DEVELOPMENT OF A STRETCHABLE, PENETRATING ELECTRODE ARRAY FOR MEASURING INTRAMUSCULAR ELECTROMYOGRAPHIC ACTIVITY

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ABSTRACT

We present the development and characterization of a stretchable microneedle electrode array (sMEA) for stimulating and recording electrical muscular activity. Such a device improves the signal fidelity and spatial resolution capabilities of prosthetic systems and muscle-computer interfaces. The device was produced via a scalable microfabication process; and was measured to have electrodes with well-matched impedance spectra, to be functional beyond a 20% tensile strain, and to be cytocompatibile for 28 days *in vitro* (DIV). When implanted on a contracting muscle, the electrodes of the array measured a variety of electromyographic (EMG) signals, suggesting the device can measure regional EMG activity.

KEYWORDS: Multielectrode Array, Electromyography, Penetrating Electrodes, Stretchable, Flexible, Muscle

INTRODUCTION

The advancement of technologies that interface with electrically excitable tissues, such as the cortex and muscle, has the potential to lend greater mobility to the disabled, facilitate the study of the central and peripheral nervous systems, and transform how people interact with technological devices. Myoelectric interfaces are currently limited in their signal fidelity, spatial resolution, and interfacial area. Such interfaces are either implanted in muscle [1] or applied to the surface of the muscle [2] or skin [3]. Thus far, the former technology has been limited in its applications due to the stiffness (several orders of magnitude greater than muscle) of its substrates, such as silicon and polyimide, whereas the latter technology suffers from poor spatial resolution and signal quality due to the physical separation between the electrodes and the signal source. We present the development of an sMEA that can function while stretching and flexing with muscle tissue, thereby enabling multi-site muscle stimulation and EMG measurement across a large interfacial area.

EXPERIMENTAL

Process Development: The sMEA (Fig. 1) was fabricated utilizing micromolding technologies. Conductive polydimethylsiloxane (cPDMS) (Fig. 2b) traces were deposited on a mold (an ICP-etched silicon wafer) using squeegee printing. Laser-micromachined stainless-steel needles (Fig. 2b, 3a) were attached to the cPDMS layer for 3-D functionality, on top of which a PDMS substrate layer was applied (Fig. 2c). The backside of the device was laminated to a Kapton flex connector (Fig. 2d), which carries the EMG signals to a data acquisition system. The backside of the microneedles were reinforced with cPDMS (Fig. 2e), and a final layer of PDMS was applied to the back to insulate the device.

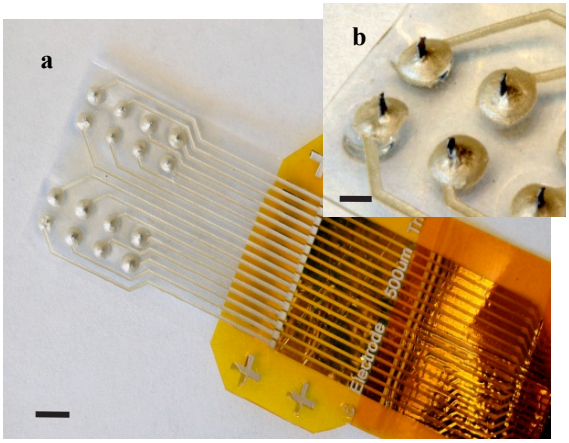

Figure 1: (a) Fully pakckaged sMEA (scale – 5mm) and (b) close up of microneedles (scale – 2mm).

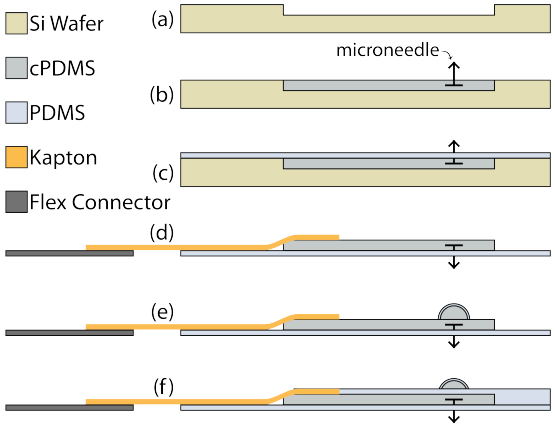

Figure 2: Fabrication process of stretchable microneedle electrode array (sMEA).

cPDMS Theory: The sMEA is capable of stimulating and measuring muscle activity over a large tensile strain because both the substrate and the conductors are composed of polydimethylsiloxane (PDMS), a stretchable and biocompatible polymer with a Young's modulus of ~1 MPa [4]. The conductive traces are a mixture of PDMS (Dow Corning) and silver flakes (Ferro), combined at a 1:4 weight ratio, and cured at 150 °C for 15 minutes [5]. The high temperature of the curing process causes the polymer matrix to reduce in volume by 20% [5], which brings the silver particles of the polymer into closer contact (Fig. 3b) and reduces the resistance of the material. Although sintering has been observed in silver nanoparticles when exposed to temperatures near 150 °C [6], submicron silver particles constitute less than 10% of the silver flakes mixture [7], thus the conductivity of the polymer matrix should primarily be due to the physical contact shared between the silver flakes.

Characterization: The impedance spectrum of the device was measured by immersing it in a saline bath (HBSS 1X, Gibco) to reproduce the ionic environment of an implantation. A platinum wire, placed in the saline bath, was used as the reference electrode. A spectrum analyzer (SRS Dynamic Signal Analyzer, SR785), augmented by a custom board, was used to measure the impedance spectrum of each of the electrodes across a frequency sweep of 10 Hz to 100 kHz.

To assess the device functioning under tensile strain, strips of the device were cut and clamped between two micromanipulators (Siskiyou), and a multimeter was used to measure the resistance between the electrodes and trace terminals. While the resistance was measured, the tensile strain placed on the strips was incrementally increased until the devices were rendered inoperable.

The cytotoxicity of the components of the device were evaluated to determine whether the device may be utilized in long term studies or implantations. Rat cortical neuronal cell cultures were grown on cPDMS, cPDMS encapsulated in PDMS, and polystyerene controls. Over a period of 28 days these cultures were visually inspected for cell death, and on the 28th day an adenosine triphosphate (ATP) assay [8] was administered to provide a quantitative indicator of cell health.

Lastly, the capability of the sMEA to measure muli-site EMG activity was assessed by implanting the device on the surface of the lateral gastrocnemius (LG) muscles of cats. All experimental procedures within this study were conducted in accordance with the guidelines of the National Institutes of Health and the Georgia Tech Institutional Animal Care and Use Committee. In each trial, the cat was tracheotomized to control its level of isoflurane anesthesia. For the purposes of recruiting and studying the animal's reflexes, the brainstem was transected at a 45 degree angle, rostral to the mammillary bodies. To induce the LG muscle with the sMEA to contract, the contralateral tibial nerve was electrically stimulated to activate the crossed extensor reflex (Fig. 4). The electrical stimuli were delivered at a frequency of 40 Hz, with 100 μs monophasic pulses, and an amplitude between 0.5 – 5 V. The electrical signals measured through the sMEA were sampled at a frequency of 3 kHz, amplified by a gain of 500, and processed through a 20 Hz high-pass filter and a 60 Hz notch filter to remove any motion artifacts and electromagnetic noise, respectively.

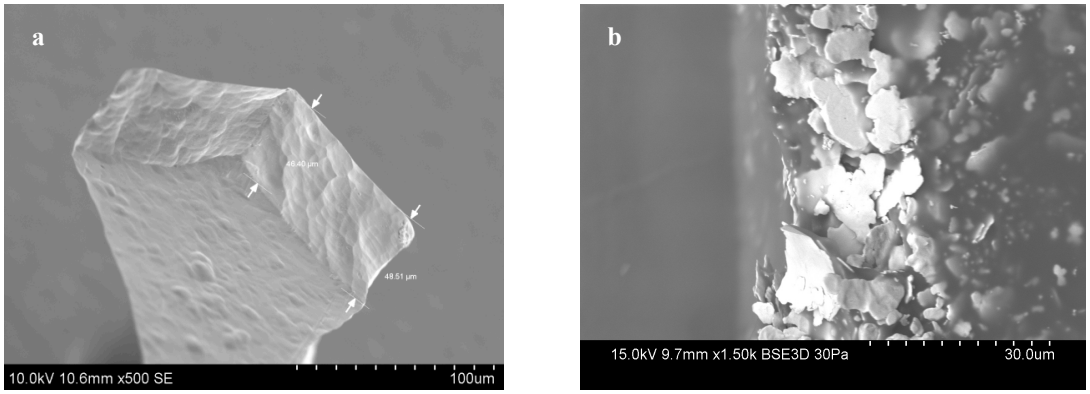

Figure 3: SEM images of (a) an sMEA microneedle (~47 μm thick) and (b) the conductive polydimethylsiloxane mixture.

RESULTS AND DISCUSSION

The impedance of the sMEA electrodes were measured to be on average ~7.6 kΩ at 1 kHz (Fig. 5), and the impedance spectra of these electrodes were observed to be well matched, indicating uniformity in the fabrication process. The sMEA was observed to maintain a resistance below 150 Ω beyond 20% uni-axial strains (Fig. 6). The rat cortical neuronal cell cultures, grown on sMEA materials, produced levels of ATP similar to those grown on the polystyrene controls, indicating excellent material cytocompatibility at 28 DIV. When implanted on LG muscles *in vivo*, the device successfully measured unique signals of EMG activity across its electrodes (Fig. 7) during both spontaneous muscle contractions, and contractions that were electrically induced via the crossed extensor reflex. Compound motor unit action potentials were observed at different times and frequencies across the electrodes of the devices.

CONCLUSION

We present a multi-electrode array that can penetrate muscle tissue, measure its electrical activity, and stretch and confirm to it during periods of contraction and extension. Additionally, the materials used in the fabrication of the device were shown to be cytocompatible for 28 DIV, suggesting it can be utilized for chronic studies and implantations. The experimental results demonstrate that the device can measure EMG activity with high spatial resolution and high signal fi-

delity across a large interfacial area. This device may be used to extend the capabilities of rehabilitative neuroprosthetic systems and to perform more thorough investigations into the recruitment of muscle.

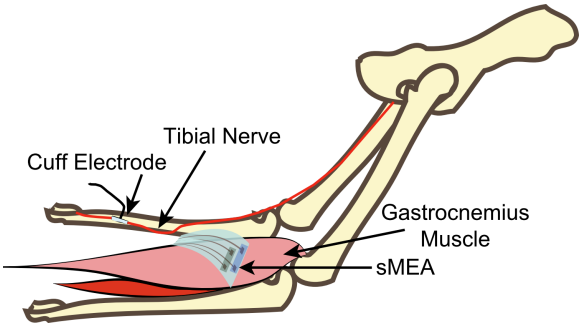

Figure 4: Schematic of the in-vivo experimental setup.

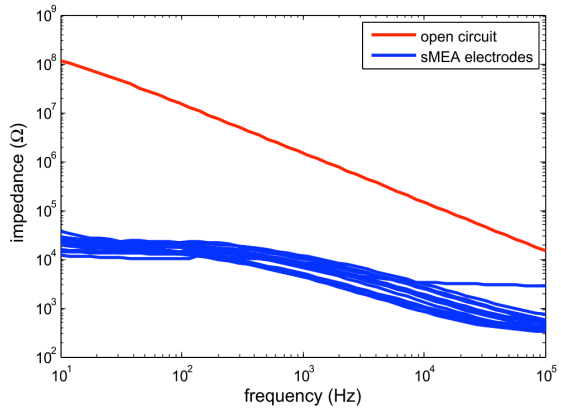

Figure 5: Full impedance spectra of the sMEA device.

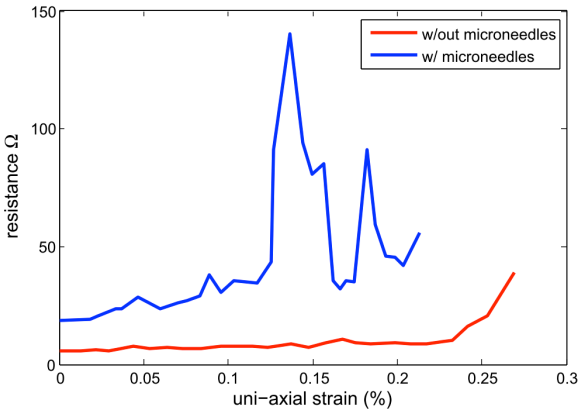

Figure 6: Impedance of sMEA traces v. tensile strain.

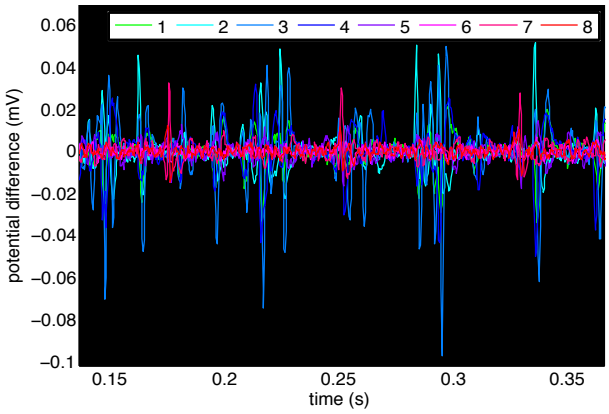

Figure 7: EMG activity across 8 sMEA electrodes.

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