HIGHLY-SENSITIVE CARBON NANOTUBE BASED SENSORS USING EVERYDAY FABRICS FOR HUMAN MOTION ANALYSIS

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ABSTRACT

Analyzing human motion is becoming increasingly important for patients requiring rehabilitation and athletes to improve performance. Motion capture cameras, currently used for human motion analysis are prohibitively expensive and complicated to use. There exists a critical need for developing innovative and cost-effective techniques to analyze motion outside of the laboratory. In this work, low-cost and comfortable wearable sensors can be created by coating everyday fabrics with nanocomposite coatings based on carbon nanotubes. A dip-coating process is used to coat fibers in a knitted fabric to create an elongation sensor. The nanocomposite coating makes the fabric electrically conductive and imparts piezoresistive sensing functionality where electrical resistance changes proportionally to mechanical deformation. A variety of mechanical tests are performed the electrical/mechanical coupling behavior. Preliminary results show ultra-high sensitivity with a resistance change of over 3,000% when an elbow sleeve sensor is worn while flexing. The sensors offer the possibility to be non-invasively integrated into clothing to create ‘smart garments'.

Keywords: *Carbon Nanotubes, Human Motion Analysis, Smart Fabric*

1. INTRODUCTION

Human motion analysis is a subject of interest for the last two decades among physical therapists and sports science researchers. Accurate measurement of human joint motion in real-time is an ongoing challenge. The most commonly used technique involves the use of motion capture cameras along with fixing markers attached to the body for tracking. Motion capture is expensive and affected by ambient lighting. Furthermore, it is difficult to monitor the subject over prolonged time periods during normal day-to-day activities. An alternative approach is wearable sensors integrated into garments that are flexible and stretchable.[1] Drapability of fabrics – the ability to conform to any shape – makes them suitable for flexible sensors which can be integrated into garments or directly attached to the skin.

Considering the difficulties faced in developing stretchable electrical conductive materials, instead of developing new materials, researchers have proposed unique structural combinations from existing materials.[1] One of the initial solutions proposed by Gibbs et al. [2] is to incorporate inelastic metallic wire in the fabric to measure the resistance across variable contact length on joint

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motion. Mattmann and co-workers [3] developed a strain-sensitive conductive fiber with a mixture of a thermoplastic elastomer and carbon black particles and were able to recognize upper body postures with an accuracy of 97%. Similarly, others have developed knitted strain sensor textiles of conductive polymeric fibers [4]. Atalay et al. [5]. developed a knitted strain sensor using silver-coated fibers. While metallic coatings give promising results, the coatings increase the stiffness of the fabric making it less comfortable. In addition, high strain levels can lead to cracking of the metallic coating. As a result, researchers have investigated the use of carbon nanotubes (CNTs) to create flexible sensors. The coupling of electrical and mechanical properties makes CNTs a suitable candidate for developing sensors. High aspect ratio CNTs form a conductive percolating network. [6] Yamada et al. [1] introduced a stretchable sensor consisting of aligned single-walled CNT thin films deposited on polydimethylsiloxane resulting in a flexible sensor capable of measuring high strain. Over the past several years the cost of CNTs has come down considerably, making them a viable material for the development of low-cost wearable sensors.

In current work, we demonstrate the fabrication of highly sensitive, comfortable to wear sensors to measure a range of human joint motion. A dip-coating technique is developed to produce a thin nanocomposite coating on a commercially-available knitted fabric. The morphology of the coating is characterized using electron microscopy and the electrical-mechanical response characterized under tension. The fabric sensor is then integrated into an elbow sleeve and the sensing response under elbow motion is investigated.

2. EXPERIMENTAL

Sensors were prepared using a dip-coating process (Figure 1(a)) developed in our previous research where the fabric is coated using a sizing composed of an aqueous dispersion of multi-walled CNTs and polymers [8]. To lower the viscosity of the sizing, 1 part of sizing was mixed with 2 parts of ultrapure water by weight. To ensure a uniform dispersion of CNTs the diluted sizing was processed using a centrifugal mixer (THINKY® ARM-310) at 2000 rpm for 120 s followed by 30 minutes of sonication in an ultrasonic bath (Branson® 1510). A knitted fabric (nylon 44%, polyester 43%, and 13% spandex) commonly used in compression garments was chosen. The nylon and polyester provide excellent wear resistance, and spandex enables high stretchability and resilience. To coat the fabric the sizing was placed in a flat-bottomed container and a piece of fabric was dipped in the diluted sizing for 10 minutes on each side. The fabric was then dried in a convection oven for 60 min at 150°C. Fabric before and after dip coating is shown in Figures 1(b) and 1(c), respectively.

Specimens for axial strain testing were cut to a size of 100 x 25.4 mm wide and electrodes and lead wires were attached to the specimen using conductive silver paint (Flash Dry, SPI Supplies, West Chester, PA) and a 2 part conductive silver epoxy resin (EPOXIES® 40-3900, Epoxies, Etc., Cranston, RI,). The electrodes were attached 60 mm apart as shown in Figure 2a. Non-conductive glass fiber end tabs were attached at the ends of the specimen to avoid shorting of the sensors in the steel grips of the testing machine. To test the sensor on the elbow, 130 x 38 mm strips of the coated fabric were stitched onto a compression sleeve made of fabric containing 82% nylon and 18% spandex and electrodes attached with a spacing of 101 mm.

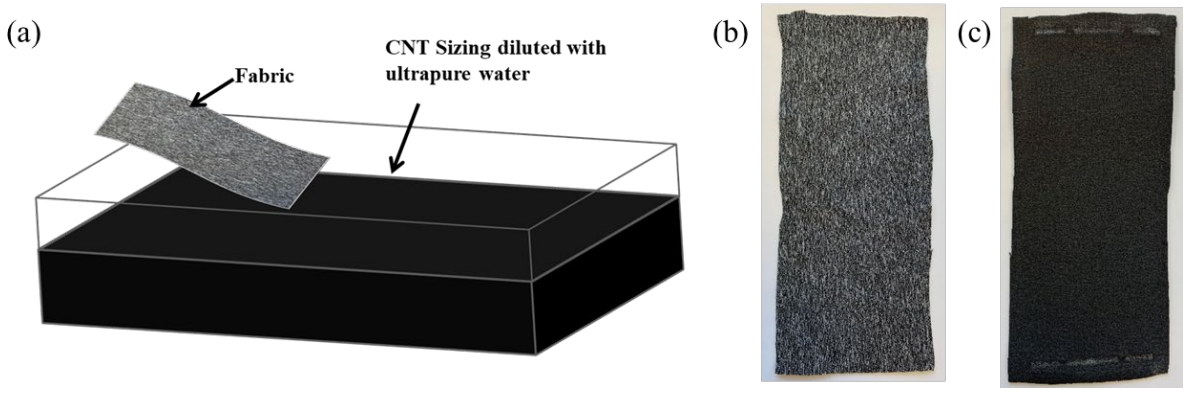


Figure 1. (a) Dip coating of fabric in CNT–sizing (b) Fabric before coating (c) Fabric after coating with CNT

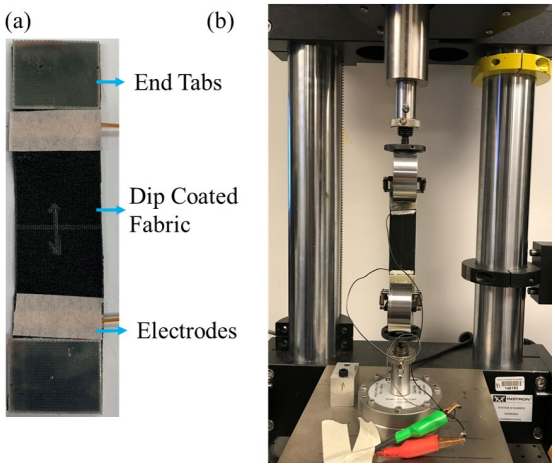


Figure 2: (a) Specimen for axial strain testing and (b) experimental setup for axial testing.

Tensile tests were conducted under controlled-displacement using an electromechanical test machine (Instron Micron Tester 5848) with a displacement rate of 2 mm/sec. To test the response to joint motion, the sensor integrated into the arm sleeve is tested under varying degrees of elbow flex. Electrical measurements were made 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 extension measurements were synchronized using a customized LabVIEW program.

The morphology of the coating was examined using a scanning electron microscope (AURIGA 60 Crossbeam). To avoid sample charging, the specimens were coated with a thin (~5 nm) conductive layer of Au/Pd using a vacuum sputter coater (Denton Desk IV, Denton Vacuum, LLC) for 60 sec. For the non-coated and CNT coated fabric, SEM was performed using an accelerating voltage of 1.5 kV and 3.0 kV, respectively.

3. RESULTS AND DISCUSSION

Figure 3(a) shows high magnification micrograph of a non-coated fiber. The surface of the fiber is smooth. Figure 3(b) shows a fiber after dip coating with CNT sizing. A uniform CNT nanocomposite coating is visible on the fiber surface. Optical microscopy of the fabric revealed that the knitted structure is a weft knit (Figure 4(a)). Figure 4(b) shows a schematic diagram of the looped structure of a weft knitted. The yarn in knitted fabrics makes symmetric loops above and below the mean path of the yarn. Loops are considered to have one head (curved part) and two legs (straight part), as shown. These loops are interlocked in course (weft) and wale direction and are easily stretchable in different directions, making knit fabrics flexible and drapable.[4]

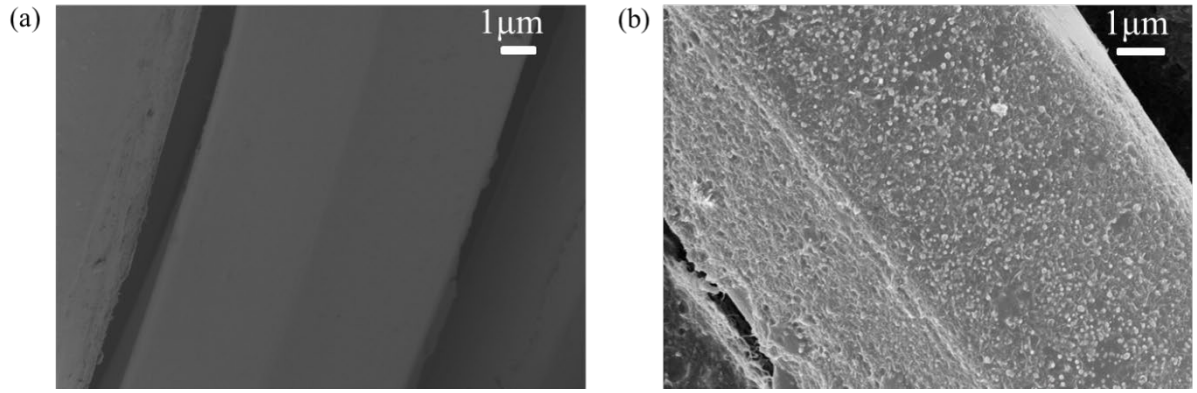


Figure 3: SEM micrograph (a) an individual fiber before coating (b) after coating with CNT sizing

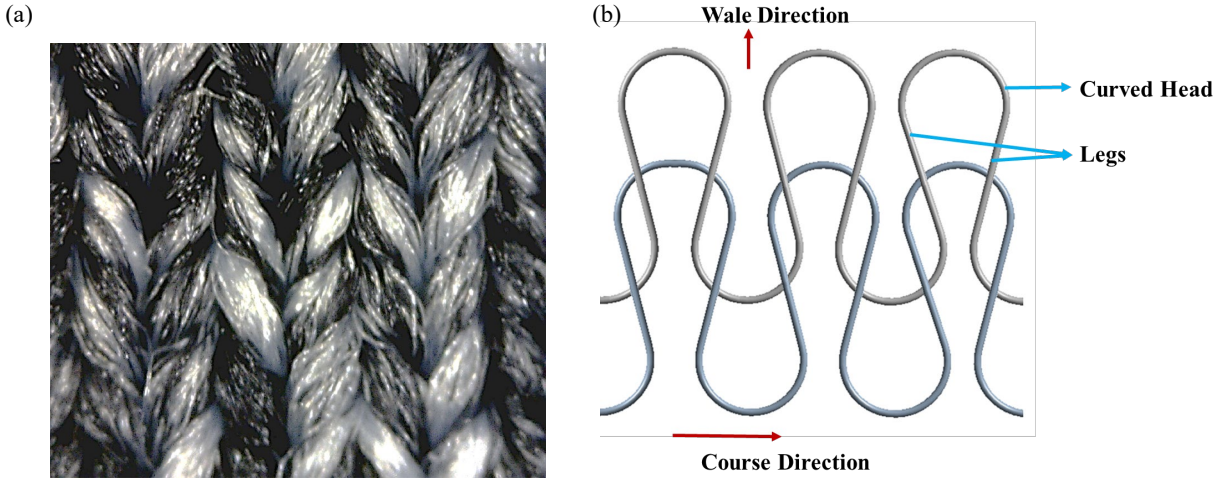


Figure 4. (a) Optical micrograph of the knitted fabric and (b) a schematic of the looped structure of a weft knitted fabric.

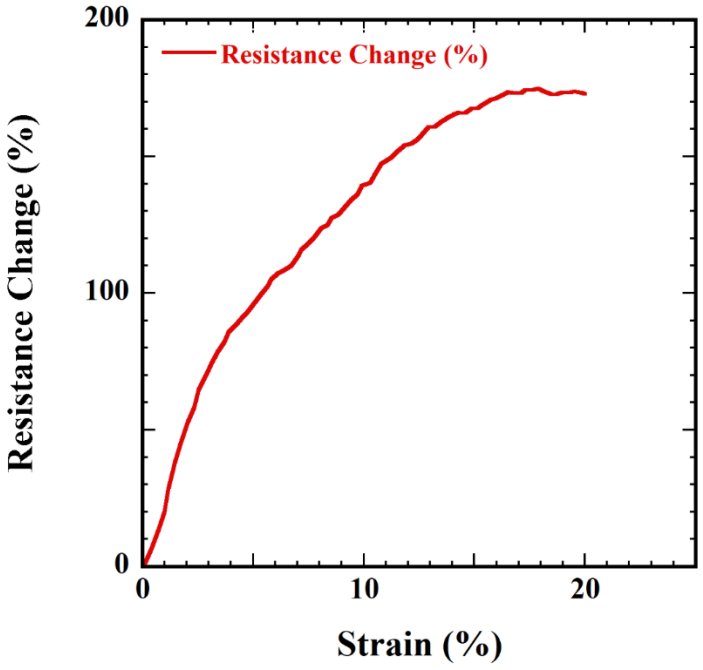


Figure 5: Resistance-strain behavior of the CNT nanocomposite coated fabric.

Figure 5 shows the change in resistance versus strain of the fabric tested in the wale direction under tensile deformation, showing a resistance change of over 150% at 20% strain. When the knit fabric is stretched in the wale direction (in the direction of the loops), the leg height increases and the curved heads become narrower, which breaks down the connection points between adjacent loops in the same row. The piezoresistivity of a knit fabric coated with CNTs is likely due to both the piezoresistivity of the CNT composite coating as well as changes in the configuration of the conductive yarns. Nonlinearity of the response is possibly due to increasing contact pressure between the loops resulting in a decrease in yarn-yarn contact resistance [10] along with decreasing resistance of the yarn bundle due to increased fiber-fiber contact under axial extension.

After coating, the stiffness and feel of the fabric is similar to the uncoated fabric making the sensor comfortable to wear. Figure 6 shows the sensor response when sewn into a compression sleeve where the coated fabric is directly over the elbow joint. While maintaining a fully extended arm position, there is no significant resistance change. When moving the arm from fully extended to a fully flexed position (approximately 70°) a resistance change of more than 3,000% observed. For partial flex (approximately 30°), the resistance change is close to 1,000%. The resistance change in the garment is substantially higher than the resistance change due to simple axial stretching. The response of the sensor depends on the fabric deformation around the joint. It has been noted that the skin around the elbow joint extends 35 to 40 percent lengthwise and 15 to 22 percent circumferentially.[2] As a result, the sensor in the elbow sleeve is simultaneously subjected to axial and transverse extension.

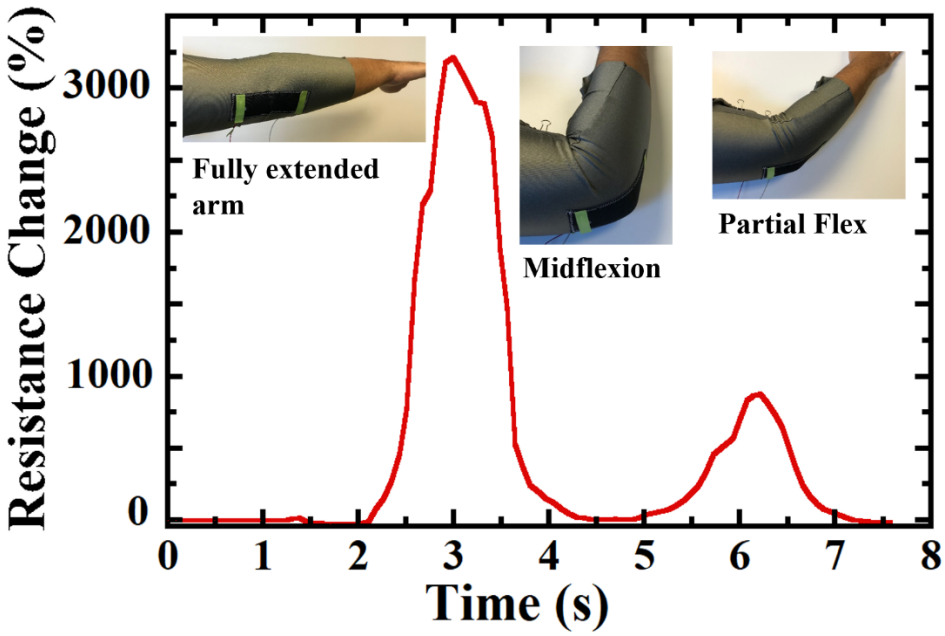


Figure 6: Change in resistance in sensor on the elbow with fully and partially flexed arm,

4. CONCLUSIONS

A dip-coating process was utilized to create a nanocomposite coating on the surfaces of the fiber in a knitted fabric to create a sensor that may be integrated into a garment for human motion analysis. The sensor response is characterized when subjected to axial extension and then integrated into a sleeve and tested for elbow joint motion, and the nanocomposite coating did not change the feel of the fabric, making it comfortable to wear. When subjected to axial tension, the sensor showed a reversible, non-linear response with electrical resistance changes over 150%. Ultra-high sensitivity is observed with elbow joint motion where the sensor electrical resistance change is over 3,000% in a fully flexed elbow. This high sensitivity compared to the response in tension is likely due to the multi-axial extension of the fabric around the elbow joint. These sensors, combined portable electronics, offer the potential to record real-time data on human motion outside of a laboratory environment.

5. ACKNOWLEDGMENTS

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