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A Preliminary Usability Study of Integrated Electronic Tattoo Surface Electromyography (sEMG) Sensors *

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Abstract— **Surface electromyography (sEMG) sensor measures the user's muscle activities by noninvasively placing electrodes on the surface of the user's skin. It has been widely used in monitoring various human movements. Recently a wearable and flexible epidermal sensor system called Electronic Tattoo (E-Tattoo) has been developed to enable intimate attachment of electrodes on the skin, improving long-term comfort. In order to make the E-Tattoo usable in monitoring muscle activities, it is always connected with a connector and signal processing blocks to collect and process the measured sEMG signals. We call it an integrated system. This paper investigates the usability of a prototype of the integrated system developed in the laboratory for monitoring muscle activities by testing its comfort with user experience surveys and comparing the quality of the sEMG signals by widely used performance metrics. Two typical movements, maximum voluntary isometric and non-isometric contractions, are considered for the experiments. Our preliminary results on five subjects demonstrate the effectiveness of the proposed integrated system. This system showed a comparable signal quality for these two movements as the commercial product with a much better comfort feeling from the user. It is also interesting to note that this prototype shows a much better signal-to-motion artifact ratio (SMR), which reflects the ability to measure muscle activities during active movements, compared with the commercial product, showing the potential of using this integrated system in monitoring sEMGs during active and dynamic movements.**

I. INTRODUCTION

Muscle fiber contraction usually generates a weak electric signal called electromyography (EMG). A surface electromyography (sEMG) sensor can noninvasively measure the bio-potentials using electrodes placed on the skin [1]. Commercial sEMG sensors such as DELSYS Trigno (Delsys INC, USA) have been widely used in many applications [2]. They are usually rigid and relatively heavy, and therefore, difficult to secure in good contact with the skin, during long-term dynamic movements. Moreover, the sweat on the skin degrades the adhesion of the sensor and increases the risk of detachment. For better user comfort and possible long-term monitoring of muscle activities in various movements, wearable epidermal electronic sensors have garnered significant attention [3]. Among them, a so-called electronic tattoo (E-Tattoo) was proposed recently [4]. The E-Tattoo is a submicrometer thick, flexible, and body-conformable membrane that is easy to wear [5]. It can also be directly laminated to the human skin [6], which requires less skin preparation time, compared with that of commercial products. The E-Tattoo has been utilized in various applications such as a human-machine interface for robot hand manipulation [7], prosthetic hand control [8], muscle fatigue measurement [9], electrophysiological signal monitoring [10], and sign language recognition [11]. In order to make the E-Tattoo usable as a commercially available sEMG sensor, an integrated system is usually developed. It consists of electrodes, a connector, and signal processing blocks to amplify the signal and filter out noises. Despite the recent advancement in materials and electronics, there has been no comprehensive usability study for the integrated system in terms of the quality of signals (with respect to various performance metrics) and the user comfort for a large family of movements, compared with the commercially available sEMG sensors. There have been studies focused on some movements such as grasping [3], [9], [12], holding a dumbbell [13], and body movement with a small range of motions [7], [14], [15]. Most of these studies have focused on single and simple movements. There are limited studies when different movements were considered, see, for example, [16] and references therein. In this study, one of the performance metrics: signal-to-motion artifact ratio (SMR), which reflects the performance influences by motion artifact, was observed to be much higher than the commercially available sEMG sensors. A similar phenomenon was observed in [17], though the authors suggested that such a high SMR might come from the metal-based connector and cable.

This work presents a preliminary usability study for two typical movements – biceps brachii repetitive maximum voluntary isometric & non-isometric contractions (MVICs & MVnICs) [18] using an integrated system developed in the laboratory. Instead of using a metal-based connector, our design uses silver paste [12], [19] and conductive tape [12] with the aim to reduce SMR. Such a design also allows the connector to be reusable. We have tested 5 performance indices that have been widely used to evaluate the quality of sEMG signals. They are signal-to-noise ratio (SNR) [20], [21], baseline noise (BN) [20], drop in power density ratio (DPR) [21], power spectrum deformation (PSD) [21] and SMR [21]. From the results of experiments with 5 subjects, the developed integrated system has comparable performance in terms of these 5 measures, compared with the commercial DELSYS Trigno sensor. User experience surveys also indicate that this integrated system is much more comfortable to wear. It is noted that our experimental results show much higher SMR performance compared with two designs in literature [16], [17], suggesting that this design can be used in monitoring sEMGs in active movements.

II. DESIGN OF THE INTEGRATED SYSTEM

The integrated system consists of electrodes, a connector, an amplifier, and a data acquisition (DAQ) system. A highly electrically conductive and biocompatible gold/chromium film was deposited on the top of metalized polymer material purchased by the original equipment manufacturer. Then, the fast and efficient manufacturing process using a programmable cutting machine called the "cut-and-paste"

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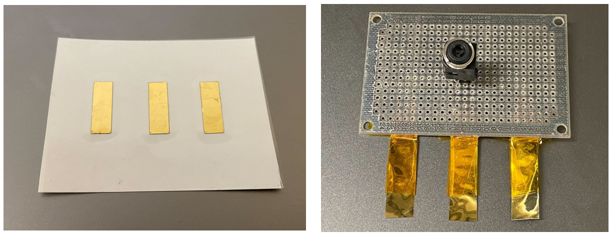
method [14] was used to fabricate the rectangular bar-type electrodes. The interface mismatch between the soft electrodes and rigid circuit board can easily rupture when attaching the electrodes to the connector. Therefore, a flexible and thin connector was customized to maintain close contact with the skin (See Fig. 1).



(a) (b)

Fig. 1: E-Tattoo (a) Electrodes and (b) Reusable Connector

In order to simplify the design, the amplifier used is a commercially available one (SEN0240, OYMotion) with a fixed gain of 1000. In the future, a customized amplifier can be designed accordingly. The amplifier is then connected to the connector via a shielded aux audio cable (See Fig. 2). The output signal of the pre-amplifier is acquired by a MyRIO DAQ system (National Instruments Corp, US).

Previously, the common methods of connecting electrodes to the power source and DAQ device were using metal buttons and wires or a connector with alligator clips to get the raw electrophysiological signal data [11]–[13]. However, using rigid and heavy snap lead buttons and alligator clips could possibly damage and destroy the thin metal-based electrodes due to the sharp edges, leading to motion artifacts, which can be measured by SMR. With the aim to improve SMR, this work uses a silver paste [12], [19] and conductive tapes [12] to build the connector.

The raw sEMG signals measured from electrodes and a connector were collected by the MyRIO DAQ system at a sampling rate of 2000Hz. The signal was filtered with a bandpass filter with the same passband as the commercial DELSYS Trigno sensor. Additionally, a notch filter of 50Hz was applied to remove the power line noise.

In this study, a commercially available sEMG sensor DELSYS Trigno sensor is used to benchmark the performance of the developed integrated system. The DELSYS Trigno was attached to the skin with a double-sided adhesive interface. The signal data was collected by Bluetooth module and the DAQ system. DELSYS sEMG data was collected with a sampling rate of 2148Hz. The signal was filtered by a digital bandpass filter with a passband between 20Hz and 450Hz [22].

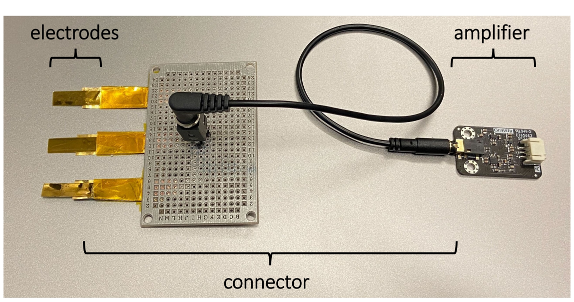


Fig. 2: Integrated E-Tattoo sEMG sensor system

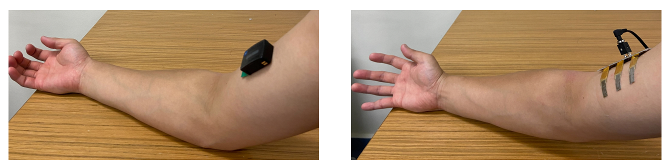
III. Experiment Method

The biceps brachii muscle was chosen as a target muscle since it is one of the largest superficial muscles in the upper body and has little hair that gives a low possibility of crosstalk from surrounding muscles [23]. Two types of muscle contraction were performed to evaluate the usability of the proposed integrated system: (1) biceps brachii repetitive maximum voluntary isometric contractions (MVICs) (2) maximum voluntary non-isometric contractions (MVnICs) [18].

A. Experimental Protocol

In this preliminary study, five healthy male subjects aged between 26 and 29 (with a mean of 27.4 and a standard deviation of 1.14) without any neurological or muscular pathology were recruited. The project was approved by the Human Research Ethics Committee of the University of Melbourne with ID #1954575.

1) Experiment Setup: The skin was cleansed with isopropyl alcohol to reduce the electrode-skin contact impedance before the sensor attachment. In order to do a fair comparison, DELSYS Trigno sEMG sensor and our integrated system were placed on the biceps brachii muscle in the same location (See Fig. 3). How to perform the MVICs and MVnICs movements were demonstrated by a researcher before the tests.



(a) (b)

Fig. 3: Placement of sEMG sensor on biceps brachii muscle (a) DELSYS Trigno (b) The proposed integrated system

2) Movement Description: For repetitive MVICs, the subjects were instructed to open the elbow to near 180° as an initial posture and perform maximum voluntary muscle contractions while maintaining the initial posture unchanged. For the MVnICs, the subjects were instructed to perform maximum voluntary muscle contractions while flexing the elbow to 90° for 4 seconds and return to the initial posture afterward.

3) Experiment Protocol: Three tests are repeated for each movement, adding up to six tests in total. The order of the tests is randomized. The identical 6 tests are repeated for either the DELSYS Trigno sensor or our integrated system sensor. The instruction for each test is summarized in Table. I with three phases. The first 4 and last 8 seconds are relaxations (Phase 1 & Phase 3), with 6 repetitions of alternation of contraction (where MVICs and MVnICs are performed) and relaxation in Phase 2. The details of the experimental protocol are summarized in the following table.

A user experience survey was conducted for each participant, asking the subject's assessments in terms of the user comfort, adhesion, and wearability of each sensor for both MVnICs and MVICs, on a scale from 1 to 5.

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TABLE I: Experimental Protocol

Muscle Movement (MVICs or MVnICs)	Repetitions	Duration
Phase 1: relax 4s	1	4s
Phase 2: contraction 4s – relax 4s	6	48s
Phase 3: relax 8s	1	8s

B. Measures of sEMG Signal Quality

The signal quality of measured sEMG signals from both the DELSYS Trigno sEMG sensor and our integrated system is measured through five widely used metrics. They are summarized as follows:

- Signal-to-noise ratio (SNR), which is one of the most important quality measures of sEMG signal [22]. It is calculated as the ratio of the total power of the sEMG signal with respect to the power of noise using the unit of decibel (dB), which is on a logarithmic scale, i.e.,

$$dB = 10log\left(\frac{\text{Signal Power}}{\text{Noise Power}}\right).$$

  A larger value of SNR indicates a high quality of the signal. In this study, we picked one algorithm, which is based on the probability density function by assuming the signal is cyclostationary, from the literature [20].
- Signal-to-motion artifact ratio (SMR), which assesses the fluctuations of the signal induced by the mechanical alteration of electrodes, i.e. motion artifacts [21]. A larger SMR indicates that the measured sEMG signals are less sensitive to active movements.
- Baseline noise (BN), which is the amplitude of the signal during muscle relaxation, reflecting mainly the stability of the skin-electrode interface. The unit of BN is dBp, a power level expressed in decibels dB with reference to one picowatt (10^{-12}W). It is calculated by a muscle activity on-off detector-based algorithm that calculates the energy of the baseline noise [20]. A smaller BN indicates less severe contamination from various noise sources.
- Drop in power density ratio (DPR) indicates whether the signal power spectrum is adequately peaked in the sEMG power spectrum's frequency range [21]. A larger value indicates a more adequate peaking.
- Power spectrum deformation (PSD) reflects the effect of disturbances of the spectrum of a signal that has a power spectrum larger than $20Hz$ [21]. A smaller value of PSD implies that the signal is less affected by disturbances.

IV. Results and Discussion

This section discusses the results observed during the experiments.

A. User Experience

The outcomes of the user experience survey are summarized in the following tables (Table II and Table III).

Table II shows that the subjects felt in the movements of MVICs, both the DELSYS Trigno sEMG sensor and the integrated system are comfortable and firmly attached to the skin. Also, the wearability of the integrated system is much better.

Table III shows that the majority of subjects felt that, during the repetitive MVnICs, the integrated system is much better in terms of comfort, adhesion, and wearability, compared with the DELSYS Trigno sensor.

TABLE II: User Experience Survey - MVICs

MVICs		S1	S2	S3	S4	S5	MEAN	STDEV
Comfort	D	4	3	5	4	5	4.2	0.56
	E	5	4	5	5	5	4.8	0.16
Adhesion	D	5	5	5	4	5	4.8	0.16
	E	5	5	5	5	5	5.0	0
Wearability	D	5	1	4	2	3	3.0	2
	E	5	5	5	5	5	5.0	0

TABLE III: User Experience Survey - MVnICs

MVnICs		S1	S2	S3	S4	S5	MEAN	STDEV
Comfort	D	3	4	3	4	4	3.6	0.24
	E	5	4	5	4	5	4.6	0.24
Adhesion	D	2	2	2	2	3	2.2	0.16
	E	5	5	4	3	5	4.4	0.64
Wearability	D	1	1	2	2	1	1.4	0.24
	E	5	5	4	3	4	4.2	0.56

B. Measures of sEMG Signal Quality

The performance comparison between the DELSYS Trigno sensor and the developed integrated system is shown in Figure 4, where E-M1 and E-M2 represent the performance using the integrated system with respect to MVICs and MVnICs accordingly. Here D-M1 and D-M2 represent the performance of the DELSYS Trigno sEMG sensor with respect to MVICs and MVnICs, respectively.

Among these five performance metrics, SNR is widely used to show the quality of signals. When detecting sEMG during active movements, SMR is a very important measure to show whether the motion artifacts will affect the quality of sEMG signals. Fig. 4 shows the performance comparison of five different measures between the developed integrated system and Delsys Trigno across all subjects for repetitive MVICs and MVnICs. It can be seen that the median SNR among the five subjects of the integrated system is $28.42dB$ for MVICs, which is a good signal quality. It is just $0.18dB$ lower than that of the DELSYS Trigno. The MVnICs show a slightly higher difference, where the median SNR of the integrated system is $30.27dB$ (good signal quality), $1.31dB$ lower than that of the DELSYS Trigno. These results indicated that the developed integrated system has a good signal quality, comparable to the DELSYS Trigno.

The non-customized and off-the-shelf amplifier could limit the SNR of the integrated E-Tattoo system as its gain is fixed at 1000 and clipping amplitude at $\pm1.5V$ from the amplifier. It is possible that the amplified sEMG signal during muscle activation is clipped during the movement. Note that this study is just to test the usability of a simple integrated system without any optimal design in terms of selecting components of this system. In our future work, we will design this amplifier accordingly.

In both MVICs and MVnICs, the SMR of the E-Tattoo signal is higher than that of the DELSYS Trigno by $5.23dB$ and $8.19dB$ respectively. These results are significantly better than the results from two designs in literature [16], [17]. These results indicated that the connector used in the integrated system, which uses a silver paste and a double-sided conductive tape, works much better compared with the metal-based connector used in the literature, as expected. The higher SMR of the integrated system is primarily owing to the significantly lighter weight of the E-Tattoo provided that the signal is not contaminated by motion artifacts noise. It is noted that SMR measures motion artifacts on the skin-electrode interface. The main source of motion artifacts is

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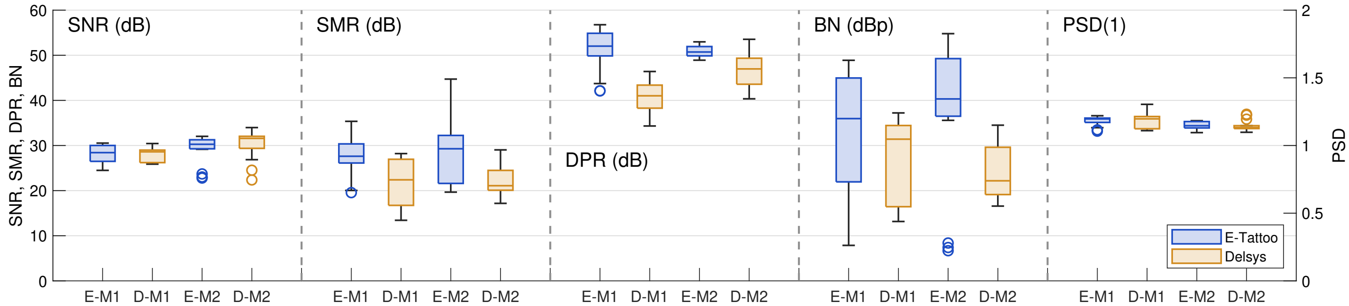

Fig. 4: Comparison of 5 metrics between the integrated system and Delsys sEMG sensor.

the relative movements between the electrodes and the skin caused by the contraction and relaxation of the muscle or the acceleration in dynamic tasks. With the thin and light electrodes and the connector of the integrated system, such motion artifacts are reduced. These results show that the integrated system can work well when monitoring active and dynamic movements.

The integrated system has a relatively large BN in both MVICs and MVnIC, compared with the DELSYS Trigno sensor. As the baseline noise is partially dependent on the subject's body fat and soft tissues [24], thus it is person-dependent. The preliminary results suggest that appropriate person-dependent filters might be needed to handle baseline noise for the integrated system.

For both DPR and PSD, the integrated system has much better performance than the DELSYS Trigno, indicating that the integrated system has more adequate peaking and is more immune to high-frequency noise.

The preliminary results suggest that the integrated system has similar performance in terms of these five measures, compared with the DELSYS Trigno with a much better user experience. This shows the potential of developing such an integrated system into a commercial sensor. Future work will include some iterative processes to fine-tune components of this integrated system to further improve the quality of the signal. A more comprehensive usability study on other different types of movements for different muscle groups with more subjects is also needed.

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