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Carbon nanotubes (CNTs) based strain sensors for a wearable monitoring and biofeedback system for pressure ulcer prevention and rehabilitation

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Abstract—**This paper presents an overview of the functioning principles of CNTs and their electrical and mechanical properties when used as strain sensors and describes a system embodiment for a wearable monitoring and biofeedback platform for use in pressure ulcer prevention and rehabilitation. Two type of CNTs films (multi-layered CNTs film vs purified film) were characterized electrically and mechanically for potential use as source material. The loosely woven CNTs film (multi-layered) showed substantial less sensitivity than the purified CNTs film but had an almost linear response to stress and better mechanical properties. CNTs have the potential to achieve a much higher sensitivity to strain than other piezoresistors based on regular of conductive particles such as commercially available resistive inks and could become an innovative source material for wearable strain sensors. We are currently continuing the characterization of CNTs based strain sensors and exploring their use in a design for 3-axis strain sensors.**

I. INTRODUCTION

Pressure ulcers (PU) are localized injuries to the skin and/or underlying superficial and deep tissues caused by prolonged exposure to compressive and shear stresses applied between a bony prominence, its surrounding soft tissue and an external surface [1]. Stress is defined as a force over a specific area of a tissue, while strain is the tissue deformation resulting from the application of a force. Strain is directly related to stress through the tissue elastic coefficient. Such tissue deformations can be classified following the nature of the resulting strain and stress: compressive, tensile and shear. In the context of PU, shear strain can also be divided into parallel shear strain (friction related) and pinch shear strain, resulting from the gradient of compressive stress. The level of compressive and shear strain required to cause PU varies according to factors such as exposition, disease processes and risk factors [2]. PU can affect people with specific conditions that increase exposition to stresses causing strains (ex: bed ridden individuals), people with the inability to move certain parts of their body without assistance, such as after spinal or brain injury or with as a consequence of neuromuscular disease, and individuals that have a chronic condition, that prevents areas of the body from receiving proper blood flow (ex: diabetes or vascular disease)[3]. Best practices for pressure sore prevention and management involve managing exposure to stresses and introducing timely measures to relieve them [4]. As most patients at risk of developing PU have altered ability to perceive ischemic pain as a response to these strains, awareness of the exposure to strains is key to taking preventive action to relieve these strains. Monitoring exposure to stresses in the context of PU prevention necessitates a method to measure in real time compressive and shear stresses applied at specific areas of the body at a given time and for long periods.

The proposed system currently under development is a wearable monitoring and biofeedback system that uses state of the art sensor technology based on carbon nanotubes (CNTs) to map stresses applied to susceptible areas. This paper presents an overview of the functioning principles of CNTs networks and their electrical and mechanical properties when used as a strain sensor and describes the system embodiment for a wearable monitoring and biofeedback platform for use in pressure ulcer prevention and rehabilitation. The paper is organized as follows: section II describes the functioning of CNTs based strain sensors and the architecture of the proposed system; section III presents experimental results on the electrical and mechanical properties of an individual CNTs strain sensor and section IV puts into context the potential applications of the system and identifies challenges and milestones for further development.

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II. WEARABLE SYSTEM WITH CNTS STRAIN SENSORS

A. *Current sensing technologies*

Measuring long-term exposure to stress under uncontrolled conditions (ambulatory conditions outside of the laboratory and clinic) is a difficult endeavor. Available sensor technologies currently marketed in different stress sensing products (Vista Medical, Tekscan, Novel and Parotec), use capacitive, resistive, piezoelectric and piezoresistive sensors[5]. Each of these sensor technologies has different limitations and problems in terms of durability, reliability, sensitivity and hysteresis, as well as their bulkiness or high production cost and none have been designed or assembled to simultaneously measure compressive and shear stresses.

To address these issues, a project leveraging CNTs as a source material for use as wearable strain sensors was started two years ago. CNTs are among the most rigid and tear resistant material known and their mechanical, electrical and thermal properties offer exceptional capacity as piezoresistive sensors [6]. Furthermore, networks of CNTs can be deposited on various types of substrates; they can be patterned with standard microelectronic fabrication techniques to achieve large-scale integration.

B. *Overview of functioning of CNTs as strain sensors*

CNTs are carbon molecules composed of at least one mono-atomic cylindrical layer. Individual carbon nanotubes demonstrate natural piezoresistivity. Mechanical strain, such as bending, stretching and torsion, can open the band gap of metallic CNTs and modify the band gap of semiconducting and quasimetallic CNTs [7, 8]. When assembled in a network, their geometrical structure and electrical interconnectivity increase the piezoresistive effect. In the latter case, the variation of the tunnelling conduction distance between the CNTs governs the electrical resistance variation under the applied strain [9, 10].

These effects can be used in mechanical sensors such as strain gauges, pressure and force sensors. If thick enough, networks of CNTs can be used to probe compressive stress. A capping material can be added on top of the CNTs to protect them from premature wear and to transmit the strain to the sensitive element. The stress and strain sustained by the CNTs films are also tuned down by the elastic properties of the capping material as illustrated in Figure 1a.

The embodiment of the proposed system is a thin (i.e. less than 1.5 mm) flexible CNTs based sensor matrix that can be encapsulated on any combination of substrate (ex: textile) and either worn by the individual or put under different support surfaces. An illustration of the sensor matrix currently under development is illustrated in Figure 1b. The configuration of the sensors (size and number) and the capping material used can be adjusted according to the requirement of the measurement application and context. The data flow of the system is illustrated in Figure 1c. The sensor matrix is connected to a small unobtrusive data collection platform that incorporate a biofeedback modality (Figure 1d).

Thresholds of stress exposure in term of peak values, time and frequency of occurrence, and cumulative exposition are programmed according to individual risk factors for PU and history. When these thresholds are reached a reminder is given to take relief actions. Stresses recorded daily are stored on the data acquisition unit and transmitted to a third party.

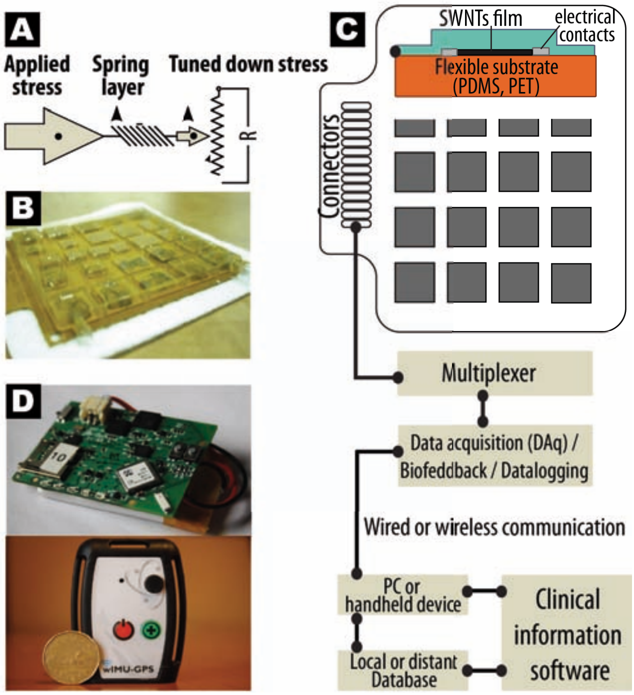

Figure 1. Overview of proposed system. a) Principles of operation of the CNTs sensor; b) Sensor matrix with PDS encapsulation; c) Data flow d) Data acquisition and biofeedback module (WIMU-GPS).

In consideration of the novel use of CNTs in the described context, we first choose to explore the electrical and mechanical properties of films of CNTs and encapsulated CNTs films to confirm their potential for our application. The next section presents these results.

III. ELECTRICAL AND MECHANICAL PROPERTIES OF CNTS STRAIN SENSOR.

A. *Piezoresistive response of CNTs strain sensor*

In order to establish the piezoresistive behavior of the CNTs networks and determine the optimum specification for the source material; two types of CNTs film were fabricated and tested. The first one was synthesized directly during the CNTs growth and its structure is made of loosely woven single-walled CNTs (~40% wt. %, single walled nanotubes-SWNTs) uniformly distributed among metallic impurities and carbon black particles. The second film was obtained by vacuum filtering a suspension of purified SWNTs. It is composed of very tightly woven SWNT bundles (~100$ wt. %). A custom piezoresistivity test system was used to measure the piezoresistive stress coefficients (Π) and the gauge factors (K). Samples from both types of films were cut into 1 cm x 1 cm pieces. Electrical contacts were then fabricated on two opposite edges of the samples with conductive silver epoxy. The samples were annealed on a hot plate at 110 ºC for 30 minutes to cure the conductive epoxy. After connecting wires to the electrical contacts, the entire assembly was capped with semiconductor dicing tape to protect it from wear. Specific pressure loads were applied on the samples and maintained for at least 30 s. For each load, the resistance changes were measured with a precision ohmmeter using a two probes technique. Between each load, we measured the film resistance without any pressure to follow the evolution of the unstrained sample resistance R_0. Figure 3 shows the piezoresistive property of the two types of film. A model based on tunneling conduction can be used to describe its high piezoresistive sensitivity of CNTs sensors to strain. Under strain, the tunneling distance is expected to change causing an alteration in the overall resistance of the films. The relative resistance measured under compressive strain ($|\varepsilon| = 1\text{-}s/s_0 = |\sigma/E|$) can be expressed as [9]

$$\frac{\Delta R}{R_0} \propto \exp\left(-\gamma s_0\left|\frac{\sigma}{E}\right|\right)-1 \qquad (1)$$

Where σ is the sustained stress, E is the film elastic modulus, s_0 is the effective distance between carbon nanotubes inside the unstrained film, R_0 is the original resistance of the films and γ is a constant which depends on the height of the insulating barrier separating each nanotube.

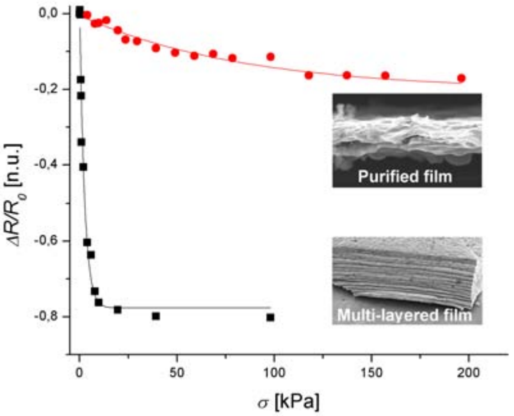

Figure 2. Piezoresistance of as-produced CNTs films (squares) and purified films (circles) under corresponding strain. Full curves correspond to the tunneling conduction model.

The solid lines in Figure 2 correspond to the model described by equation (1). As illustrated, the nature of the CNTs film has a huge influence on the sensor sensitivity to pressure and on its saturation. We can estimate the gage factor with the values γs_0, which correspond to ~76.3 and ~3.5 for the loosely woven and the purified films, respectively. Alternatively, the calculated piezoresistive stress coefficients Π are ~4x10^{-4} and ~1.2x10^{-5}. Such values are relatively small compared to a single CNTs's gage factor, although they are comparable with values obtained in semiconductors and metallic strain gauge in the case of the multi-layered film and the purified film, respectively.

B. *Mechanical response of CNTs strain sensor matrix*

To map stress and strain, matrices of sensors were fabricated on PCB-flex substrates. Purified CNTs films were deposited and capped with a molded polydimethylsiloxane (PDMS) patterned layer (Figure 1b). Electrical contacts to each sensor were routed on the PCB-flex to a connector. The mechanical response of these devices was characterized with a commercial compression-traction system configured with a 1 kg load cell. We applied five compressive loading and unloading cycles to each sample, maintaining the maximum strain for 5 seconds and letting the devices relax for 5 seconds between each cycle. The probe speed was set to 0.1 mm/s and maximum strain levels of 5, 10, 15, 20 and 25% were reached. The devices' mechanical response to applied compressive strain is displayed on Figure 3. The time response curve (Figure 3b) shows that under constant strain, the resulting stress tends to relax itself exponentially with time, underlining the viscoelastic nature of the capping material. This is also displayed by the hysteresis between the loading and unloading curves on Figure 4. Under these tests conditions, the slope of the stress/strain curves increases with the applied strain until it reaches a constant value of ~1.8 MPa for strain levels higher than 10%. This value corresponds to the measured [11] Young modulus of the PDMS polymer used in this study.

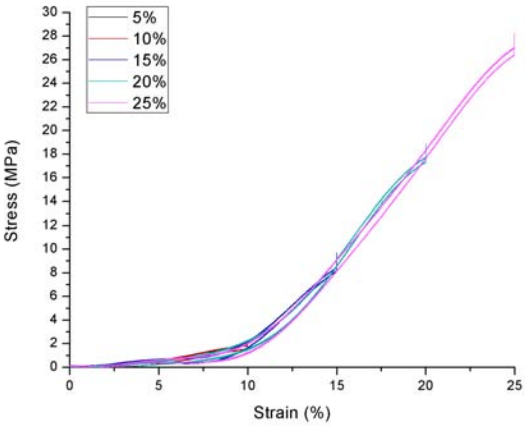

Figure 3. Mechanical properties of the CNTs sensor devices capped under compressive strain, the device is capped with a 2 mm tick PDMS layer; a) probe displacement, b) time response of the accumulated stress under forced strain and c) stress-strain curves for different maximum strain values.

In the current speed regime, below 10% strain, deformations along the polymer chains have time to occur which reduces the effective elastic modulus of our devices. Since the relaxation time of our device is ~ 1 s, we can expect that under faster compression, the polymer chain adaptation would not have time to occur and the device mechanical response would correspond to its behavior under strain higher than 10%. Despite the capping material viscoelastic properties, the system mechanical response is reproducible over each cycle and for all the maximum strain levels tested. Under these conditions CNTs can be used to measure static or quasi-static deformation or pressure. Based on their mechanical response, these devices could also be used for fast movement measurement such as walking or running. However, because of the resulting hysteresis, situation involving a rapid and sustained strain application would be more difficult to measure as an apparent decrease of the applied strain would be observable. However, such cases could be corrected by analysis the dynamic response of the sensor and by applying a proper model.

Figures 5c and 5d show the calculated response of the CNTs sensor based on the two studied CNTs films. The applied strain conditions are the same as described earlier and a 25% maximum strain was reached. The responses were calculated from a mechanical model obtained from the stress/strain curves and from the piezoresistance model of both films. It can be seen that, while the loosely woven film based sensor demonstrates a resistance change about 8 times higher than the purified film, its non-linear response makes it much more sensitive to the mechanical noise. The noise ratio to maximum signal is about 50% for the multi-layered film while it is 5% for the purified one.

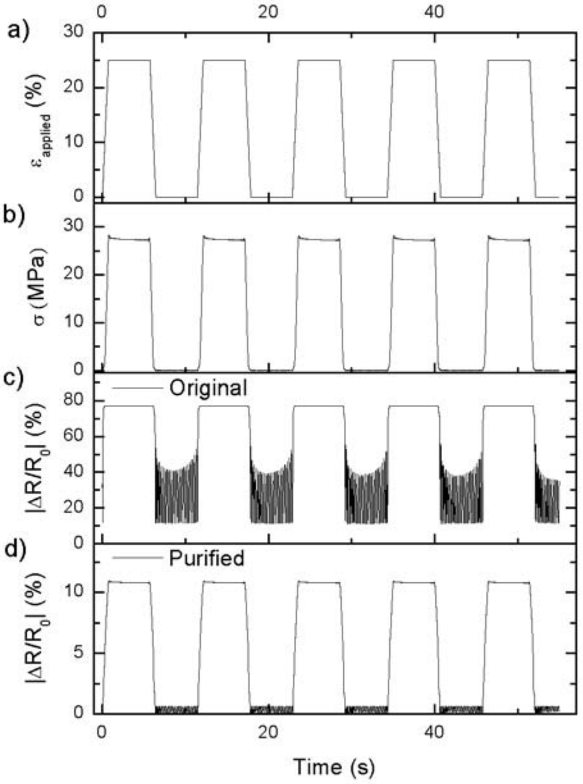

Figure 5. Mechanical response of the CNTs sensor devices capped under compressive strain, the device is capped with a 2 mm tick PDMS layer; a) applied strain, b) resulting stress, modeled piezoresistive response of a sensor using c) a multi-layered CNTs film and d) a purified film.

IV. CONCLUSION

The experimental results presented in this paper offer insights on the use CNTs as piezoresistive strain sensors. Two types of CNTs films (multi-layered CNTs film vs. purified film) were characterized electrically and mechanically for potential use as source material for a wearable matrix of strain sensors with a dedicated monitoring and biofeedback system. The loosely purified CNTs film showed a substantially smaller sensitivity then the multi-layered CNTs film but had an almost linear response to stress. The purified film was also less affected by the mechanical noise of the testing system.

As CNTs have the potential to achieve a much higher sensitivity to strain than other piezoresistors based on regular network of conductive nanoparticles such as commercially available resistive inks [12], we are currently exploring their use in a design for a 3-axis strain sensor. Indeed, when positioned non-collinearly, the CNTs sensors have the potential to distinguish the different stress components, separating compressive, parallel shear strain and pinch shear strain. In this design, a mobile structure is embedded in a compliant material and linked with an immobile frame. Under applied stresses, the displacement of the mobile structure results in different resistance variations from each CNTs sensitive element. Through calculations and comparison of the signal from the separated CNTs elements, the different strain components (linear and shear) could be determined. This could be determinant for the proposed application in PU prevention.

Finally, while the primary application targeted for CNTs as strains sensors in this paper is pressure ulcer prevention, applications of this wearable sensing technology could also be considered in the field of rehabilitation as a mean to monitor weight bearing under ambulatory conditions. Weight bearing, defined as the amount of weight supported by a limb, is an important clinical outcome for rehabilitation specialists.

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