Tactile sensorized glove for force and motion sensing

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***Abstract*—Frequent use of mobile gadgets has led to hand injuries, including thumb tendonitis and carpal tunnel syndrome. Despite the high incidence rates and severity, current monitoring tools are still limited and are ineffective in performing hand assessment. To overcome this, we developed a flexible and soft wearable tactile sensor glove capable of measuring forces and finger motion. The tactile sensor system comprised flexible and stretchable strain gauge and pressure sensor. The sensing elements are almost imperceptible to the user, and can be easily embedded into the glove for tactile sensing applications. The sensorized glove provides minimal discomfort to the user. The electrical signals are measured and transmitted via a custom-built wireless module. The dynamic electrical resistance profile of individual sensors may be retrieved for further analysis. Accordingly, we demonstrate the simultaneous measurements of thumb movement and reaction forces exerted on the thumb. Overall, we envision this technology to provide both clinicians and users real-time dynamic monitoring and measurements of finger movement for rehabilitation or therapy.**

Keywords— wearable electronics; flexible sensor; stretchable strain gauge; tactile glove.

I. INTRODUCTION

Our fingers are extremely dexterous and are capable of fine motor movements, such as tip pinch and small objects manipulation [1]. Therefore, impairment to the fingers, either through trauma, stroke, neuropathological or autoimmune diseases, will inevitably impede many activities [2], and hence reduce our quality of life. Recently, the pervasive use of mobile gadgets has led to an alarming trend of users suffering from repetitive strain injuries, prevalently on the thumb and wrist [3]. Often, these patients suffer from tingling sensations and limited range of motion. If untreated, these patients may develop thumb tendonitis or carpal tunnel syndrome [4], which may eventually lead to permanent disability. Despite its high incidence rate and severity, finger assessment is still limited to hand dynamometers which provide only static results. Furthermore, these devices are bulky and restrict natural hand movements. Other tools require motion capture technology but this requires the subject to be within the cameras' field of view [5], thus limiting the ease of use.

Here, we developed a tactile sensorized glove system capable of measuring finger forces and finger motion. The glove system consisted of multiple thin-film flexible and stretchable strain gauges and force sensors to independently measure finger movement and pressure. Data were transmitted wirelessly through a custom built module attached to the glove sleeve, and were recorded for further analysis. The entire glove system was worn within minutes with minimal discomfort to the user. With this, we were able to provide real-time dynamic measurements of finger movements for assessment.

II. TACTILE SENSING PRINCIPLE

Tactile sensing in terms of texture, softness, shear forces or normal forces define the sensory system on our fingers. These information is derived usually through a combination of forces and motion. Therefore, in order to create an artificial tactile sensing system, independent stretchable strain gauges and flexible sensors were used. In particular, these thin-film physical sensors that are nearly imperceptible to the user were used in our sensorized glove. The fabrication methods and operational principles of the sensors are further described.

A. Strain gauge

The design of the flexible strain gauge is shown in Fig. 1 (a). The conductive trace follows a U-shaped loop of width 2 cm, length 14 cm, width 2 cm and gap 5 cm. The fabrication of the strain gauges was previously described [6]. Briefly, it utilized screen printing technology to deposit silver ink on a silicone elastomer to create an electrically conductive trace. The conductive trace can be assumed to be a variable resistor of resistivity ρ_m, length l, and cross-sectional area A. Correspondingly, the electrical resistance of the strain sensor, R_m, may be calculated in (1).

$$R_m = \frac{\rho_m l}{A} \tag{1}$$

The strain sensors were embedded at the dorsal end of the thumb phalange to measure its movement. Consequently, when the thumb was flexed, the silicone elastomer was stretched. The length of the mesh network was then increased and the cross-sectional area of the mesh network was reduced, resulting in proportional increase in the resistance.

B. Pressure sensor

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In order to achieve pressure sensing of maximal flexibility, robustness, sensitivity and compliance, we used a novel flexible liquid based microfluidic sensor, as previously described [7]. The design of the microfluidic sensor is further illustrated in Fig. 1 (b). Briefly, silver electrodes were printed on the polyethylene terephthalate (PET) substrate of 50 μm thickness. Next, the top layer was designed and fabricated using soft lithography techniques. The functionalized PET substrate and platinum cured silicone elastomer layer were then adhered together after exposure to ultraviolet ozone for five minutes. Finally, conductive metallic liquid (eutectic gallium indium) was injected into the microstructure and sealed using uncured silicone rubber. The flexible sensor was embedded near the fingertip within the glove. The sensor location allowed measurement of reaction forces acting on the anterior side of the distal thumb phalange. Due to the small strain, the sensor may be assumed to follow Newtonian load-compression behavior, and the electrical resistance could be derived as (2).

$$R_F = \int_{-r}^{r} \frac{\rho_f}{2h\sqrt{r^2 - x^2}}\, dx = \frac{\pi \rho_f}{2h} \tag{2}$$

where R_F is the electrical resistance of the pressure sensor, ρ_2 is the resistivity of the sensor, r is the radius of pressure sensing region and h is the microchannel height. Using equation (2), when forces were applied to the sensor region, the microchannel height collapsed, resulting in a proportional increase in its electrical resistance.

III. Wearable Sensor Glove System

As proof-of-concept, we developed a tactile sensorized glove system using the strain gauge and pressure sensor as previously described. The user may put on the glove for measuring thumb movement and thumb pressure during object manipulation. Fig. 1 (c) illustrates the wearable glove system and the positions of various components: strain gauge, pressure sensor, wireless module, and lithium polymer battery. The open glove system allowed ease of access to the sensors and ensure fit for users of different hand sizes. The sensors were connected to the custom-built wireless module, as shown in Fig. 1 (d). The module, measuring approximately 50 mm by 40 mm, was powered using 7.4V lithium polymer battery. Data were sampled at 10 Hz and transmitted wirelessly using Bluetooth to a connected PC.

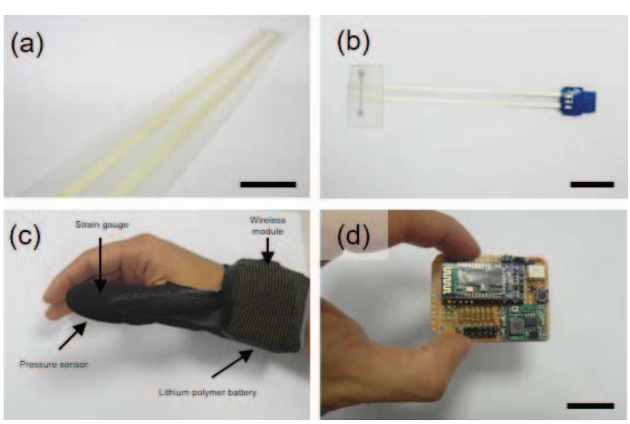

Fig. 1. Overview of the wearable sensor glove system. (a) Design of the flexible strain gauge, and (b) flexible pressure sensor. (c) Photograph of the wireless tactile sensorized glove, indicating the positions of the various components. (d) Photograph of the custom built wireless module for data transmission. Scale represents 2 cm.

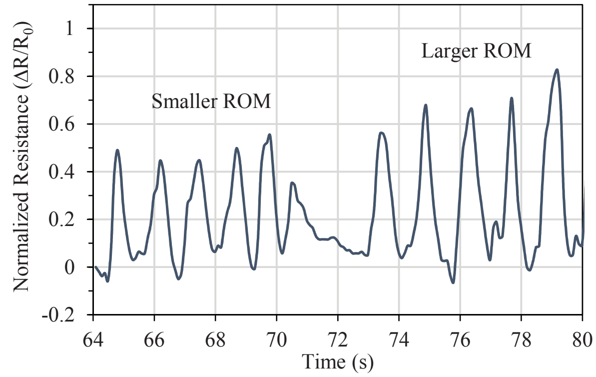

Fig. 2. Normalized resistance values of the strain gauge when the thumb was in circular motion.

IV. Results and Discussion

We first characterized our strain gauges and microfluidic sensors based on the various finger movements, such as thumb rotation, thumb bending and reaction forces on the thumb during pinch grips. We further analyzed the potential of the tactile sensor glove to assess finger dynamics while using a mobile phone.

A. Thumb rotation

To demonstrate the potential of the strain gauge to measure thumb rotation, the subject was asked to rotate his thumb about its long axis of the carpometacarpal joint in a circular motion, of arc radius approximate 25 mm. Subsequently, the radius was then increased to approximately 30 mm. Notably, when the thumb was fully adducted and pronated, the strain gauge was in its most stretched state. Fig. 2 shows the normalized resistance of the strain gauge corresponding to the thumb rotation. As expected, the normalized resistance peaked when the thumb was fully opposed. When the range of motion was increased, the strain gauge was further stretched, resulting in an increase in its electrical resistance.

B. Thumb bending

Next, we assessed the capability of assessing thumb bending using the same strain gauge. The subject was asked to flex his thumb about the metacarpophalangeal joint. Fig. 3 shows the normalized resistance values of the strain gauge

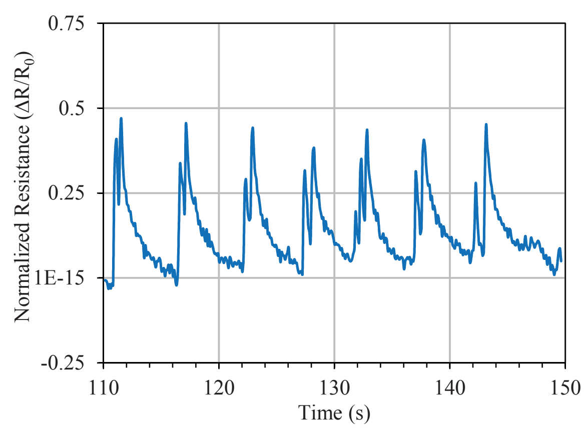

Fig. 3. Normalized resistance profile of the strain gauge when the thumb is bent.

when the thumb was flexed. Here, we noted that the normalized resistance profile was distinctly different from that of the circular motion. Particularly, we observed a distinct two sharp peaks when the finger was flexed. We hypothesized that the sharp peaks could be attributed to a sharp kink in the strain gauge, leading to temporary discontinuity but recovered quickly with material relaxation.

C. Reaction forces on the thumb

To further assess the microfluidic sensor in measuring reaction forces, the subject was asked to perform repeated key pinch grips, where the thumb pad opposed the radial lateral side of the index finger, and then relaxed. Fig. 4 shows the normalized resistance profile of both sensors during the grip movements. We observed that the distinct peaks were formed when the thumb was engaged in the pinch position. Subsequently, when the thumb was relaxed, the electrical resistance fell back to its original baseline. Similarly, we noted a corresponding periodic resistance profile of the strain sensor arising from the slight movements of the thumb. Overall, the sensors were consistent and repeatable in measuring the key pinch strength exerted by the user.

D. Simultaneous thumb movement

Finally, to assess the usability of the sensorized glove, the subject was asked to perform several manipulations on the smartphone, such as typing on a touchscreen, tapping at buttons on the touchscreen and making swiping motions on the touchscreen. Data were collected simultaneously from both sensors and transmitted wirelessly to the PC. Fig. 5 shows the data that were recorded during the task manipulations. Evidently, it demonstrated that distinct electrical signatures may be obtained from the different thumb gestures. We further observed that the thumb movements and forces during these tasks were well characterized. Altogether, the sensors captured the forces and motion consistently and worked independently from one another.

V. Conclusion and Future Work

Hand dexterity is critical in many daily activities, and serves as an important measure of one's quality of life. In this aspect, many factors including neurodegeneration and even repetitive strain injuries may attribute to loss of hand motor functions. Hand rehabilitation may regain some of these functions, but its assessment is currently limited and somewhat lacking. In order to provide dynamic assessment with minimal obtrusion to user, we proposed a sensorized glove system

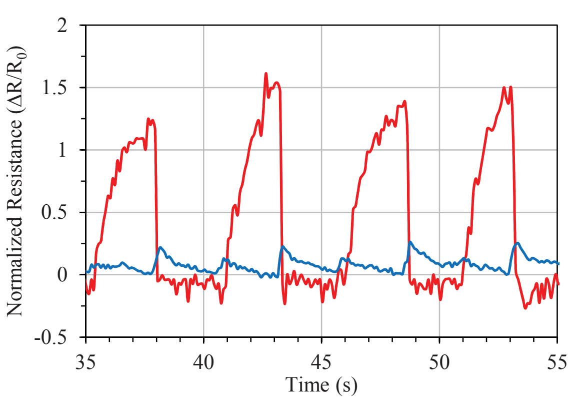

Fig. 4. Normalized resistance profile of the pressure sensor (red) and the strain sensor (blue) on the thumb during repeated key pinch and relax actions.

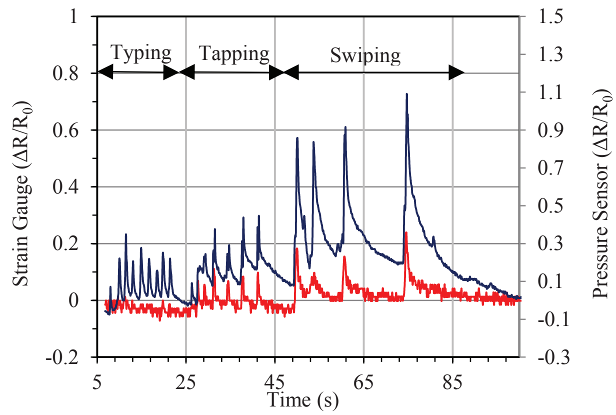

Fig. 5. Normalized resistance profile of the strain gauge (blue) and pressure sensor (red) during mobile phone usage.

capable of measuring reactive forces and finger movement. To achieve this, we employed a novel combination of flexible strain gauge and flexible sensors. We demonstrated its potential in measuring finger rotation, finger bending and reaction forces on the finger. Currently, our work is limited to thumb movements on healthy volunteers. We aim to extend this study to the assessment of other fingers, as well as rehabilitative patients. Overall, we believe the use of wearable electronics for finger dexterity assessment will be useful for hand rehabilitation and therapy.

Acknowledgments

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