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APPLIED RESEARCH

Low-Cost, Wireless Bioelectric Signal Acquisition and Classification Platform

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ABSTRACT Bioelectric signal classification is a flourishing area of biomedical research, however conducting this research in a clinical setting can be difficult to achieve. The lack of inexpensive acquisition hardware can limit researchers from collecting and working with real-time data. Furthermore, hardware requiring direct connection to a computer can impose restrictions on typically mobile clinical settings for data collection. Here, we present an open-source ADS1299-based bioelectric signal acquisition system with wireless capability suitable for mobile data collection in clinical settings. This system is based on the ADS_BP and BioPatRec, both open-source bioelectric signal acquisition hardware and MATLAB-based pattern recognition software, respectively. We provide 3D-printable housing enabling the hardware to be worn by users during experiments and demonstrate the suitability of this platform for real-time signal acquisition and classification. In conjunction, these developments provide a unified hardware-software platform for a cost of around $150 USD. This device can enable researchers and clinicians to record bioelectric signals from non-disabled or motor-impaired individuals in laboratory or clinical settings, and to perform offline or real-time intent classification for the control of robotic and virtual devices.

INDEX TERMS Bioelectric signal, data acquisition, EMG, open source, pattern recognition.

I. INTRODUCTION

Skin-surface electromyography (sEMG) systems have been drawing attention within the biomedical field in the past decade. The reason behind this focus is the desire to enhance prosthetic functionality as well as contribute towards research in rehabilitation technologies [1]. These systems are typically divided into two sections: data acquisition and data processing. On one hand, data acquisition measures the sEMG representative of active muscle contractions. And on the other hand, data processing primarily aims to denoise the acquired sEMG signals and to perform analyses such as pattern recognition, which in turn can be used to control rehabilitation devices such as prostheses [2].

The acquisition process is performed using a device that collects the electrical activity from the muscles with the help of skin-surface electrodes. The signals acquired from the electrodes are in the order of millivolts with a frequency

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that ranges between 0.01 to 500 hertz [3], [4]. Given the millivolts range of amplitude, the sEMG signals are highly sensitive to different sources of noise like motion artifacts or electromagnetic radiation [5]. Therefore, sEMG systems need to carefully eliminate unwanted noise while maintaining the essential information the signal carries.

In addition to sEMG, there exist other bioelectric signals which are of interest in medical research and rehabilitation contexts. For example, electrocardiography (ECG) is also measured at the millivolt range, and electroencephalography (EEG) is measured in the microvolt range, with frequencies ranging from 1 to 30 hertz. Generally speaking, all bioelectric signals measure the same physiological phenomenon – skeletal and cardiac muscle contraction for EMG and ECG, and neural action potentials for EEG – and despite their varied applications, all bioelectric signals are subject to the same challenges in their acquisition and are susceptible to electromagnetic interference (e.g., power grid noise). In addition, bioelectric signals can be cumbersome to acquire via a direct physical connection (especially if measured concurrently with physical activity), and commercially-available devices can be prohibitively expensive. Several low-cost solutions for bioelectric signal acquisition have been proposed [3], [4], [6], [7], [8], [9], [10], [11], [12], [13], however these solutions often do not consider clinical applicability.

Data processing is also a critical step for working with bioelectric signals and can vary widely depending on the application. For work related to the control of rehabilitation devices, data processing typically comprises treatment of the raw signals, extraction of time- or frequency-domain features, and application of pattern recognition algorithms to decode the executed movement correlated with the sampled signals. Some of the aforementioned devices can perform raw signal treatment via hardware and firmware filtering [3], [4], [6], [12], [13], but custom software must typically be written to complete subsequent signal classification.

Previous open-source bioelectric signal acquisition signals present several limitations for researchers and clinicians. For example, they do not feature wireless capabilities meaning they cannot be used for mobile tasks, and do not come paired with compatible software meaning that they cannot be used without additional software development. The system described in this paper is a complete bioelectrical acquisition platform comprising hardware, namely the ADS_BP, and its respective software, namely BioPatRec. The ADS_BP acquires sEMG signals (or other bioelectric signals including electrocardiography (ECG) and electroencephalography (EEG)) and streams them wirelessly via Wi-Fi to a connected computer running BioPatRec [14], [15]. BioPatRec, originally intended for researching intuitive control of prosthetic devices, is an open-source MATLAB-based platform which provides a variety of algorithms for bioelectric pattern recognition and robot control. BioPatRec provides tools for signal recording, labelling and storing, signal treatment and pre-processing, feature extraction and classification, and evaluation as well as a virtual reality environments for controlling virtual limbs. These tools can be customized and operated via a Graphical User Interface (GUI).

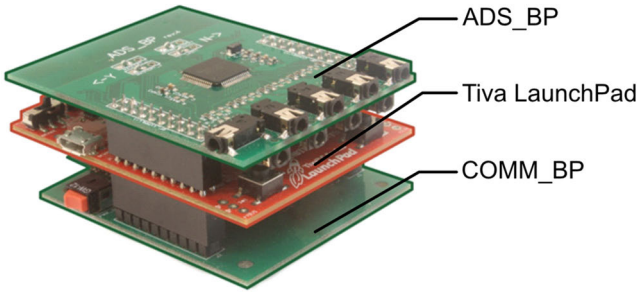

FIGURE 1. The ADS_BP device comprises the ADS_BP board, Tiva LaunchPad, and COMM_BP board.

The rest of the manuscript is organized as follows. Section II describes the hardware and software comprising the ADS_BP and BioPatRec, their design philosophy, and the cost breakdown. Section III presents validation and performance of the ADS_BP and its comparison to other open-source bioelectric signal acquisition devices. Finally, Section IV presents our recommendations for the optimal use of the ADS_BP in research and clinical settings.

II. METHODS

The overall design philosophy of the ADS_BP was to create a bioelectric signal acquisition device that:

- Is affordable, modular, and customizable;
- Comprises open-source PCBs, 3D-printed housing, firmware, and modular software designed for bioelectric signal treatment and analysis benchmarking;
- Can acquire multi-channel, low-noise bioelectric signals suitable for applications with EMG, ECG, and EEG;
- Isolates the subject from the electrical mains via wireless communication; and
- Is suitable for low-power, wearable applications such as measuring bioelectric signals during mobile physical activity such as walking.

The following sections will go into greater detail on the design philosophy and decisions for the individual components comprising the ADS_BP.

A. HARDWARE DESCRIPTION

The first version of the ADS_BP was released in 2017 by Mastinu et al. addressing the need for an open-source and low-cost bioelectric signal acquisition device [15]. Since then, the device has evolved with improvements in communication, firmware, and enclosure. The latest version of the device includes a Wi-Fi module to facilitate wireless transmission of the digitalized data to the test computer. The modular design philosophy also extends to the power source, which now uses a portable USB power bank that can be easily recharged and replaced as needed (see Fig 3a). Changes were also made to the software for full compatibility with the ADS_BP. The assembled ADS_BP is shown in Fig. 1, and descriptions of the individual components are provided in the following sections.

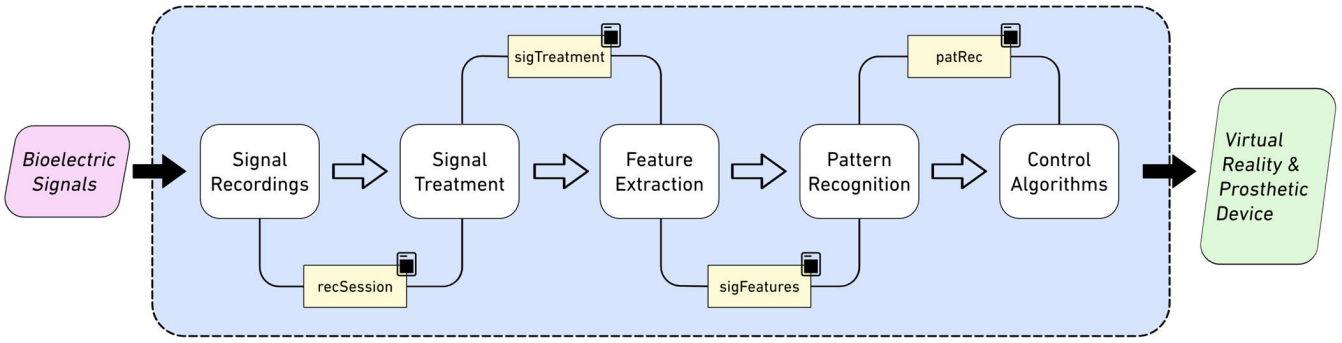

FIGURE 2. BioPatRec comprises modular structure arrays which are passed between processes. This allows other researchers to inject or replace their own algorithm without interfering with prior or subsequent processes. Figure adapted from [13].

1) ADS_BP BOARD

A detailed summary of the ADS_BP and MCU boards is provided in [15]. Briefly, the main ADS_BP board comprises an ADS1299 analog front-end (Texas Instruments, USA) installed on a PCB designed using DipTrace (Novarm, Ukraine). The ADS1299 was selected as the analog front-end due to its low cost and previous performance benchmarking with other integrated circuits [16]. The ADS1299 provides 8 fully differential channels with independent programmable gain, simultaneously oversampled by a 24-bit $\Delta\Sigma$ converter. Its excellent low-noise performance, combined with built-in programmable features (Right-Leg Driven amplifier, flexible input multiplexer, basic electrostatic discharge (ESD) protection, electrodes connection monitor), makes it particularly suitable for EMG, EEG, and ECG applications.

In our ADS_BP design, an optional antialiasing filter or RC high-pass filter can be added for input channels to provide initial signal conditioning, or the PCB components can be replaced with 0 Ω resistors if initial signal conditioning is not required. An opto-isolated USB port is included for a wired but safe computer interface. Jumpers are provided to expand the number of acquisition channels via daisy-chaining additional boards over the Serial Peripheral Interface (SPI). In the present configuration proposed herein, an updated ADS_BP board is mounted above the MCU board, which itself is mounted above a new COMM_BP board.

The ADS_BP board has an optional isolated USB port to communicate with a computer instead of the COMM_BP board. In the current paper, the components are left unpopulated. The ADS_BP boards are also designed to allow daisy-chaining of multiple units based on the selector jumpers. The current scope involves only one unit.

The ADS_BP board offers three ways for referencing the analog front-end to the body of the user for optimal bioelectrical signal recordings. The reference electrode can be shorted to the ADS_BP system ground node, or to an op-amp buffered and shielded version of the ground node, and additionally, to a dedicated bias driver circuit. The ADS1299 offers the possibility to improve noise-rejection by using a built-in amplifier and an external RC net to drive the user's bias voltage similarly to a classic Driven-Right-Leg circuit [17]. These options are made available on the ADS_BP via two jumper resistors, R_REF_GND and R_REF_SHD, for selecting the physical reference electrode connection, and a BIASINV pin (the inverting input pin of the driven amplifier) for a bias driving optional electrode. Note that the bias driving circuitry must be enabled via firmware by setting the dedicated configuration registers.

Considering the intended applications in clinic and home environments, particular care was taken in the choice of the analog front-end. The ADS1299 was designed for low-noise applications specifically intended for bioelectric signals. It includes basic ESD protection circuitry up to $\pm$ 1000V. Its impressive common-mode rejection ratio (CMRR) of -110dB was confirmed with previous benchmarks [16] and years of use in the lab and clinics [18], [19]. Components R1-R16 and C1-C16 are used to condition incoming bio-signals for receiving with the ADS1299 chip.

2) MCU BOARD

The Tiva LaunchPad (Texas Instruments, Dallas, USA) was selected as the MCU platform for the ADS_BP. It is based on the ARM Cortex-M4 core which runs up to 80 MHz, includes dedicated hardware for floating point math, and features 256 kB of internal flash memory and 32 kB of SRAM. The Tiva LaunchPad board comes in a low-cost and stackable format, for which a series of compatible Booter Packs were available to assemble a complete system (e.g. for adding a battery, SD card or various sensors). Such format provided the basis for the design of the ADS_BP, and easy access to power lines, general-purpose inputs/outputs (GPIOs), and peripherals.

3) COMM_BP BOARD

The COMM_BP Board consists entirely of a Zentri AMW136 Wi-Fi module (Silicon Labs, Austin, USA), breakout pins for communication and power, and appropriate grounding to minimize electrical interference. The module was chosen for its balance of data throughput, cost, power consumption, and ease of implementation.

The AMW136 module features a maximum baud of 5.25 Mbps and contains an 802.11b/g/n transceiver, a built-in antenna, Universal Asynchronous Receiver/Transmitter (UART) modules, and a Cortex M4 processer for control.

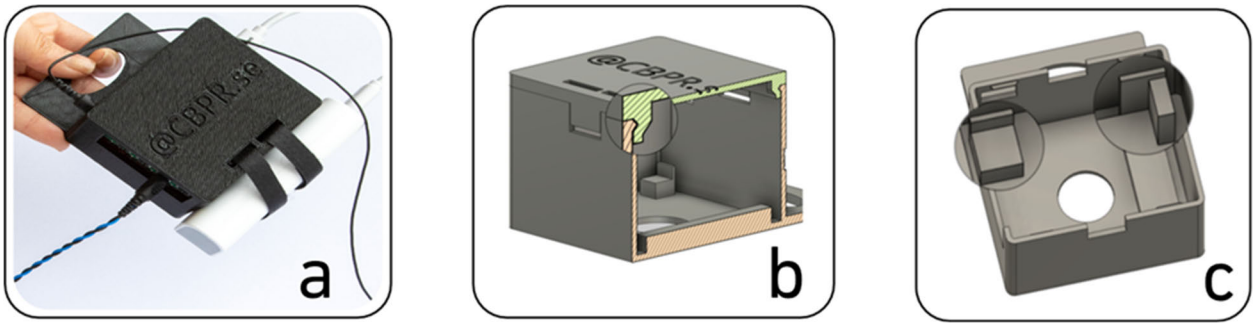

FIGURE 3. 3D-printed housing was designed to store and protect the ADS_BP during research and clinical use. (a) The housing features openings for the signal electrodes (left), reference electrode (back), and power (right). A USB power bank can be suspended from the front face of the housing, and the entire assembly can be worn or suspended using a lanyard. (b) A snap fit design holds the lid securely to the case without the need for additional components. (c) Supports were added to provide a secure platform on which the ADS_BP rests in the housing. The hole in the bottom surface aids the removal of the PCB from the case.

It is worth noting that, although the COMM_BP board uses a Wi-Fi module, it communicates solely with the local computer, and is not connected to the internet.

0Ω resistors are used to connect or disconnect either the SPI or UART interfaces depending on communication mode used for interacting with the ADS_BP board and TIVA board. In the current paper, we connect the UART traces to connect the TIVA to the computer system and leave the SPI traces disconnected to allow the TIVA to control the ADS_BP board directly. A developer could program the microcontroller on the AMW136 module to communicate directly with the ADS_BP, in which case the TIVA would be unnecessary. However, this is beyond the current scope.

The RESET_N pin on the AMW136 is not externally driven, so the C5 capacitor is used to bypass noise to prevent unintended resets.

The COMM_BP board operates best when there are no traces or conductors near the antenna. The antenna sticks out from the main PCB and should not be impeded by the circuit boards in the proposed system, but looping wires and other conductors should be kept away from that end of the unit during operation.

4) ADS_BP FIRMWARE

After powering up, the Tiva MCU goes through the initialization stage to prepare the ADS_BP system for signal acquisition and to receive commands from the computer interface. This initialization stage includes, in brief, GPIOs and peripherals initialization to enable communication with the ADS1299 and the AMW136, via SPI and via UART respectively. After the communication interfaces are established, the ADS1299 is configured to the default mode (8 channels; 1kHz sampling frequency; externally applied refence on GND; amplification factor of 1 Two digital IIR filters, a first order 50 Hz notch filter and a second order 20 Hz high-pass filter, are implemented to reduce signal noise from power grid and motion artifact, respectively. Direct Memory Access (DMA) is enabled and used for receiving/transmitting messages via UART to reduce the burden on the microcontroller main tasks and ultimately the communication latency. After initialization, the device is ready to decode and execute commands from the computer interface. The device operation loop constitutes waiting for messages, processing any received command, executing and acknowledging such commands, and acquiring and transmitting ADS1299 samples (if sample streaming is enabled). A GPIO Interrupt Service Routine is configured for handling processes related to acquiring ADS1299 samples, filtering the acquired signals, and preparing the data for transmission to BioPatRec or any other computer interface on a connected device.

5) BIOPATREC SOFTWARE

The ADS_BP has been designed to work in concert with the open-source bioelectric signal pattern recognition software, BioPatRec [14]. Briefly, BioPatRec is a modular platform implemented in MATLAB (Mathworks, USA) designed to perform signal acquisition, preprocessing including frequency and spatial filtering and signal segmentation, extraction of time- and frequency-domain features, pattern recognition via linear and nonlinear classification, and real-time control and evaluation. It is intended as a unifying platform with which researchers in different fields may benchmark their algorithms, which may only entail one of the aforementioned steps, and determine their impact on prosthetic control. BioPatRec comprises modular structure arrays which can be updated or replaced without affecting prior or subsequent processes, as shown in Fig. 2 above. This allows researchers and developers to implement their own algorithms within the modular structure arrays while ensuring compatibility with prior and subsequent modules. The open-source nature of the software, too, allows for these developments to be easily shared with other researchers around the world.

The BioPatRec user interface is simple and straightforward, and a recording session with the ADS_BP can be easily started using default settings in minutes. Additionally, nearly all settings are customizable, allowing users an extensive level of control over signal processing, classification, and evaluating using the built-in settings. Since its initial release in 2013, BioPatRec has seen five released

TABLE 1. ADS_BP cost breakdown.

Component	Total Cost [USD]	Source
ADS_BP PCB	$11.00	Eurocircuits*
COMM_BP PCB	$11.00	Eurocircuits*
ADS_BP Components	$85.44	Digi-Key
COMM_BP Components	$25.37	Digi-Key
Tiva Launchpad	$16.99	Texas Instruments
Total cost	**$149.80**	

*PCB costs provided are an upper estimate as unit costs are dependent on quantity and source

versions. Communication with data acquisition hardware in these earlier versions was accomplished via a Session-Based Interface (SBI) paradigm, with additional support for Serial Computer Interface (SCI) routines for communication with microcontrollers. The most recent modifications presented herein include support for direct wireless communication with the ADS_BP via Transmission Control Protocol/Internet Protocol (TCP/IP) routines. It should be noted that, while communication with the ADS_BP uses TCP/IP, BioPatRec does not utilize internet functionality. All processing is performed on the local computer, and all data are saved locally.

Specifically, there are four possible commands from BioPatRec for controlling the ADS_BP device, each identified by a unique opcode.

- TEST CONNECTION (opcode 1), used to check if the connection with BioPatRec is established and requires the device to respond with an acknowledgement message (ACK).
- START STREAMING (opcode 2), used to start sample acquisition. For this purpose, the microcontroller enables the Read Continuous Mode in the ADS1299, enables the NDRDY GPIO interrupt, and prepares the transmission packages. It is noted that, during streaming mode, the status LED will be on, indicating that the device is acquiring EMG samples.
- STOP STREAMING (opcode 3), used to stop sample acquisition. Consequently, the microcontroller disables the Read Continuous Mode, disables the NDRDY GPIO interrupt, resets the buffers, and turns off the status LED.
- SET ADS_BP (opcode 4), used to configure the ADS1299 analog front-end by setting up the sampling frequency, setting up the amplification factor and, optionally for testing purposes, enabling/disabling the internal oscillator.

The ADS_BP is always expected to acknowledge any received command.

6) HOUSING

ADS_BP housing was designed using Fusion 360 (Autodesk, San Francisco, USA) with a minimum wall thickness of 2mm and inside dimensions of 68 × 60×43 mm. The housing is designed to firmly hold the ADS_BP assembly and to offer good accessibility, as shown in Fig. 3(a). To facilitate use and portability while recording bioelectric signals, a point

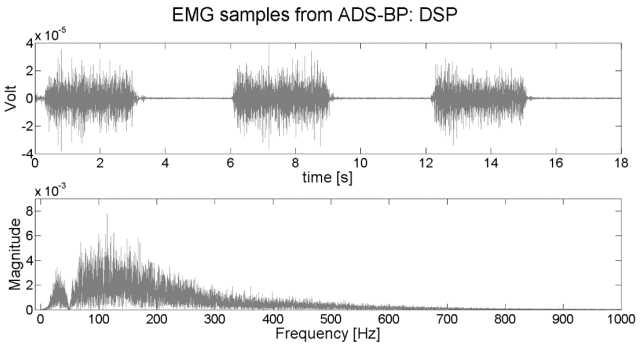

FIGURE 4. sEMG recordings in time and frequency domains while measuring contraction and relaxation of the extensor digitorum [14].

of lanyard and the use of a standard USB power bank were added. To hold the power bank to the case, there are two additional cutouts in the case and cover allowing a Velcro or other strap to pass through.

Fig. 3(b) shows a cross-section emphasizing the snap fit design holding the cover and the case together. The snap fit was used to ensure a structure that guarantees durability while using the device.

Emphasizing the need for secure housing for the PCB, supports were added in each corner of the inner base of the case. In this way, the PCB is centered and secure in the horizontal plane. A hole was created on the bottom surface to push the circuit board out of the case, as shown in Fig. 3(Fig. 3c).

The housing shown in this manuscript was prototyped using a Flash Forge Dreamer 3D printer (Zhejiang Flashforge 3D Technology Co, Jinhua, China) using 18 meters of polylactic acid (PLA) filament with a 0.00124 g/mm^3 density and 1.75 mm diameter, for a total weight of 53g. Printer settings focused on balancing material savings with stable print quality; hexagonal infills were used after the fifth solid print layer. Other manufacturing techniques may be more appropriate when producing larger quantities of cases, but this is beyond the scope of the present manuscript.

B. BILL OF MATERIALS SUMMARY

An inventory of the finalized components is provided below. Power bank and USB cable costs are not included in the cost estimate. Detailed component and cost breakdowns are provided in the Bills of Materials available as supplemental materials. The PCB printing costs provided are an upper estimate, as unit costs will be dependent on quantity and source – PCBWay quoted $1 USD per board and Eurocircuits quoted $11 USD per board when ordering 10.

In addition to the per-board components listed below, the AMW136 Wi-Fi module on the COMM_BP board requires an AMW136-E03 development board ($59.00, Digi-Key) for configuration. It should also be noted that End of Life for the AMW136 Wi-Fi module went into effect on 21 December, 2021; parts stocks are still available for purchase at the time of writing, and replacement parts are available from the manufacturer (WGM160PX22KGA3, Silicon Labs, Austin, USA

TABLE 2. Comparison of open-source bioelectric signal acquisition systems.

Device	Wireless	Biosignals	ADC Used	ADC Resolution	Sampling Rate	Gain (V/V)	SNR (dB)	Cost (USD*)
ADS_BP	Yes	sEMG, ECG, EEG	ADS1299	24 bits	≤ 2 kHz	1-24	27	$150
Fortune et al, 2019	No	sEMG	AD7768	24	1 kHz	237-3400	-	$136
Kimchi et al, 2020	No	sEMG, EEG	NI PCIe-6323	16	1 kHz	1000	24	$600
McKenzie et al, 2021	No	sEMG	AD7768	24	1 kHz	418	-	$166

*Costs are reported as inflation-adjusted USD (2024).

C. RISKS

Connecting any sort of electronics to the human body involves inherent risks, primarily dependent on the level of electrical isolation between the electronics and the subject. Risks are mitigated as much as possible in the current work using a low-voltage battery pack and wireless communication, resulting in no physical connection between the subject and the power grid.

III. RESULTS

In previous work by Mastinu et al., the performance of the ADS_BP was analyzed and compared between different AFEs. sEMG signals were sent to BioPatRec via wired communication with a USB connection [15], [16]. Data were recorded from eight different people with full mobility of their arms, who were asked to perform 10 hand and wrist movements. Sample sEMG recorded from the ADS_BP are displayed in both time and frequency domains in Fig. 4. The measured SNR of the ADS_BP ranged between 19 and 27 dB [15]. Due to the relative magnitudes of ECG and EEG signals, we expect SNR of these signals to be lower; however, the ADS1299 has previously successfully been used in EEG applications, demonstrating its viability within this context [20]. Signal quality can nonetheless be maximized by using recommended skin preparation and placement of surface electrodes [21].

Table 2 provides a comparison between the ADS_BP and other open-source bioelectric signal acquisition systems. Despite the lower signal gain of the ADS_BP, SNR is similar to other devices. Furthermore, the cost of the ADS_BP is comparable to or less than other devices, and has similar signal resolution and sampling rates. Finally, the ADS_BP is the only open-source device which is completely wireless, allowing for data collection during mobile activities such as walking.

Additional validation focused on the performance of the system while using Wi-Fi to send the acquired signals from the ADS_BP to BioPatRec. For this validation, the number of communication errors were counted during a 60-second recording session. Preliminary testing of the ADS_BP revealed factors which could significantly affect the number of communication errors, including the type of power supply used and the network settings of the test computer [22].

Computers usually scan through different wireless networks aiming for the best possible access to the internet. This feature, called wireless auto-scanning, is typically enabled by default. Since the ADS_BP does not have internet access, a computer will continue scanning for other networks even while connected to the ADS_BP. Because of this scanning process, communication between the ADS_BP and the computer experiences a greater frequency of errors.

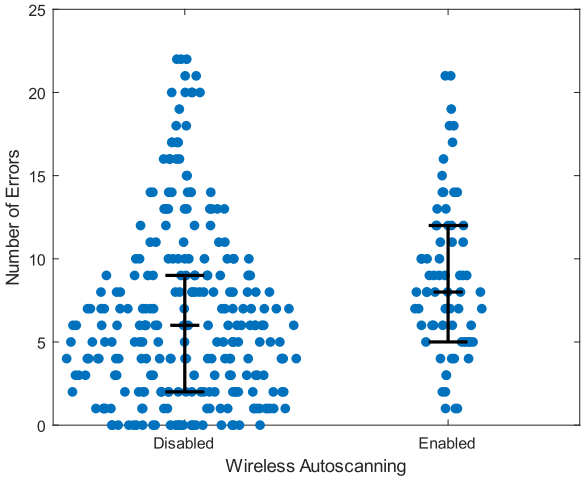

FIGURE 5. Comparison of communication errors demonstrated that enabling wireless auto-scanning on the test computer resulted in significantly more communication errors than when the setting was disabled. Error bars show median and quantiles.

To characterize the effect of wireless autoscanning on communication errors, the ADS_BP was set up in a laboratory environment with several available wireless networks. Data were sampled from two channels (without attached electrodes) at a sampling frequency of 1 kHz. The host computer was placed 6 meters away from the ADS_BP. A total of 372 measurements were taken, each lasting 10 seconds. The number of communication errors during trials with wireless autoscanning enabled or disabled are shown in Fig. 5.

The Wilcoxon rank-sum test was used to statistically compare the medians of error distributions between the two auto-scanning settings. Our results confirmed that disabling wireless auto-scanning yielded fewer communication errors (median [quartiles]: 6 [2, 9]) than when wireless auto-scanning was enabled (8 [5, 12]; $p < 0.001$). Although wireless auto-scanning did tend to result in more communication errors, completely disabling the feature may bring its own challenges. The computer may need to forget all previous wireless networks, meaning it loses the option to easily switch between networks.

Another variable influencing the communication error onset is orientation between the ADS_BP and the test computer. Since the COMM_BP board has an antenna built into

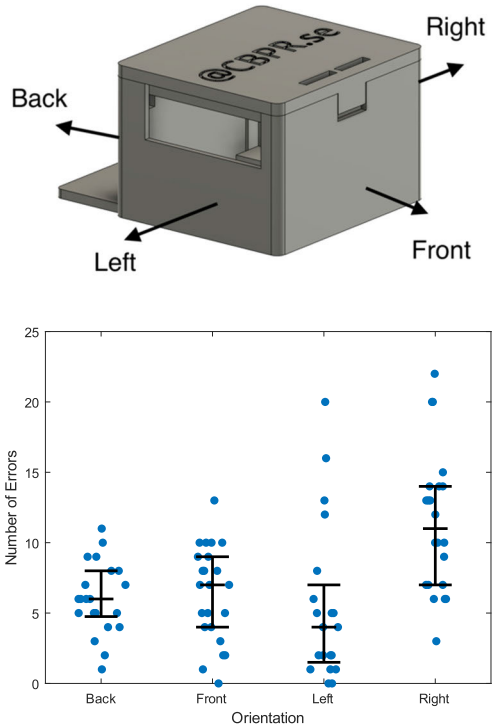

FIGURE 6. The ADS_BP was placed in various orientations relative to the test computer (top) Analysis of the number of communication errors (bottom) shows significantly more errors when the test computer was located towards the Right side of the ADS_BP. Error bars show median and quantiles.

the PCB, certain orientations have a higher probability of communication errors. This was again characterized by setting up the ADS_BP in a laboratory environment with the setup details described previously. The ADS_BP orientations tested in this validation are shown in Fig. 6. Following those orientations, the right side corresponds to the power supply port (as also shown in Fig. 3(a)). Test results shown in Fig. 6 demonstrate that by placing the ADS_BP with the right side facing the computer tends to generate more communication errors than other orientations.

The Wilcoxon rank-sum test was similarly used to statistically compare the medians of error distributions between the four orientations; Holm-Bonferroni corrections were used to adjust for family-wise error rate. The results showed significantly more communication errors occurred when the test computer was located towards the Right side of the ADS_BP (median [quartiles]: 11 [7, 14]), compared to all other orientations ($p < 0.005$). Additionally, we found no significant differences ($p > 0.312$) in communication errors between the Back (6 [8, 4.75]), Front (7 [4, 9]), and Left orientations (4 [7, 1.5]). Furthermore, the minimum number of measured errors was also higher with the power supply port (Right) facing the computer, which also suggests a higher likelihood of experiencing more errors in this orientation.

It is therefore not recommended to orient the ADS_BP with the power supply connector facing the test computer, when possible.

IV. DISCUSSIONS

The field of biomedical engineering can be prohibitively expensive and difficult for early-career researchers and researchers in economically disadvantaged regions to enter. This has the potential to weaken the overall quality of the output within the field by promoting homogeneity in research centers and topics, and an omission of research focused on the needs of disadvantaged areas from the overall body of literature. A healthy body of research is one in which a diverse range of researchers can participate, which in turn necessitates adequate access to critical equipment.

The ADS_BP and BioPatRec are designed to provide researchers of all backgrounds with an inexpensive platform for research related to bioelectrical signal acquisition and classification. Examples include the control of prosthetic devices using EMG signals and brain-computer interfacing using EEG signals. Additionally, these serve as a benchmarking platform through which signal processing and classification algorithms can be tested using comparable hardware, ensuring a level playing field for comparisons. However, we note that while the performance of the ADS_BP is adequate with respect to measuring sEMG signals, performance is expected to worsen when measuring ECG, and especially EEG, due to their smaller signal amplitudes, although previous work has demonstrated the viability of the ADS1299 within these contexts [20]. This is nonetheless a limitation of the system, one which requires proper placement of the electrodes and preparation of the electrode sites to alleviate.

Enabling wireless communication on the ADS_BP represents an important advancement in terms of safety and clinical utility. First and foremost, wireless communication ensures electrical isolation from the power grid, which was not the case when the device was connected to the PC via a wired connection. This provides an additional layer of safety for the subject. Second, wireless communication allows for a broader range of data collection scenarios, notably walking. This opens the door for researchers interested in fields such as gait rehabilitation for stroke [23] and gait prediction for prosthetic legs [24].

Despite the advantages of the added wireless communication, it is not without its drawbacks. Dropped data packets are an unavoidable complication of wireless communication. Knowing this, we investigated several ways to minimize these errors. Disabling wireless autoscanning and ensuring the ADS_BP is oriented such that the computer is not to the right of the device is shown to significantly reduce these communication errors. While the former can easily be set up on the test computer, the orientation requirement may be more difficult depending on the task. For seated tasks, the computer can simply be placed in a static location relative to the ADS_BP to ensure optimal communication. However, for walking tasks, researchers may decide to only collect data while users are walking in one direction, and omitting data while the user walks in the other direction when more communication errors are expected. Regardless of the methods used to minimize communication errors, it should be

noted that some instances of missing data are to be expected. Such missing data may be estimated using data modeling postprocessing techniques [25], [26], however this is beyond the scope of the present work.

The ADS_BP presented in this work represents an advancement in capabilities for open-source bioelectric signal acquisition devices; however, there nonetheless exist some limitations. The ADS_BP is capable of sampling at up to 2 kHz, but doing so requires fewer channels to be selected. For some applications, 8 electrodes may not be sufficient, thus acquiring additional signals would require modification of the ADS_BP board to daisy-chain additional sensors, or otherwise using a second ADS_BP which may not synchronize sampling with the first. Finally, the ADS_BP does not include any output channels, which may be useful for applications including providing vibrotactile sensation for user feedback during tasks. However, the open-source nature of the ADS_BP allows for the possibility of future development to modify the device to add or refine these functionalities.

V. CONCLUSION

Here, we present recent work for a complete bioelectrical acquisition platform. In contrast to other open-source bioelectrical signal acquisition devices, the ADS_BP hardware interfaces inherently with the BioPatRec software to allow for out-of-the-box acquisition-to-output signal classification. The low cost of the ADS_BP hardware makes for an accessible benchmarking platform which lowers the bar to conducting research with bioelectrical signals such as EMG, ECG, and EEG. Wireless capabilities improve the safety and broaden the scope of the ADS_BP to include research involving gait. Overall, the open-source design of the ADS_BP and BioPatRec helps to remove barriers to conducting research in the field of biomedical engineering, allowing for bioelectric signal recording in laboratory and clinical settings, as well as offline and real-time intent classification, all for a cost of approximately $150 USD per device.

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SUPPLEMENTARY MATERIALS

All source files for the ADS_BP and BioPatRec can be found in the following repository on the Open Science Framework: https://osf.io/k5yut/.

A user guide describing in detail the assembly and set-up procedures for the ADS_BP can be found in the Supplementary Materials for this manuscript.

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