CARBON NANOMATERIAL BASED MULTIFUNCTIONAL FABRICS FOR CHARACTERIZING HUMAN JOINT MOTION

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ABSTRACT

Scalable processes such as electrophoretic deposition and dip coating are used to deposit carbon nanotubes (CNTs) on non-conductive fabrics such as cotton, nylon, wool, and aramid to develop multifunctional, smart garments. Functionalized CNTs create a flexible and electrically conductive nanocomposite film on the surface of the fibers. The CNTs also impart piezoresistive properties to the fabrics making them an ideal candidate for sensor-related applications, where the electrical resistance of the fabric changes with applied pressure. This property can be used to create functional garments that can be used to measure/characterize human joint motion.

The ease of use for assistive devices, particularly in physical-therapy applications would be improved if the devices are comfortable to wear and more helpful to standard ordinary exercises. In such wearable assistive devices, real-time sensing and feedback are critical for seamless movements and spontaneous motion support. In this research, we are depositing functionalized CNTs onto a non-woven aramid fabric to create flexible pressure sensors that are used to measure the applied pressure by a Kevlar sleeve on a manikin arm during flexion and extension. When the manikin arm wrapped with Kevlar sleeve is flexed, the CNT coated sensor underneath the sleeve is compressed due to the applied pressure, which causes a decrease in the electrical resistance. In this paper, we discuss the experimental characterization and applications of these sensors and their potential applicability to provide real-time feedback in assistive devices.

Keywords: Carbon Nanotubes, Multi Scale Composites, Human-Fabric Interaction, Smart Fabric
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1. INTRODUCTION

The world health organization recently projected that the worldwide number of people over 60 years of age would double by 2050 [1]. Touch sensitive assistive devices embraced the new idea of developing equipment to optimize human interaction and support. A soft-type wearable robots are preferred over hard robots due to discomfort associated with higher weight and bulkiness of the latter [2]. Despite the latest technical advancements, the development of assistive devices is facing various challenges such as designing and placing actuators, sensing external disturbances, and controlling the structure of these systems.

Human-machine interaction is important for communication with assistive devices. Van *et al.* [3] have developed a multi-layered (two dielectrics and one conductive layer) robotic sensing skin for proximity and pressure sensing towards the development of the soft human-robot interface. Gerhardt and co-workers [4] developed a textile friction analyzer for the tribological assessment of skin–fabric interactions and measured human-fabric contact-pressure using pressure-sensitive film (Tekscan Inc). Gerratt *et al.* [5] also reported an e-skin designed to be worn over the hand, monitor live finger movement, and register distributed pressure along the entire length of the finger. Tekscan I-SCAN50 and Fujifilm pressure sensing skin are commercially available tactile sensing systems. These sensors have challenges in real-time repeatable sensing and are not easily integrable in garments as a result of which, they are not comfortable to wear for long times. In human-machine interaction, it is also important to understand the influence of various parameters, such as fabric properties, sleeve-fitting, and sleeve friction, affecting the human-garment interface. Erol *et al.* [6] demonstrated a direct connection between a key element related to tactile comfort and task performance: the friction between the representative arm and the sleeve. He developed an experimentally validated finite element model to parametrically study the effect of friction.

CNT nanocomposites have emerged as potential materials for sensor applications due to their piezoresistive mechanical-electrical coupling properties. Multiple flexible strain sensors using CNTs were proposed by researchers [7- 9] and found applications in human joint characterization. Ali *et al.* [10] developed CNT based composite element and tested it as a pressure sensor. Doshi and Thostenson [11] developed a non-woven aramid textile-based CNT pressure sensor with an ultra-wide sensing range (0.0025 MPa – 40 MPa). These sensors, combined with portable electronics, can be used for real-time sensing applications [12].

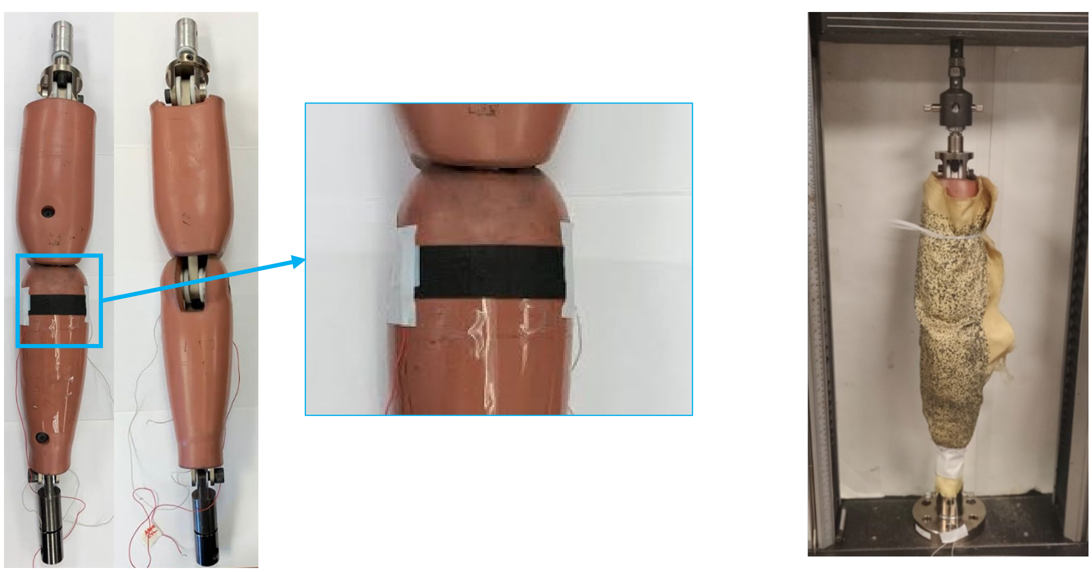
In the present study, a CNT-based non-woven aramid pressure sensor is prepared and tested to measure human-fabric interaction close to the elbow joint. Mechanical testing, using a manikin arm, is performed to measure human-fabric interaction. Finite element analysis (FEA) was used to model the human-fabric interaction and validated with experiments to study the behavior of forces experienced by manikin arm near the elbow due to human fabric interaction.

2. EXPERIMENT AND SIMULATION

Sensors were manufactured using a dip-coating process as described in our prior work [9, 13]. Non-woven aramid fabric (20601, Technical Fiber Products, Inc.) with an areal weight of 50 g/m^2 was coated using a commercially available aqueous dispersion of multi-walled CNTs. To lower the viscosity of the dispersion, 1 part of the dispersion was mixed with 2 parts of ultrapure water by weight. Uniform mixing was ensured by processing diluted dispersion using a centrifugal mixer (THINKY® ARM-310) at 2000 rpm for 120 s and then 30 minutes of sonication in an ultrasonic bath (Branson® 1510). Due to the hydrophobic nature of aramid fabric, the fabric was dipped in ultrapure water until the fabric was completely wet. To coat the fabric, the dispersion was poured in a flat-bottomed container, and a piece of fabric was dipped in the diluted dispersion for 10 minutes on each side. The fabric was then dried in a convection oven for 60 minutes at 150°C.

Figure 1: Photograph of sensor pre-loading and calibration.

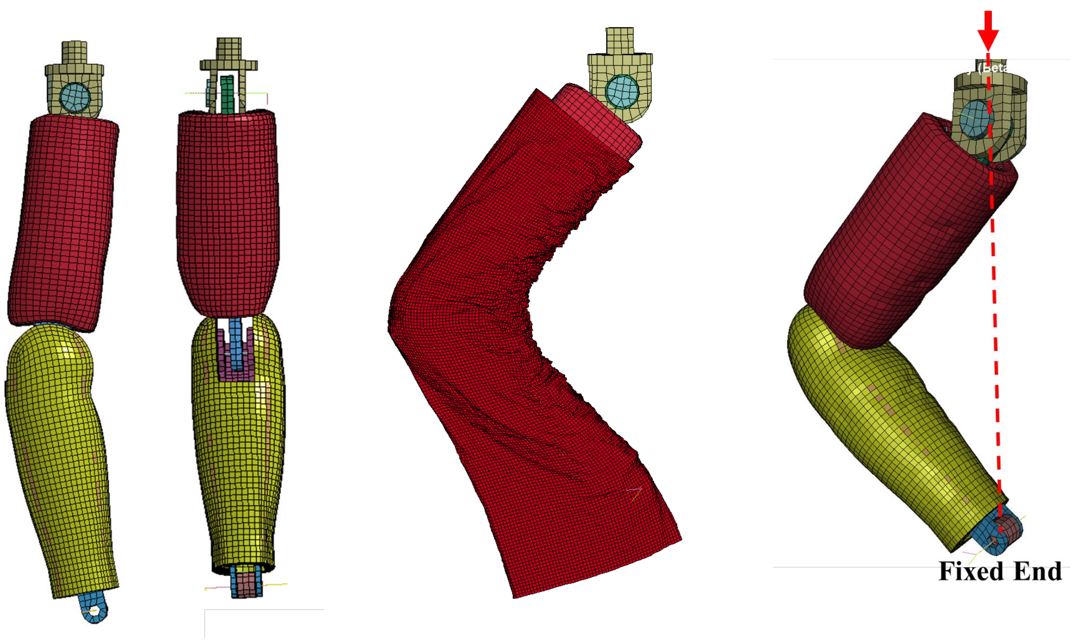
Sensors were cut to a size of 100 mm in length and 25.4 mm wide. Electrodes and lead wires were attached to the specimen using conductive silver paint (Flash Dry, SPI Supplies,) and a 2 part conductive silver epoxy resin (EPOXIES® 40-3900, Epoxies, Etc.). The electrodes were attached 90 mm apart. Prior to testing on manikin arm, the sensor was pre-loaded up to the maximum expected force of 1200 N using a universal testing machine (Instron 5567), Figure 1 for improved and repeatable response followed by cyclic loading, as discussed by Doshi and Thostenson [11]. The sensor was electrically insulated to avoid interference with resistance measurement. Resistance was recorded using a voltage-current meter (Keithley 6430 sub-femtoamp remote sourcemeter). The current was measured across the electrodes on the application of a constant source voltage, and resistance and force measurements were synchronized using a customized LabVIEW program.



(a) (b)

Figure 2: (a) Sensor location on a Hybrid-III manikin arm and (b) manikin arm test setup with Kevlar sleeve.

A Hybrid III manikin-dummy right arm was used for mechanical testing. A cylindrically shaped fabric sleeve, diameter 100 mm, was sewn from hydrophobic Style 706 plain-woven Kevlar fabric (600 denier KM2 woven, weight 184 g/m^2, 0.23 mm thick). This fabric is well characterized and can be used in passive actuation in assistive devices. CNT coated aramid fabric pressure sensor is attached to the manikin arm near the elbow joint, Figure 2a. The Kevlar sleeve was mounted directly on the manikin arm, Figure 2b. The manikin arm was tested using a screw-driven mechanical testing load frame. Prior to loading, the arm is bent at a small angle (50 mm initial downward displacement from full extension) at the initiation of the experiments to avoid locking of the joint when crosshead of the Instron moves downward, causing the bending of the elbow joint. The prescribed motion corresponds to a combination of elbow flexion motion and shoulder adduction on the coronal plane keeping the wrist joint and shoulder joint in one line.



(a) (b) (c)

Figure3: (a) FE model of manikin arm, (b) manikin arm model with sleeve and (c) loading direction of the manikin arm

The finite element model developed in a previous study [6] was utilized for modeling the sleeve/arm interaction. 'Detailed hybrid III 50th percentile dummy model for LS Dyna' was downloaded and rotated to keep in the vertical position of the arm similar to the experimental configuration, Figure 3a. The FEA model has five joints defined and modeled as elastic-plastic stiffness and frictional moment as inputs. These parameters of joints were fine-tuned to achieve the force values similar to the experiment. The Kevlar sleeve was modeled as a fully integrated shell element of LS-DYNA and a refined mesh is used to capture the wrinkling of fabric, Figure 3b. Fabric material was defined as linear orthotropic material for the initial study. To simulate the motion similar to experiment, the shoulder joint was accelerated and deaccelerated along a line of motion, Figure 3c, keeping the wrist pin fixed.

3. RESULTS AND DISCUSSION

The sensor was pre-loaded to a pressure of 0.52 N/mm^2 (1.5 times of the expected pressure) to ensure the repeatability and consistency in the response. The sensor was loaded and the crosshead was held for approximately 20 seconds in the same position. It can be seen in Figure 4a, that there is close to 15% resistance change recorded and it was stable during the hold time. Repeated loading was also tested and verified for repeatability.

To examine the sleeve/arm interaction, the manikin arm was tested with and without the sleeve. The force values for both cases are shown in Figure 4b**.** The test with the sleeve requires a higher force for bending the manikin arm. Without the sleeve, the applied force is only dependent on the torque required to overcome joint friction. Due to the frictional interactions between the Kevlar sleeve and the arm, the compressive force required is higher with the sleeve. The additional force needed to bend the manikin arm with the sleeve can be calculated by these two forces i.e., subtracting the force required to bend the manikin arm from the force required to bend the arm with a sleeve.

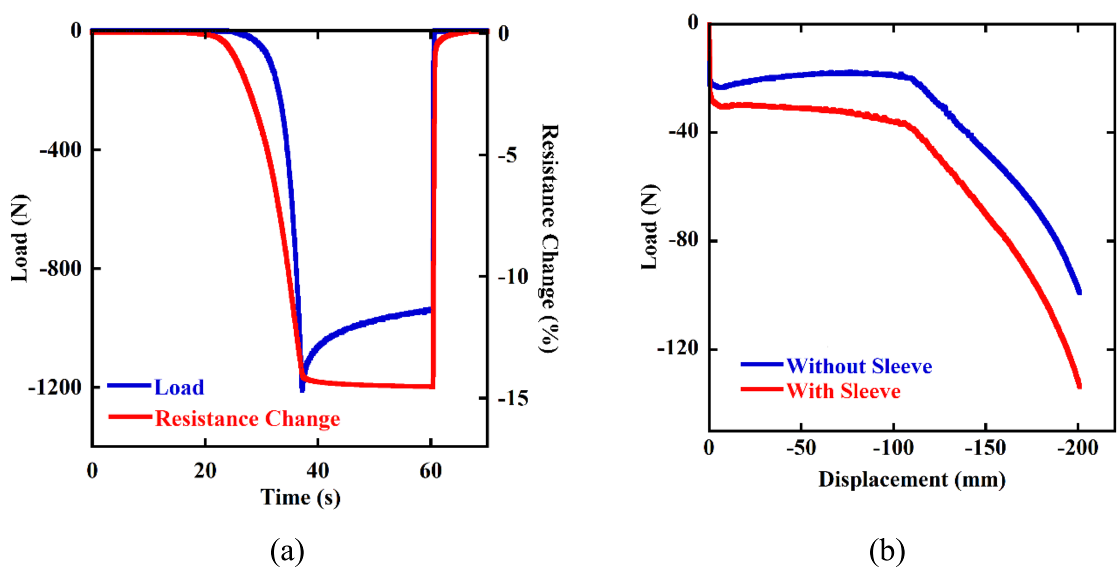


Figure 4: (a) Sensor response during pretesting and (b) force required to bend the arm with and without the Kevlar sleeve.

Resistance data from the sensor was measured for vertical downward displacement of the crosshead. Initially the crosshead was kept 50 mm downward from the full straight arm position. Resistance at this position was recorded as initial resistance for calculation of the resistance change. The sleeve is in contact with the manikin arm near sensor. During flexion motion, pressure is applied to the sensor by the fabric and resistance decreases. Under extension the resistance comes back to its original value. A slight overshoot of resistance during extension is likely because the sensor sticks slightly to fabric while sleeve gets separated from the sensor gradually. Similar behavior was also observed in previous study [11]. Multiple cycles of 120 mm displacement were repeated, and about 2.5 % resistance change was recorded (Figure 5). The response is consistent and repeatable.

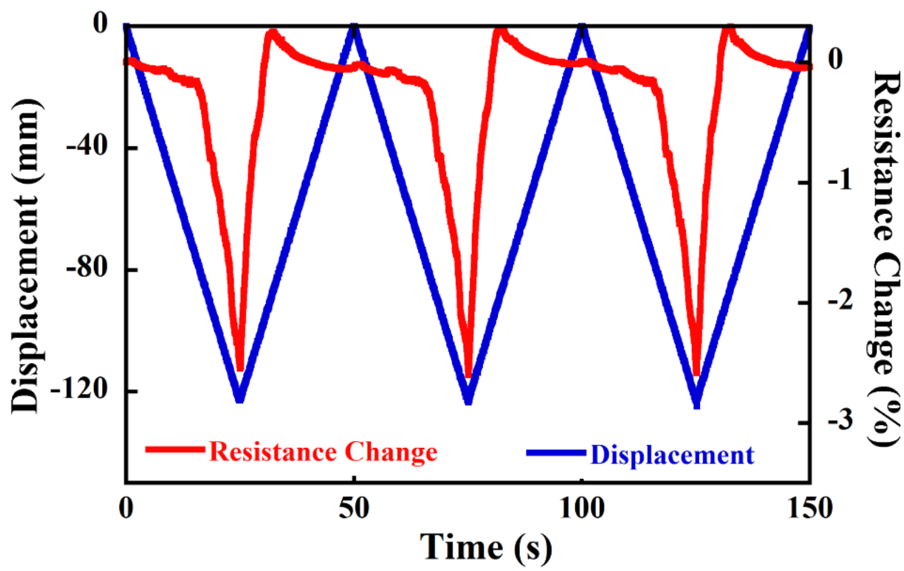


Figure 5: CNT sensor response in multiple displacement cycles.

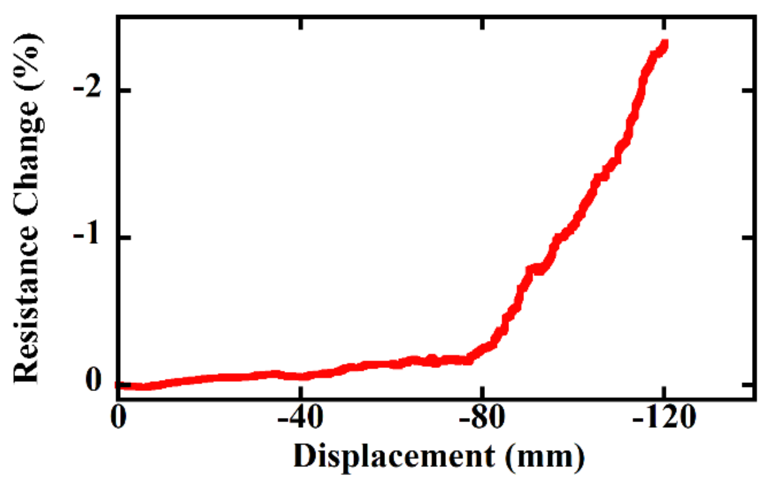


Figure 6: Sensor response in a single flexion motion.

Figure 6 shows resistance change with displacement for an isolated flexion cycle. It is observed that during flexion, the sleeve experiences tensile forces (sensor side). In the first 80 mm of crosshead displacement, no significant pressure was applied by the sleeve on the CNT pressure sensor. In the remaining cycle, pressure was applied gradually on the sensor, and a linear decrease in resistance change was recorded.

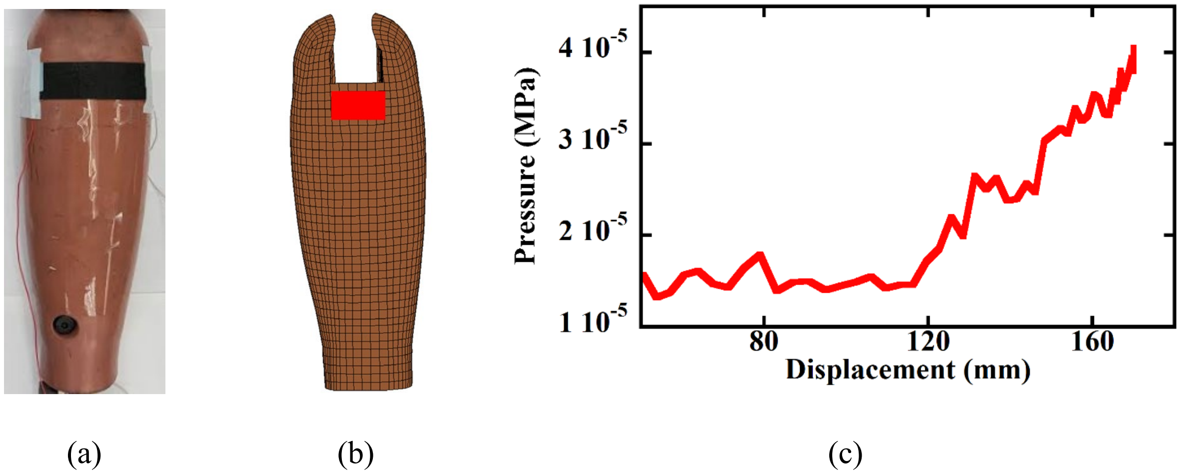
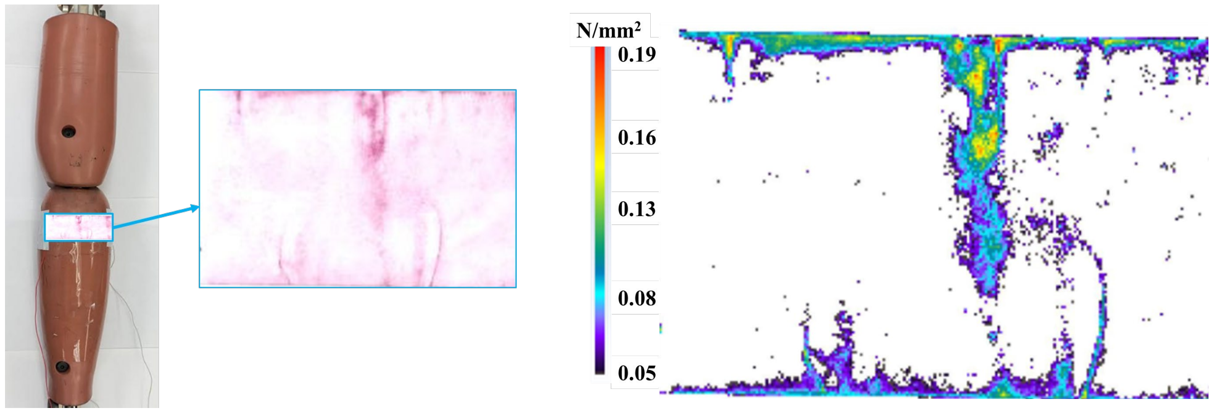


Figure 7: (a) Sensor location, (b) element location for average pressure measurement in the finite element model, and (c) average pressure during flexion at location shown in (b).

FEA was performed for a single cycle with a displacement rate similar to realistic human motion, flexion and extension in less than one second. No significant dynamic effects were expected, as established in a previous study [6]. FEA results show that the sleeve is loading the arm symmetrically across the centerline. Pressure was applied gradually with flexion with time due to the contact between sleeve and arm close to sensor location (Figure 7a). The average pressure due to contact between sleeve and arm was calculated for the location shown in Figure 7b. Finite element analysis was performed for 170 mm downward displacement of shoulder joint. Figure 7c shows the average calculated pressure applied by the fabric over the sensor area. Data is shown starting at an initial displacement of 50 mm to be consistent with the initial displacement from mechanical testing. Pressure variation calculated in FEA matches closely with the experimental resistance response recorded by CNT sensor.

Fujifilm Prescale® tactile pressure indicating sensor film provide by Sensor Products Inc. was used to measure the pressure applied by fabric sleeve on the manikin arm at the sensor location, Figure 8a. Extreme low, 0.05 N/mm^2 to 0.2 N/mm^2 (7.2 psi – 28 psi) pressure range, type film was used and tested for one cycle. Transparent thin film changes its color, Figure 8a, based on the applied pressure by the Kevlar sleeve on the manikin arm. Figure 8b shows the pressure distribution after analysis of the film using a Topaq® Pressure Analysis System. The pressure distribution indicates that on flexion motion, maximum pressure was observed near centerline with an average value of pressure 0.08 N/mm^2 (12 psi). It also supports that 2.5 % resistance change in CNT pressure sensor corresponds to 0.08 N/mm^2 pressure applied by fabric on the centerline of the pressure sensor. Discontinuation in the centerline pressure profile on moving towards forearm is likely because the thin pressure film is not conformal to manikin arm surface and unable to capture the interaction between manikin arm and fabric sleeve. Another factor contributing to the missing pressure data is the limitation of thin film pressure sensor to record pressure values in the range of 0.05 N/mm^2 to 0.2 N/mm^2 (7.2 – 28 psi). Pressure value below 0.05 $N.mm^2$ (7.2 psi) will not be recorded. A different pressure film, ultra extreme low (Fujifilm Prescale® Tactile Pressure Indicating Sensor Film) type, is required to measure pressure below 0.05 $N.mm^2$ (7.2 psi). Pressure variation is according to the behavior observed during testing that fabric is loading manikin arm gradually with an increase in flexion.



(a) (b)

Figure 8: (a) Tactile pressure indicating film placement on manikin arm and response after one cycle and (b) pseudocolor pressure representation of the film.

4. CONCLUSIONS

A non-woven Aramid CNT-based pressure sensor is capable of recording fabric-manikin arm interaction based on resistance change. The fabric based CNT sensor can be integrated with garments to provide real time sensing to assistive devices. Once verified and validated for different material sleeves, finite element model developed can be used to do parametric studies such as examining sleeve fitting, sleeve diameter, and friction between manikin arm and sleeve.

Future work will focus on modeling natural flexion motion, keeping the arm horizontal. In such a setup, the joint angle can be characterized with pressure sensor. After the calibration of CNT pressure sensor with commercially available thin-film tactile pressure sensors, the sensors will be characterized for spatial mapping of pressure response using electrical impedance tomography as discussed by Dai and Thostenson [14].

5. ACKNOWLEDGMENTS

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