Novel Wearable EMG Sensors based on Nanowire Technology

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***Abstract*—Wearable electrodes made of silver nanowires (AgNWs) have demonstrated great potential for sensing a variety of physical and physiological signals. This paper aimed to study the feasibility of AgNWs electrodes for measuring surface electromyographic (sEMG) signals. One human subject was recruited and instructed to perform wrist extension repetitively or to produce no movement in the experiment. sEMG signals were collected from the right *extensor digitorum communis* of the human subject by an AgNWs electrode and a commercially available Ag/AgCl wet sEMG electrode, separately. The quality of recorded sEMG in time and frequency domains was compared between the two types of electrodes. The results showed that the sEMG signals recorded by the AgNW electrode were comparable with that by the Ag/AgCl electrode. Since the dry AgNWs electrodes are flexible, wearable, and potentially robust for daily use, novel AgNW-based EMG electrodes are promising for many biomedical applications, such as myoelectric control of artificial limbs.**

***Keywords*— Silver nanowire, surface electromyography, EMG electrodes**

I. INTRODUCTION

Surface electromyography (sEMG) is a technique for measuring electrical potentials generated by active motor units, comprising groups of muscle fibers [1]. sEMG can be detected by electrodes placed on the skin surface during muscle contractions, and have been used in various applications, such as diagnosis of neuromuscular disorders, evaluations of muscle fatigue, and control inputs for powered prosthetic/orthotic devices [2-5]. Two types of surface electrodes are commonly in use: wet and dry electrodes. Conventional silver/silver chloride (Ag/AgCl) wet electrode used electrolytic gel as a chemical interface between the skin and the conductive layer of electrode to measure good-quality sEMG signals. A dry electrode, on the other hand, measures sEMG signals via direct skin contact without gel. Commonly-used dry sEMG electrodes were made of noble metals (e.g. platinum, gold, or silver), carbon, or sintered Ag/AgCl [6].

sEMG signals have been used for prosthetic limb control [7-12]. In this case, sEMG electrodes must be embedded into the prosthetic socket. In addition, obtaining high-quality and reliable sEMG recordings in daily living is essential in order to make EMG controlled artificial limb clinically practical. The wet electrodes are difficult to be applied because (1) adding gel within the prosthetic socket is impractical, and (2) wet electrodes lack reliability for long-term EMG recordings because the sensor impedance changes over time while gel becomes dry. Dry sEMG electrodes are more practical and have been applied in myoelectric prostheses. Usually the dry metal electrodes are fixed in the prosthetic socket or gel liner and directly contact the skin of a residual limb for sEMG recordings. However, limitations of such a setup still exist. First, relative motions between skin and electrode contact have been observed during prosthesis use, which poses a challenge for the reliability of dry electrodes for consistent sEMG measurements. In addition, to ensure good electrode-skin contact, dry contacts usually protrude from the electrode-base, which creates regions of high pressure and friction against the residual limb, leading to discomfort in users, especially lower limb amputees [13]. Solutions for designing dry sEMG electrodes for artificial limbs, which are reliable, wearable, and minimally intrusive, are needed.

Electrodes based on silver nanowires (AgNWs) provide a promising new technology for sEMG measurements for prostheses. AgNWs have high conductivity for high-quality electrophysiological signal recordings without using gel Therefore, AgNW-based sensors can be worn on various locations of the body and retain soft electrode-skin contact. Additionally, various manufacturing techniques used for AgNWs (such as screen printing and spray coating) can create conductive, thin, and flexible sensors [14, 15]. Furthermore, the AgNW electrode retains a stabilized conductivity (~5285 S cm^{-1}) [14] after being repeatedly strained and released. This indicates that the electrode can give consistent readings under different strain and flex conditions, which is critical to provide reliable sEMG recordings in prosthesis use. Finally, the fabrication process of the dry electrode is simple and can potentially be scaled up in manufacturing, further reducing cost.

Motivated by these beneficial properties of AgNWs, this study aimed to investigate the feasibility of nanowire technology for sEMG recordings for the first time. sEMG signals recorded by the AgNWs dry electrodes were compared with those by commonly-used Ag/AgCl wet electrodes. The results of this study demonstrated a novel sEMG electrode design based on AgNWs that is wearable and reliable for long-term recordings on a daily basis.

Research supported partly by NSF through ASSIST Center at NCSU (EEC-1160483), DOED/NIDRR #H133G120165/ H133G130308, NSF (#1406750 and #1361549).

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II. METHODOLOGY

A. Sensor Design and Fabrication

AgNWs (Blue Nano: 90nm wires in ethanol solution) were cast onto a pre-cleaned silicon substrate. After the ethanol was completely evaporated, a network of AgNWs remained, and liquid polydimethylsiloxane (PDMS) (Sylgard 184, Dow Corning Company, Midland, MI) was poured over the nanowires. At this stage, a metal snap was pressed on top of the AgNWs/PDMS mixture. This snap allowed for the integration of the dry electrode with lead wires used in current equipment. The substrate was placed in vacuum to remove air bubbles from the PDMS and cures at 100 ℃ for 1h. When the cured PDMS was peeled off the substrate, the AgNWs network was visibly bonded to the PDMS, and the snap was securely connected to the AgNWs/PDMS network. A schematic of the fabrication process is shown in Fig. 1. More detailed procedure for fabricating AgNWs electrodes has been reported elsewhere [14, 15].

B. Evaluation Experiments

One male, healthy subject with no history of neurological diseases participated in this study. Informed consent was collected before the experiment. The study protocol was approved by the Institutional Review Board at the University of North Carolina, Chapel Hill.

The AgNW dry electrode was compared against a commercially available pre-gelled Ag/AgCl electrode (Norotrode 20, Myotronics, WA). Electrodes were positioned on the right *extensor digitorum communis* after shaving the skin area and cleaning the skin by 70% Isopropyl Alcohol. A bipolar electrode configuration was applied. The longitudinal axis of electrode was oriented parallel to the direction of muscle fibers, with a 22-mm center-to-center spacing. In order to guarantee the consistent electrode placement between electrode types, marker was used to confirm the electrode location on the skin. A self-adhesive ground Ag/AgCl electrode (3M Red Dot, 3M, AK) was placed on right lateral epicondyle.

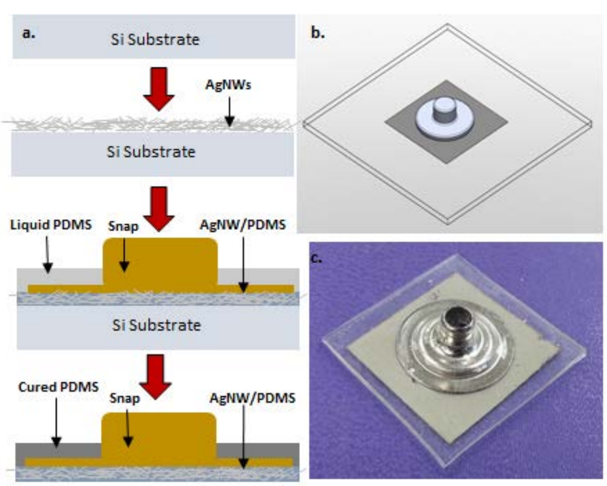

Fig 1. (a) sEMG electrode fabrication schematic (b) CAD model of electrode (c) Picture of fabricated AgNWs sEMG electrode.

For each electrode type, the subject performed the following two types of trials.

1) Settling trial: The subject was in a sitting position with his back straight and left arm relaxed. He was asked to place his right forearm on a flat table with a pronation position. The wrist was in neutral position in terms of radial/ulnar deviation and extension/flexion. Approximate 30 seconds of data was recorded without any muscle contractions.

2) Wrist-extension trial: The initial posture was the same as that described in the settling trial. During the data collection, ten wrist-extension contractions were conducted. Each contraction lasted 3 seconds. The duration between two continuous contractions was 10 seconds. The subject was asked to perform every contraction with a 60-degree wrist extension and consistent contraction effort.

The type of electrodes and type of trials were assigned randomly. To avoid muscle fatigue, the subject was allowed to rest between each trial.

sEMG signals were collected by a 16-channel EMG system (MA 300, Motion Lab System, LA). The system contained a preamplifier that band-pass filtered the sEMG signals between 10 and 2000 Hz with a pass-band gain of 20. Then the system filtered signals between 20 and 420 Hz with an adjustable pass-band gain set to 1000. The sEMG signals were sampled at 1000 Hz.

C. Signal Processing

Data analysis was conducted offline using MATLAB (Mathworks, MA). DC offset was removed from all the recorded signals for the following processing.

First, the signal-to-noise ratio (SNR) was calculated for each type of electrode. The SNR was defined as:

$$\mathrm{SNR_{dB}} = 10\log_{10}\left(\frac{A_{signal}}{A_{noise}}\right)^2 = 20\log_{10}\left(\frac{A_{signal}}{A_{noise}}\right), \quad (1)$$

where A is root mean square (RMS) of the signal. A_{noise} was estimated by using the sEMG data recorded in the settling trials because there was no muscle contraction in this condition. A_{signal} was computed from data in the muscle contraction periods in the wrist-extension trial. To determine the contraction onset and offset timing in wrist-extension trials, a simple threshold detection algorithm based on sEMG envelope value was applied. In order to obtain the sEMG envelope, the sEMG signals were (1) band-pass filtered (15-300 Hz), (2) rectified, and (3) low-pass filtered at 3Hz. The contraction onset time was identified when the sEMG envelope exceeded three standard deviations from the average value in the settling condition. Then sEMG data without DC offset from each contraction period were concatenated to calculate A_{signal}.

Additionally, the frequency components of recorded sEMG signals were analyzed. Two spectral parameters were used for the comparison of two types of electrodes: mean frequency (MNF) and median frequency (MDF) [16]. The definition of MNF is

$$MNF = {\sum_{i=1}^{M} f_i P_i} \Big/ {\sum_{i=1}^{M} P_i}, \quad (2),$$

where f_i is the frequency value at the i_{th} frequency bin, P_i is the sEMG power spectral density (PSD) value at the

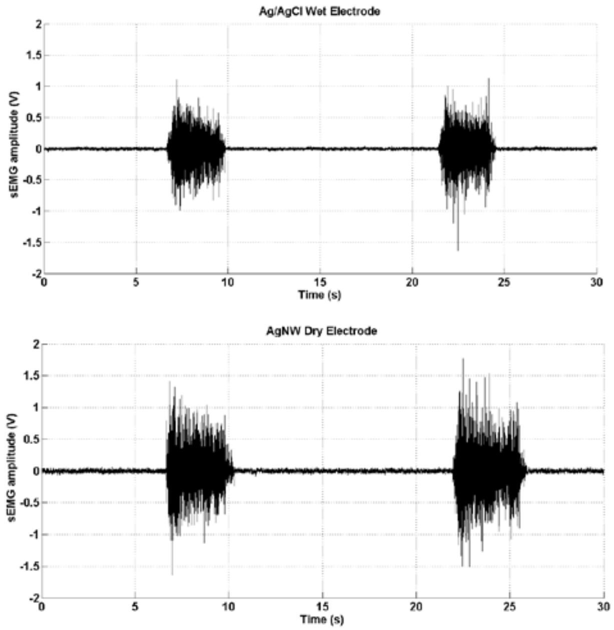

Fig 2. Representative sEMG data from Ag/AgCl gel electrode (above) and AgNWs dry electrode (below) during two continuous wrist-extension contractions.

frequency bin i, and M denotes the total number of frequency bins. MDF is a frequency, where the sEMG PSD is divided into two segments with the same amount of cumulated power, i.e.

$$\sum_{i=1}^{MDF} P_i = \sum_{i=MDF}^{M} P_i = \frac{1}{2}\sum_{i=1}^{M} P_i. \quad (3)$$

In this study, the sEMG PSD for each muscle contraction was estimated from sEMG signals without DC offset via Welch's averaged modified periodogram [17]. Sliding hamming windows, each of which had 512 samples in length and an increment of 256 samples, were used in the PSD estimation. For each electrode type, the averaged PSD values across ten contraction periods were calculated and normalized by the maximum value. Based on (2) and (3), MNF and MDF were obtained from the normalized PSD values.

III. Results

Fig. 2 shows a set of representative sEMG data in wrist-extension trials recorded from the two types of electrodes. Two muscle contractions with the period of inactivity in between were measured. Both types of electrodes showed discernable recordings of the sEMG signal of the right *extensor digitorum communis*. The amplitude of sEMG signals recorded by the AgNWs dry electrode was higher than the wet electrode from visual inspection. However, the SNR of commercially available Ag/AgCl wet electrode (27.3 dB) was slightly higher than the SNR of AgNWs dry electrode (24.7 dB).

Fig. 3 shows PSD of sEMG derived from wrist-extension trials. The dominant frequency components were between 25Hz and 180Hz for both sEMG signals based on visual inspections. The spectra derived from both electrode types were comparable. The MNF and MDF values are listed in Table I. The mean and median frequencies of the dry AgNW electrode were about 4 Hz lower than those of the Ag/AgCl wet electrode.

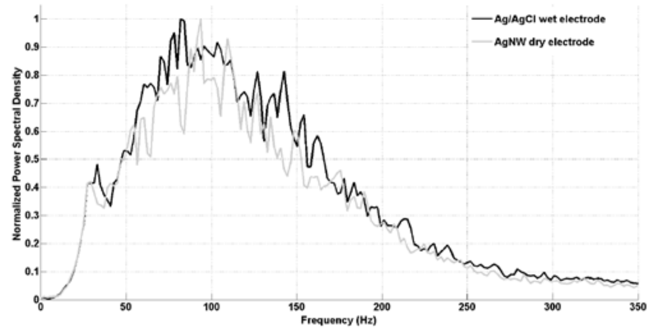

Fig 3. Normalized power spectral density from the wrist-extension contractions for both types of electrodes.

TABLE I. MEAN FREQUENCY AND MEDIAN FREQUENCY FOR TWO TYPES OF ELECTRODES

Electrode type	Mean frequency	Median frequency
Ag/AgCl gel electrode	139.0 Hz	119.1 Hz
AgNW dry electrode	135.6 Hz	115.2 Hz

IV. Discussion and Conclusions

In this study a novel AgNW dry electrode was fabricated and used to measure sEMG signals from a human subject. The recorded sEMG signals were compared with those by a commercially available Ag/AgCl wet electrode. The AgNWs dry electrode recorded very clear and strong sEMG signals, although its signal-to-noise ratio was ~2dB lower than that of the Ag/AgCl wet electrode. The power spectrum density estimated from the sEMG signals recorded from two studied electrodes was similar. These results suggested that our AgNW dry electrode can serve as an alternative for high-quality sEMG recording.

The novel AgNW dry electrode is a preferable choice for powered artificial limb control for the following reasons. 1) The AgNW electrodes are comfortable to wear. Compared with the dry metal electrode used for myoelectric prostheses, the AgNW electrode is a thin layer embedded in rubber that is flexible/stretchable. The electrode can be easily integrated into a gel liner system for prosthetics. The user can wear the electrodes by simply rolling the gel liner onto the residual limb before donning the prosthetic socket. 2) The AgNWs electrode can provide stable skin contact by adhering to the skin. This feature can solve the problem of unreliable sEMG recordings caused by relative motion between metal electrodes and the skin. 3) The capability of AgNW electrode for remaining stabilized conductivity after being repeatedly strained and released indicated the potential of reliable sEMG recordings during the limb movements for prosthesis use. 4) It is possible to integrate other types of sensors based on AgNWs into the same substrate to produce a multifunctional electrode (e.g. an electrode that can measure sEMG signals and mechanical pressures at the same time). This property offers another potential to improve the reliability of sEMG recordings over time by exploring various sensor fusion approaches. 5) The fabrication process of this AgNW electrode is simple, indicating its potential to scale up in manufacturing at reduced cost.

This presented study is preliminary in order to demonstrate the feasibility of AgNWs technology for sEMG recordings. In our future work, we will systematically quantify the potential of AgNWs electrode for reliable, long-term sEMG monitoring. Additionally, engineering efforts will be focused on integrating the novel AgNW electrode into prosthesis control and developing new wearable sensors for recording electrophysiological signals.

ACKNOWLEDGMENT

The authors would like to thank Fan Zhang at North Carolina State University for his assistance in data collection.

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