soft sensing glove and synchronized animation.

control interface for the virtual reality with a improved sensor calibration by a machine learning algorithm.

VI. Acknowledgment

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