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A versatile wearable sEMG recording system for long-term epileptic seizure monitoring

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***Abstract*—Surface electromyography (sEMG) can be used to detect motor epileptic seizures non-invasively. For clinical use, a compact-size, user-friendly, safe and accurate sEMG measurement system can be worn by epileptic patients to detect and characterize a seizure. Such devices must be small, wireless, power-efficient minimally invasive and robust to avoid movement artefacts, friction, and slipping of the electrode, which can compromise data integrity and/or generate false positives or false negatives. This paper presents a highly versatile device that can be worn in different locations on the body to capture sEMG signals in a freely moving user without movement artefact. The system can be safely worn on the body for several hours to capture sEMG from wet Ag/AgCl electrodes, while sEMG data is wirelessly transmitted to a host computer within a range of 20 m. We demonstrate the versatility of our sensor by recording sEMG from five different body locations in a freely moving volunteer. Then, simulated seizure data was captured while the device was placed on the extensor carpi ulnaris. We show that sEMG bursts were successfully recorded to characterize the seizure afterward. The presented sensor prototype is small (5 cm x 3.5 cm x 1 cm), lightweight (46 g), and has an autonomy of 12 hrs from a small 110-mAh battery.**

I. INTRODUCTION

Epilepsy is a chronic neurological condition of various causes characterized by recurrent spontaneous seizures. Seizures occur as the result of abnormal excessive neuronal discharges that lead to various manifestations depending on the location, intensity and propagation of the epileptic discharge. Seizures are broadly divided in focal (when the ictal discharge begins in a focal/regional cortical area) or generalized (when the ictal discharge rapidly engages both hemispheres). Manifestations range from minor subjective symptoms (ex. Déjà vu auras) to disabling seizures with altered awareness and tonic-clonic seizures. Latter seizures are obviously associated with an increased risk of injuries or even death. Hence, aggressive medical (or even surgical) treatment is necessary to reduce morbidity, mortality and improve quality of life. Unfortunately, a third of patients continue to have seizures despite optimal treatment. Seizure detection devices can be helpful in the management of patients with epilepsy [1]. Rapid detection of seizures can allow for acute interventions to abort seizures or prevent complications. Epileptic seizure detection is traditionally done using electroencephalography (EEG) monitoring, which is not applicable for long-term home monitoring. Because the muscles are heavily activated during several types of seizures, like focal tonic-clonic seizures, for instance, one of the most disabling type of seizure, surface electromyography (sEMG) can be leveraged to build effective non-invasive seizure monitoring and detection systems. Different types of wearable sEMG sensors prototypes have been developed for seizure monitoring and are now at various stages of validation [2-4]. The design of versatile, robust, safe and minimally invasive systems that can be safely worn on the body during several hours to capture seizure data with high quality for characterizing seizures without artefacts is an opened challenge.

We present the design and the validation of a robust and clinically sound wearable sensor node to capture sEMG signals during epileptic seizures. Such a system is intended to be worn by epileptic patients during clinical trials for as long as 12 hrs to capture and characterize seizure data [5]. The wearable sEMG sensor design is versatile to monitor several types of seizures in different body locations. Additionally, the prototype is safe, robust and small, so it can be used is clinical trials with epileptic patients. In Section II, we give an overview of the system architecture. In Section III, we describe the design of each building block. In Section IV, we present the measured performance and the experimental sEMG recording results collected with the presented system during simulated seizure. Conclusions are drawn in the last section.

II. SYSTEM OVERVIEW

A representation of the presented wearable sEMG sensor node prototype is shown in Fig. 1. The system uses commercial off-the-shelf electronic components (COTS). The ADS1291 analog front-end from Texas Instruments, is used as the sensor interface circuit for sEMG measurement [6]. It contains all the electronic building blocks for signal amplification, filtering, and digitization. The MSP430F5529 low-power microcontroller, also from Texas Instruments, and the nRF24L01+ low-power transceiver from Nordic Semiconductor is used for control and wireless data transmission [7]. All COTS electronic components are mounted on a lightweight custom rigid-flexible printed circuit board (PCB), which can be easily placed in different parts of the body to monitor different types of seizures. A graphical user interface allows to access the serial port to retrieve, store and visualize the collected sEMG data in real-time (Fig. 1(d)). Table 1 summarizes the characteristics of the proposed device. The measured performance of the sensor node prototype is reported and compared in Section IV in terms of signal, placement, and types of seizure. The system uses three conventional Ag/AgCl electrodes with electrolytic gel, which are commonly used in clinical practice. They are inexpensive and offer excellent skin-electrode contact impedance. The

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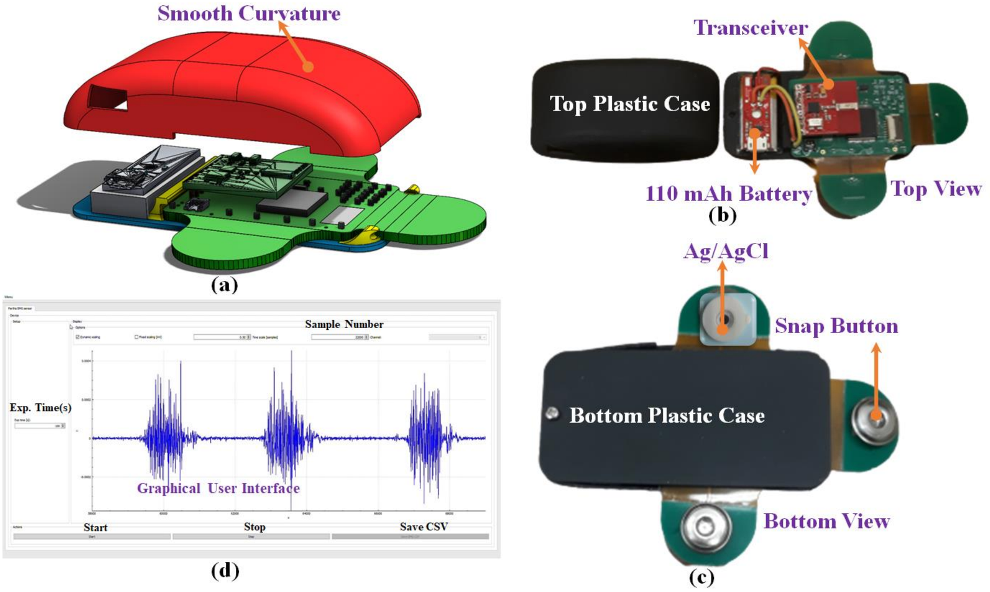

Fig. 1. The presented sEMG wearable sensor design. (a) 3D representation, (b) Top view, (c) Bottom view, and (d) the graphical user interface.

Figure 1. Table 1: Performance summary of the proposed sEMG device.

Characteristics	Value
Supply voltage	3.7V
Battery Autonomy	12 hrs @110mAh
Power consumption	30 mW
Sampling Frequency	2 ksps
Resolution	24 bits
Wireless transmission rate	2 Mbps
Transmission range	20 metres
Dimensions	5 x 3.5 x 1 cm
Signal bandwidth	20-500 Hz

prototype uses a 3.7-V lithium polymer battery to power up the whole system.

III. SYSTEM DESIGN

Fig. 2 shows the complete architecture of the sEMG system. The prototype uses components COTS. Ag/AgCl electrodes can be connected to the analog front-end through the printed circuit board using snap connectors. The analog front-end (AFE), the microcontroller unit (MCU), the power management unit (PMU), and the wireless transceiver unit are the main building blocks of this prototype. A base station is used at the other end of the wireless data link to retrieve the sEMG data. The ADS1291 from Texas Instruments, a low-noise and low-power AFE, is used to sample the muscle signal at a frequency of 2 ksps. This AFE provides one recording channel featuring an integrated 24-bit analog to digital converter. The sEMG signal is bandpass filtered from 20 Hz to 500 Hz. The measured raw samples are retrieved through its serial peripheral interface (SPI) using a low-power MCU, the MSP430F5529 from Texas Instruments, and passed to the wireless transceiver (nRF24l01+, Nordic Semiconductor, Norway), which transmits the data to the base station in the 2.4-GHz ISM band, as shown in Fig. 2. The base station consists of a second MSP430F5529 microcontroller and nRF24L01+ wireless transceiver. The retrieved sEMG data is transferred to the PC host through the universal serial bus

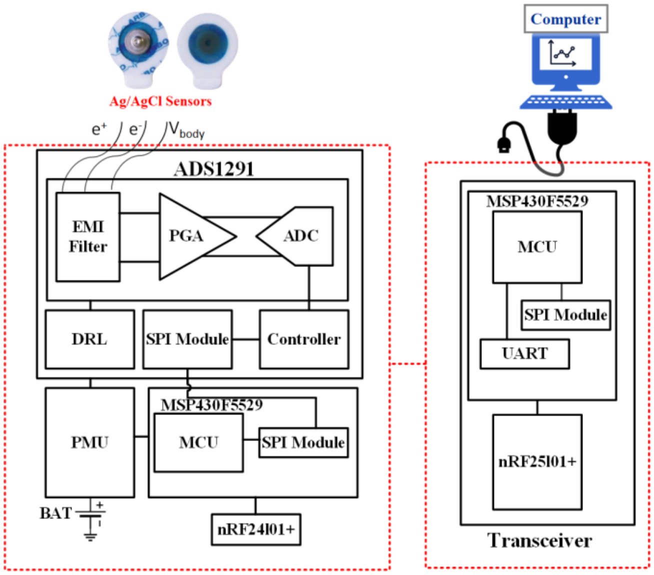

Fig. 2: Block diagram of the multi-sensor data acquisition system, and circuit schematics of the patch sensor nodes.

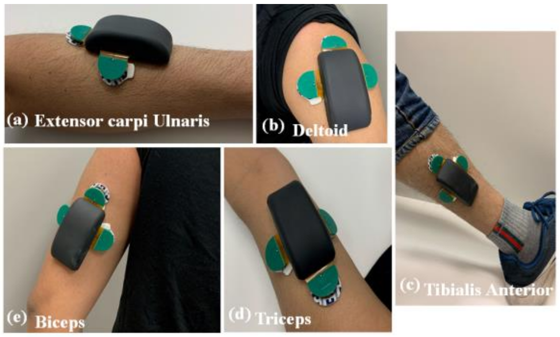

Fig. 3: The sEMG sensor placement.

Table 2: Comparison with other sEMG recording systems.

Devices	sEMG capability	Autonomy	Placement	Small Size and weight	Wearable under fabric	Place at any angle and removable
This work	Yes	12 hrs	Everywhere	Yes, 46g	Yes	Yes
Brain Sentinel SPEAC	Yes	24 hrs	Biceps	No, 326g	No	No
Smartwatch Inspyre	No (ACM only)	16 hrs	Wrist	Yes, NA	No	No
Empatica Embrace	No (ACM, EDA, Temperature, Gyroscope)	48 hrs	Wrist	Yes, 13g	Yes	No
Nightwatch	No (ACM, PPG)	12 hrs	Wrist	Yes, 35g	Yes	No
Epi-Care Mobile	No (ACM only)	23 hrs	Wrist	Yes, NA	Yes	No
EmFit	Movement	15.5 hrs	External	No, 120g	Yes	No

¥ Accelerometry=ACM; Electrodermal activity=EDA; Photoplethysmography=PPG; Surface electromyography=sEMG; Tonic-clonic seizure=TCS.

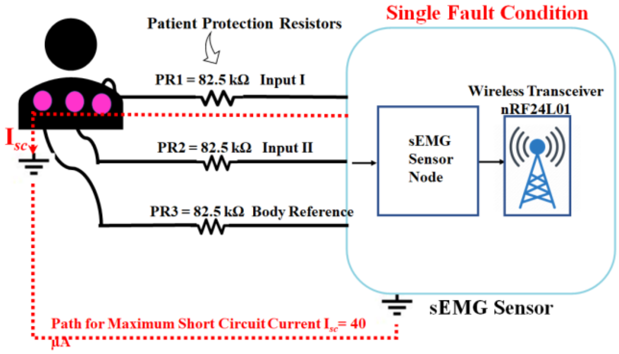

Fig. 4: Block diagram of the sEMG sensor attached to the body showing the electrical protection resistors protecting the patient in a single fault condition.

(USB). A polymer lithium-polymer battery (3.7V, 110 mAh) 0939-PRT is used to power up the electronic board. The size and weight of the battery is 31 x 14 x 4 mm and 10 g. The battery voltage is stepped down to 3V to power up the MCU, the AFE, and the transceiver using a low-dropout regulator NCP603 from ON semiconductor. The measured current consumption of the whole prototype during continuous operation is 10 mA. The sensor node prototype has an autonomy of 12 hours, and the time required to charge the battery is around 15 min. A dedicated graphical user interface (GUI) implemented using Qt is used to display the sEMG signal in real-time and to manage the data.

A. Device Placement

The sensor uses conventional Ag/AgCl electrodes having an active circular area and a diameter of 20 mm. The electrodes are connected with the PCB through snap button connections mounted on the PCB (Fig. 1c). To measure the sEMG signal, the Ag/AgCl electrodes are placed in a bipolar configuration, 50 mm apart from each other on different parts of the body, as illustrated in Fig. 3. Thanks to the utilization of flexible PCB material and sticky Ag/AgCl electrodes, the sensor can be placed in several different locations to monitor sEMG from different muscles on the body, such as from the extensor carpi ulnari, the deltoid, biceps, triceps, and the tibialis anterior, as shown in Fig. 3.

B. Electrical Safety

Special care is put in this design to ensure electrical safety during long-term clinical trials. In a single fault scenario, a short circuit current can flow between the supply line of the battery-powered sensor and the common reference voltage point of the sensor, through the body, from one of the input or from both inputs to the body reference, as depicted in Fig. 4. The IEC 60601-1 standard recommends limiting any current flowing between the applied parts through the body to 50 µA [8]. Therefore, this design includes protection resistors PR1, PR2 and PR3 (Fig. 4) to limit the current flowing between any applied parts in this scenario bellow the recommended value. The protection resistors use a value of 82.5 kΩ, which allows a maximum current of 40 µA to flow through the body from the 3.3-V supply voltage. Additionally, to decrease the probability of single fault conditions, the whole sensor was encapsulated inside a light-weight 3D-printed plastic box, which protects and provides electrical insulation with the electronic board of the sensor. While increasing user comfort, the round edges of the plastic enclosure also contribute decreasing any single fault condition probability.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

The measured performance of the presented system is reported in Table 1. For the validation during simulated seizures, sEMG signals were recorded with the prototype from a healthy subject (34 years-old man) using conventional Ag/AgCl electrodes, at the Centre Hospitalier Universitaire de Montréal (CHUM). To generate the sEMG signal from simulated seizures, we use the procedure describe in [3]. The device was placed over the extensor carpi ulnaris as shown in Fig. 3. The signals collected during five different simulated seizures which are shown in Fig. 5. The volunteer performed muscle contractions and relaxations under different body movement conditions [9]. The sEMG signals amplitudes were varied within the range ±.0005V through different muscles contraction intensities. Fig. 6 shows a comparison of the power spectrum of the measured forearm sEMG for the

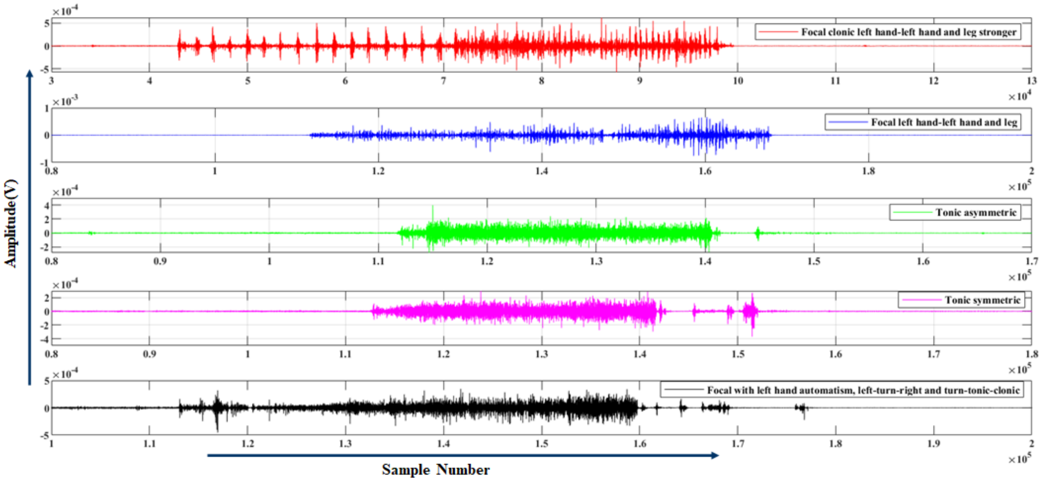

Fig. 5. sEMG recording under different seizure condition.

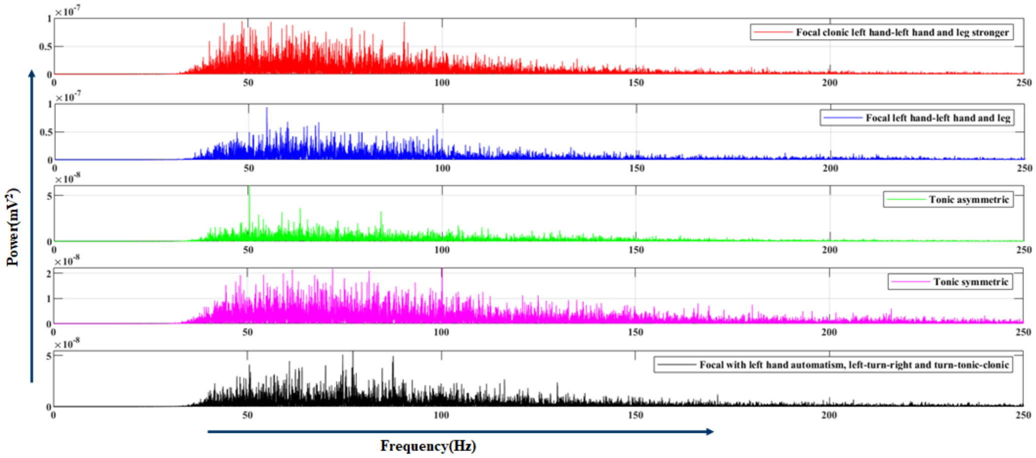

Fig. 6. Power Spectrum of obtained sEMG signals.

different types of simulated seizures. The different power spectrums show variation according to the type of seizure. For instance, the power spectrum of the *Tonic symmetric* seizure is much stronger than for the *Tonic asymmetric* seizure. Additionally, the tonic symmetric seizure has better signal to noise ratio (SNR=25.12 dB), root mean square value (RMS=26 μV), mean absolute value (MAV=0.21 μV), and variance (Var=0.66 μV^2) compared to tonic asymmetric: SNR=20.97 dB, RMS=25 μV, MAV=0.20 μV, Var=0.67μV^2. Table 2 compares the prototype sensor shown with the most relevant portable sEMG sensor solutions. In addition to be wearable during long time periods, our solution is the only one capable of capturing seizure data without movement from any location on the body.

V. CONCLUSION

In this paper, we presented a highly flexible and wearable sEMG sensor node for seizure monitoring. Our solution improves user comfort, robustness, versatility, safety and provides an extended autonomy compared to previous solutions through a dedicated PCB and the utilization of low-power COTS building blocks. The results collected with the sensor during simulated seizures show that it can properly capture sEMG data in freely moving users, during seizures, for monitoring purpose. In our future work, we will combine these advances in robust wearable sensor design with the latest approaches in artificial intelligence to analyze the sEMG data in real time and perform early detection of epileptic seizures to reduce seizure-related mortality and co-morbidities.

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