A Stretchable and Flexible System for Skin-Mounted Measurement of Motion Tracking and Physiological Signals

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Abstract— **In this paper, we present a stretchable wearable system capable of i) measuring multiple physiological parameters and ii) transmitting data via radio frequency to a smart phone. The electrical architecture consists of ultra thin sensors (< 20 µm thick) and a conformal network of associated active and passive electronics in a mesh-like geometry that can mechanically couple with the curvilinear surfaces of the human body. Spring-like metal interconnects between individual chips on board the device allow the system to accommodate strains approaching ~30%. A representative example of a smart patch that measures movement and electromyography (EMG) signals highlights the utility of this new class of medical skin-mounted system in monitoring a broad range of neuromuscular and cardiovascular diseases.**

I. INTRODUCTION

Health and wellness monitoring devices that are ultrathin, flexible and mechanically matched to Young's modulus of human skin have the potential to unlock a wealth new physiological data from patients outside of the hospital setting. However, conventional health monitoring technologies used to date consist of bulky and rigid electronics components [1, 2]. Their wearability is thus limited by the soft form factor and curvilinear morphology of the human body. Such limitations are particularly challenging for monitoring movement disorders [3, 4], like Parkinson's disease, Lou Gehrig's disease, and muscular dystrophy, which typically arise from aberrant electrical firing patterns of motor neurons that synapse on muscle fibers. To track these electrical patterns involves attachment of electrode pads to the skin with adhesive tapes and conductive gels to minimize contact impedances.

Several studies have reported recent developments in wearable sensors that can be attached on skin for epidermal physiological measurements (skin hydration, temperature, heart rate, and Galvanic skin response) [5-8]. However many of these sensors still rely on tethered electrical connections for data transfer and signal processing. Wired connections along with bulky associated electronics together preclude the adoption of wearable health monitoring systems during normal daily activities and tracking of patients in the home setting.

Here we present a new class of wearable electronics, combining ultrathin physiological sensors, a thin battery, an analog front-end (AFE) processor, a core microprocessor, a flash memory module, and wireless communication (Bluetooth low energy) in a flexible and stretchable format. The overall system is less than 2 mm thick with a soft elastomeric encapsulation layer that interfaces with skin via a biocompatible adhesive.

II. SYSTEM SCHEMATIC

A schematic of the wearable EMG and motion sensing system is demonstrated in Figure 1a. The epidermal electronics are assembled on the multiple-islands design with serpentine interconnections. The islands and interconnections are fabricated with a standard polyimide based flexible circuit process. The size and thickness of the individual islands are optimized for stretchability, reliability, and comfort for wearing. The integrated system is then over-molded with room temperature vulcanization (RTV) silicone to produce an encapsulated system protected from moisture and contamination. The ultra-thin electrodes are connected to the system with a re-useable board-to-board connector (micro connector, Molex Inc.). The sensing system patch will be attached to the skin via a double-sided skin adhesive (silicone adhesive, Adhesive Research), while Tegaderm$^{\text{TM}}$ dressing (Tegaderm$^{\text{TM}}$, 3M) is used to affix the electrodes onto the skin surface. The serpentine interconnections between the islands provide the strain isolation and decoupling from the rigid electronics. Therefore the localized strain within the islands are reduced to <0.1% while the system is under 20% mechanical strain. Figure 1b demonstrates the deformed system under mechanical stretching.

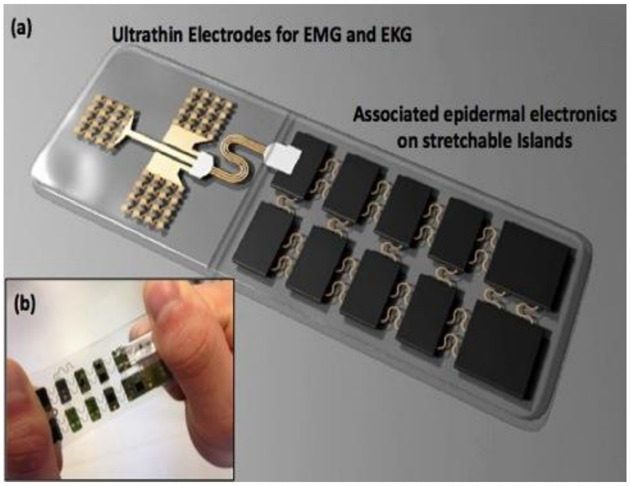

Figure 1. a) System schematic with the multiple-islands design and ultra-thin skin electrodes, b) The fabricated system being stretched under 20% strain.

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B. *System Architecture*

The sensing platforms incorporate an on-board rechargeable battery unit, coupled with memory, Bluetooth communication, a low-power micro-controller unit, an accelerometer, and a low-power Analog-Front-End (AFE) for electrophysiological recordings (Figure 2). The sensing system contains a high pass filter (<10mHz) to remove the DC offset noise from the high-impedance electrodes. The 16 bits analog to digital output of the AFE directly communicates with the low-power micro-controller. The accelerometer and EMG/EKG data can be either streamed simultaneously with Bluetooth communication for live monitoring or stored into flash memory for downloading via Bluetooth afterwards. The system can operate for about 5 to 10 hours depending on the use case and Bluetooth advertising rate. The rechargeable battery can be charged through the on-board micro connector or wirelessly using RF energy harvesting.

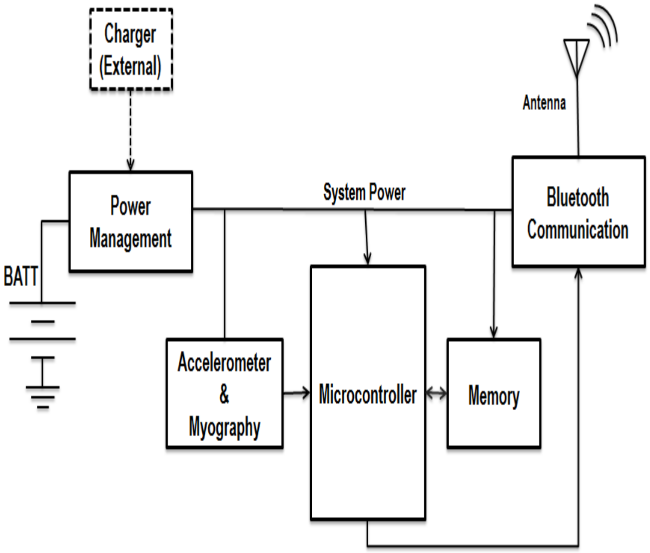

Figure 2. System Architecture of the sensing platform includes an accelerometer, power control, memory, a microcontroller, wireless communication, and sensing units.

III. INTEGRATED SYSTEM

Figure 3a shows the EMG electrode and motion-sensing platform placed on the forearm for wrist flexor muscle and activities measurements. As can be seen from the picture, the ultra-thin dry electrode is conformally attached on skin without conductive adhesive or gel. In Figure 3b, the electrode is twisted yet remains in conformal contact with the skin under stretching. The layout of the electrode with soft elastomer provides linear elastic responses to applied force, with the capability to bend, fold, and deform onto different curved surfaces. These features are especially significant for skin-mounted sensors (EKG, EMG, and EEG) to enable sufficient electrical coupling for high quality measurement. In particular, the signal to noise ratios (SNR) of recorded signals significantly benefit from low output impedance at the electrode and skin interface.

The encapsulated patch system is attached onto the forearm with the skin-compatible adhesive. As shown in the picture, stretchable electronics offer the key advantage of softness and are designed to match the physical properties (modulus, thickness, and area mass density) of the epidermis itself. Thus the soft form factor allows the system to be placed on arbitrary and curvilinear surfaces – anywhere on the body.

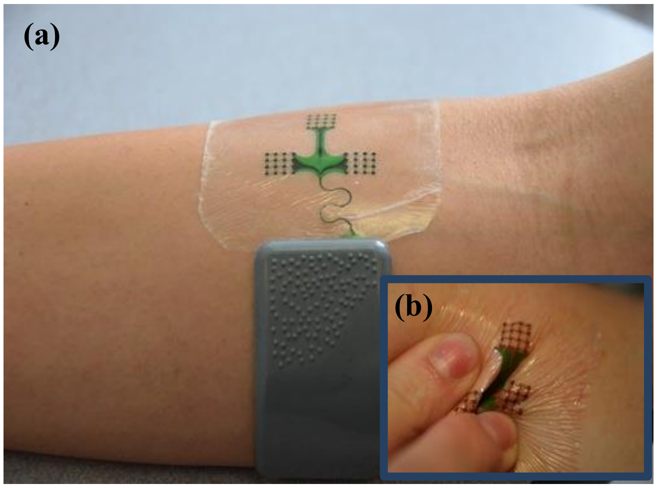

Figure 3. a) Integrated system of the electrode with the patch. b) The ultra-thin electrode remains conformally attached to the skin when twisted.

IV. EXPERIMENTAL RESULTS

A. *Electromyography*

The placement of MC10 Electrode was shown in Figure 3 to perform the EMG measurements. The center electrode was used as the reference electrode for differential measurements. The signals were recorded with a 500Hz sampling rate to cover the significant frequency range of EMG bandwidth (50 Hz ~ 150 Hz). A 60Hz notch filter was used to remove the background noise. Three different exercises were executed to validate the functionality of EMG measurements,

- Wrist Flex Test: The testing subject holds a 5 lb. weight in the right hand and flexing the wrist twice during a 4-second window while keeping the forearm resting on the table.
- Squeezing Test: The testing subject holds a squeezable plastic ball in the right hand and performs two squeezing motions with all five fingers during the 4-second window.
- Finger Movement: With nothing held in the hand, the testing subject performs middle finger bending twice during the 4-second window.

The results are shown in Figure 4. Figure 4a, 4c, and 4e show how the patch and electrodes were placed on the forearm for the three movements. Each movement can be identified with different amplitudes (Flexing motion: 10 μV peak-to-peak, Squeezing motion: 5 μV peak-to-peak, and Finger movement: 2 μV peak-to-peak) and frequency responses. SNR analysis was evaluated with MATLAB from the data stored in the flash memory. SNR values of 15 to 30 were calculated depending on the movement performed.

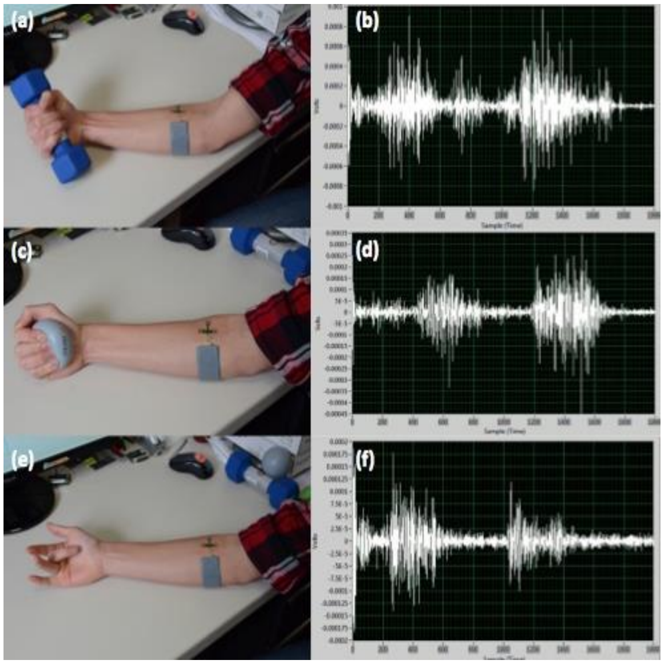

Figure 4. Movements performed for EMG testing a) and b) wrist flexing with a 5 lb. weight, c) and d) squeezing action with a ball in hand, e) and f) middle finger flexing.

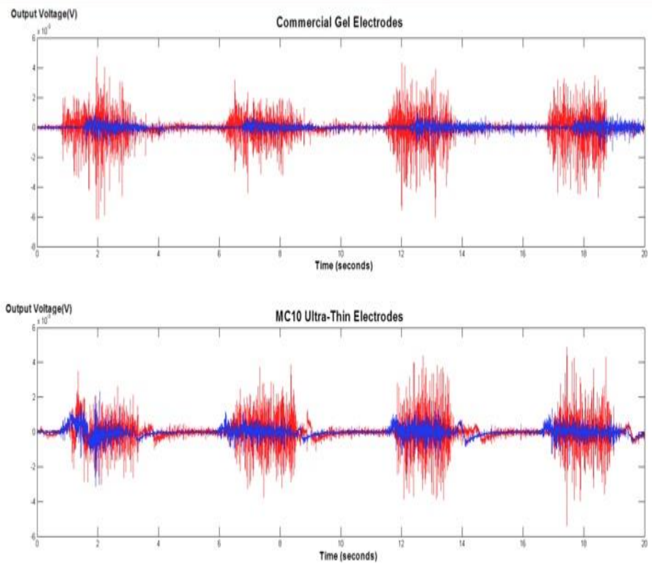

Figure 5. Comparison between commercial gelled electrode (top) and MC10 ultra-thin dry electrodes. The blue graph shows the flexing motion with a 1 lb. weight, and the red graph shows the flexing motion with a 5 lb. weight.

A comparison test was performed to verify the performance of MC10 ultra-thin dry electrodes. A commercial gel electrode (T3402, Thought Technology) was connected to the patch system for a flexing test. The electrode was placed in the exact same location as shown in Figure 4a. The measurement signal is presented in Figure 5, as the blue graph indicates the EMG signals with a 1lb. weight, and the red graph indicates the EMG signals with a 5lb. weight, both of which reflect flexing the right wrist. After the test was completed, anMC10 electrode was placed at the same location, with the same flexing movement performed. As can be seen from the results, both the MC10 electrode and commercial gel electrode obtained similar magnitudes during the flexing tests (1 lb. weight: 0.8 μV peak-to-peak and 5 lb. weight: 4 μV peak-to-peak).

The newly designed thin-film electrode can be integrated onto the bottom of the motion-sensing platform to create a system with reusable electrodes underneath the encapsulation (shown in Figure 6b). With the electrode fully integrated with the sensor patch system, a conductive adhesive is used to maintain the quality skin-electrode interface. In Figure 6a, the sensor patch was placed on the shin area (Tibialis anterior) and EMG signals were collected during toe tapping movement.

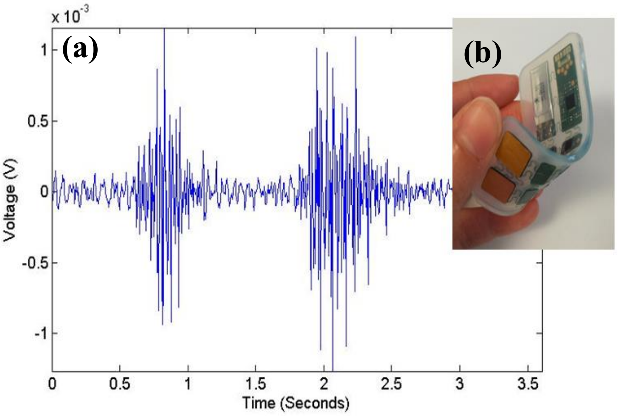

Figure 7. a) EMG signal recorded from Tibilais anterior muscle group b) Thin film electrode integrated underneath the sensor patch.

B. *Movement Tracking*

The system was placed on an oscillating table with variable speed to evaluate the performance of the accelerometer. The table was tilted at an angle of 22^{o} with respect to gravity and the device was placed in the lower right corner of the table with its accelerometer's z-axis normal to the table and x and y axes parallel to the table. With the table's oscillation speed set at the maximum of 25 RPM, the device recorded the data found in Figure 7 at a resolution of 2 mg of acceleration. The data showed that the x and y axes experience a sinusoidal acceleration—corresponding to the oscillating frequency of the table—while the z-axis precesses around gravity at the same rate.

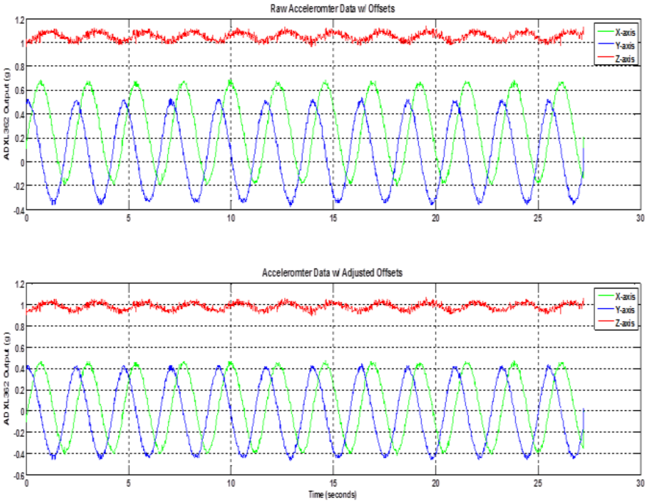

Figure 7. x-y-z axis measurements with the system placed on an oscillating table. Top: raw data, Bottom: adjusted data with offsets.

C. Electrocardiography

The electrode and patch shown in Figure 3 was attached to the upper left chest, close to the clavicle for electrocardiography (EKG) measurements. The electrode was placed between the fourth and fifth ribs, central-left to the sternum. The Bluetooth communication was first enabled to verify the functionality of the system then turned off during the recording to avoid noise from transmission. The data was written to the flash memory on the sensor patch with a sampling rate of 250Hz. The signal was recorded for 10 seconds and data was downloaded via Bluetooth after communication was enabled. The recorded wave data was then processed with MATLAB using a high pass filter (cut-off frequency at 30Hz) to remove the background noise. The result is presented in Figure 8. A clear pattern of heart rate can be distinguished. Further analysis such as R-R interval and heart rate can be obtained.

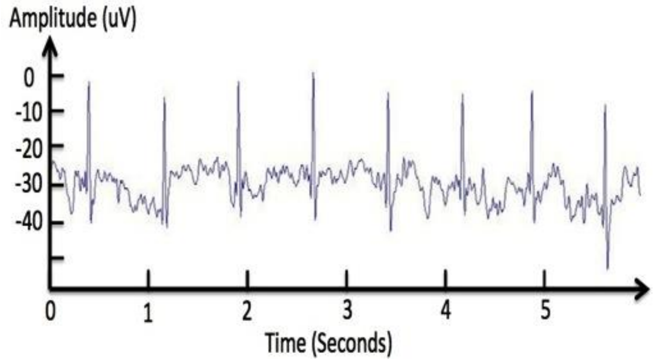

Figure 8. EKG signal measured on the trunk of the body. The electrode was placed near the left upper chest. R-R interval can be clearly calculated with a significant signal to noise ratio.

V. CONCLUSION

The design and characterization of a stretchable system for electronic components and ultra-thin skin electrodes were demonstrated with mechanical testing and physiological measurements. The functional devices can be further developed into an ideal monitoring assistant for patients with movement disorders during daily activity. The wearable system not only delivers quantitative measurements in motion tracking and EMG/EKG data, but also offers unique comfort for users due to the epidermal-compatible properties. Combining the advantages above, the wearable system with ultra-thin sensors has the potential to become a quality tool for continuous health monitoring.

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