Data Acquisition, Conditioning and Processing System for a Wearable-based Biostimulation

Leonardo Sestrem[a], Raul Kaizer[b], João Gonçalves[c], Paulo Leitão[d], João Paulo Teixeira[e], José Lima[f], Tiago Franco[g] and José Augusto Carvalho[h]
Research Center in Digitalization and Intelligent Robotics (CeDRI), Instituto Politécnico de Bragança, Campus de Santa Apolónia, 5300-253 Bragança, Portugal

Keywords: Wearable Bioestimulation, Data Acquisition, Electromyography, Artificial Intelligence.

Abstract: Data acquisition by electromyography, as well as the muscle stimulation, has become more accessible with the new developments in the wearable technology and medicine. In fact, for treatments, games or sports, it is possible to find examples of the use of muscle signals to analyse specific aspects related, e.g., to disease, injuries or movement impulses. However, these systems are usually expensive, does not integrate data acquisition with the muscle stimulation and does not exhibit an adaptive control behaviour that consider the pathology and the patient response. This paper presents a wearable system that integrates the signal acquisition and the electrostimulation using dry thin-film titanium-based electrodes. The acquired data is transmitted to a mobile application running on a smartphone by using Bluetooth Low Energy (BLE) technology, where it is analysed by employing artificial intelligence algorithms to provide customised treatments for each patient profile and type of pathology, and taking into consideration the feedback of the acquired electromyography signal. The acquired patient's data is also stored in a secure cloud database to support the physician to analyse and follow-up the clinical results from the rehabilitation process.

1 INTRODUCTION

In 2030, according to the World Health Organisation, it is expected that the number of people aged 60 years and older will be approximately 1.4 billion. With the coming of age, movement difficulties and pathologies, such as arthritis, become frequent, consequently increasing the workload of the physiotherapists. As these pathologies make difficult, expensive and burdensome to constantly leave home to receive the treatment, cheap and easy-to-use alternatives must be developed to support the home healthcare.

One of the rehabilitation treatment methods makes use of the electrostimulation, namely the Functional Electrical Stimulation (FES), which uses low frequency electrical currents to provoke the muscles contraction, increasing the muscle activity, along with exercises, contributing significantly to improve the ability to carry out functional activities. Aiming to simplify the everyday activities and allow its remote execution, the functions required to carry out the treatment may be implemented in a wearable system.

Wearable systems can be used by patients to perform health treatments and the continuous monitoring locally at home, specially not requiring other devices like screens and peripherals. In a wearable system, the collected muscle data by biosignals measurements, e.g., cardiac, neurological and musculoskeletal, are biological samples in time and space of biological events. The musculoskeletal signal, or the myoelectric signal, is a result of the bioelectricity phenomenon that occurs when a potential difference exists between the internal and external sides of the muscle cell membrane (Ferraz et al., 2021).

The eletromyography (EMG) is the electrodiagnostic medicine technique used to monitor the electrical activity produced by skeletal muscles (Robertson et al., 2013). The usage of electrodes placed on the skin to acquire this type of signal is known as surface

---

[a] https://orcid.org/0000-0002-9344-3075
[b] https://orcid.org/0000-0001-9273-2257
[c] https://orcid.org/0000-0002-3502-7444
[d] https://orcid.org/0000-0002-2151-7944
[e] https://orcid.org/0000-0002-6679-5702
[f] https://orcid.org/0000-0001-7902-1207
[g] https://orcid.org/0000-0001-8574-4380
[h] https://orcid.org/0000-0002-6074-8112

Sestrem, L., Kaizer, R., Gonçalves, J., Leitão, P., Teixeira, J., Lima, J., Franco, T. and Carvalho, J.
Data Acquisition, Conditioning and Processing System for a Wearable-based Biostimulation.
DOI: 10.5220/0011002300003123
In *Proceedings of the 15th International Joint Conference on Biomedical Engineering Systems and Technologies (BIOSTEC 2022) - Volume 1: BIODEVICES*, pages 223-230
ISBN: 978-989-758-552-4; ISSN: 2184-4305

electromyography (sEMG), and presents the advantage of being a non-invasive EMG technology that is capable of monitoring the nerve-muscle interactions signals (Ergeneci et al., 2018a). The disadvantages of sEMG are the complexity to obtain accurate data signals and the difficulty of electrostimulation, namely the need of the exact positioning of the electrode, the concern with noisy electrical environments and the patient biological conditions (Rodrigues et al., 2020).

The commercial wearable systems usually present the EMG signal acquisition or electrostimulation functions separately, due to the complexity and difficulty to integrate without compromising the efficiency, signal accuracy and comfort. To address these requirements, the employed hardware needs to present a greater and reliable performance, increasing the solution investment.

Having this in mind, the paper describes the development of a wearable electroestimulation system to support the remote and autonomous rehabilitation of the vastus medialis muscle in elderly people. The developed solution uses dry thin-film electrodes on the skin surface to acquire the EMG signal, and considers the electrostimulation system integrated with the signal acquisition and conditioning, stimulating the muscle during a rehabilitation session according to an adaptive control based on the biofeedback from the EMG biosignals and artificial intelligence (AI) algorithms. A continuous remote monitoring system allows the patient to get the treatment sessions at home, with the gathered biofeedback data being transmitted through Bluetooth Low Energy (BLE) technology to a smartphone which serves as mediator to the cloud, where the physician can visualise the results of the sessions and prescribe new sessions.

The rest of the paper is organised as follows: Section 2 presents the related work and Section 3 describes the proposed architecture for the signal acquisition, conditioning and processing system for the wearable-based biostimulation. Section 4 presents the implementation of the proposed system and Section 5 analyses the preliminary experimental results. Finally, Section 6 rounds up the paper with the conclusions and points out the future work.

2 RELATED WORK

The wearable electronic technology has revolutionised the traditional medical diagnosis methods as well as current medical devices by providing convenient, remote, wearable and portable functions (Lou et al., 2020). The progress in electrical measurements and electronics has enabled the development of wearable medical systems, which have real-time monitoring capabilities, flexibility, easy mobility, and compatibility with the data and signal processing fields (Chun et al., 2019; Trung and Lee, 2016).

There is a tendency to include extra functionalities in the wearable medical systems aiming the integration with other systems, e.g., non-invasive real-time monitoring and analysis of vital human parameters (Lou et al., 2020). Current solutions rely on medical monitoring systems including wearable sensors, wireless communication modules, displays, and efficient power supply for improved performance and reliable data collection (Koh et al., 2016). The combination of intelligent sensors and algorithms can not only provide these extra functions to the system but also offers processed data and independent working mode with self-healing, self-evaluation, and self-calibration features (Lou et al., 2020).

Several commercial solutions for wearable systems based on sEMG data acquisition are currently available, namely Biometrics DataLOG (Biometrics Ltd, 2021), Bitalino (Da Silva et al., 2014) and Delsys Trigno Lab (Delsys, 2021), providing a reliable and accurate EMG signal acquisition, but they are usually expensive and mainly focused in the signal acquisition functions. In the same manner, several academic works are available for this purpose, e.g., (Park et al., 2021; Zhu et al., 2021; Ergeneci et al., 2018a; Chen et al., 2017; Li et al., 2021). In spite of their benefits, mainly focused in the signal acquisition, they are missing important features for the development of reusable wearable biostimulation based on the EMG signal acquisition. As examples, the solutions proposed by (Park et al., 2021; Biometrics Ltd, 2021) present a lack of wearability that do not allow sufficient motion freedom and others do not use wireless data transmission which are not suitable for general use outside the laboratory environments (see (Park et al., 2021; Chen et al., 2017)). In the same mannner, e.g., the setup proposed in (Ergeneci et al., 2018a) uses the Wi-Fi technology to stream the acquired data, which in spite of its suitability for real-time monitoring, the energy consumption is a drawback to wearable systems, being required a low power solution to an extensive treatment period.

The use of wet electrodes may cause allergic reactions and skin irritation (Fayyaz Shahandashti et al., 2019), and the electrolytic conductive gel that helps to reduce the skin-electrode impedance, dehydrate over time, hence worsening the conductivity (Ergeneci et al., 2018a). Another disadvantage of wet electrodes is that they need to be changed every few or every session while dry electrodes can be reused for many sessions depending on the material that it is made (Peng et al., 2016). Several works, e.g., (Zhu et al., 2021; Park et al., 2021; Li et al., 2021), use wet/disposable electrodes, which do not offer reusability.

Although dry electrodes do not require the need to use conductive gel to work properly and are reusable, they present higher skin-electrode impedance than the wet ones, which may increase the biosignal noise and demand higher voltage to stimulate the muscle. Some solutions found in the literature employ dry sensors that use high-cost materials in their composition such as gold, offering a signal quality many times superior to those obtained with the wet electrodes, but increasing the price of the system (Ergeneci et al., 2018b).

The aforementioned solutions are usually based on wearables that consider wet electrodes and only present the acquisition function and do not include stimulation to aid the muscle rehabilitation. Another functionality that is usually missing in the stimulation systems is the use of AI to assist the physician in the diagnosis and even to adjust the treatment protocol during an electrostimulation session according to the pathology and the patient's response.

3 BIOSTIMULATION SYSTEM ARCHITECTURE

The solution proposed in this work was designed to accomplish the requirements for the rehabilitation of the *vastus medialis* muscle, particularly addressing the elderly people.

3.1 System Requirements

The wearable healthcare systems need to be comfortable to wear, and an ease adaptation with skin or human body surface, with compatibility, durability, and abrasion resistance (Lou et al., 2020). In addition, these healthcare systems can not merely improve the health status but also enhance the development of medical technology allowing to detect an emergency situation and preventing accidents (Park et al., 2021).

When designing the electrodes, the shape, size and material are the first aspects to take into account (Di Flumeri et al., 2019), influencing the price, comfort, signal quality, contact stability and biocompatibility. The material must present unchanged characteristics for long periods so the electrodes do not have to be changed. This guarantees the right connection and easy use for elderly people in their homes.

The electrodes must also be designed in a way that allows them to be washed together with the wearable without having their position changed and avoiding the risk of compromising the connection stability. To avoid damages from the contact with sweat and other body fluids, the corrosion resistant materials must be used but they must be materials that do not show significant changes in their electrical properties when in contact with liquids (body fluids) (Tallgren et al., 2005) to not hurt the skin with the stimulation signals.

There is the concern with electric damaging the skin while applying the FES system through dry electrodes because of the body fluids. Thus, the stimulation system must be designed to be capable of stimulate the muscle with the lowest possible voltage. To achieve this, biphasic square wave pulses must be used and manipulated in terms of amplitude, duration and frequency.While maintaining the frequency between 10 and 100 Hz and the pulse duration lower than 999 µs, the amplitude is subjective as each treatment and human body requires a different value. For this reason, implementing biphasic pulses guarantees to reduce the tissue damage and irritation provoked by the stimulation in long periods of time (Tallgren et al., 2005), and helps to avoid the muscle's premature fatigue (Lynch and Popovic, 2008).

To identify the original responses of the muscle and compare to the current responses, the sampling rate for the acquisition of the skeletal muscle signals must be at least 1 kHz on a frequency bandwidth of $18 - 480$ Hz. The correct acquisition of signals from 0.8mV requires the use a resolution of 12 bits in the conversion from analogue to digital.

In terms of investment, the developed system should provide a low-cost and competitive price when compared to commercial solutions, e.g., (Biometrics Ltd, 2021), and the signal acquisition and stimulation functions should be completely integrated. In fact, the rehabilitation routines should be adapted by AI algorithms according to the biofeedback that takes into account the patient profile and the specific injury.

3.2 System Architecture

The proposed system architecture, illustrated in Figure 1, ensures the adequate acquisition and conditioning of the EMG signal (e.g., amplification, filtering and conversion) to support the monitoring and the stimulation of the muscle, as well as the transmission of the acquired data to the mobile application running in the smartphone, and later to a secure cloud where the physician can follow-up the clinical results. The design of this innovative biostimulation system allows to reach a modular, scalable and low cost solution.

The wearable system comprises a pair of dry electrodes to acquire the EMG signal and to perform the FES, that are placed in the patient skin near the *vastus medialis* muscle. The first module, i.e. data acquisi-

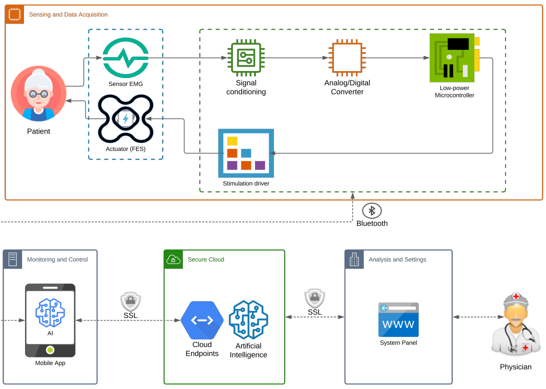

Figure 1: System architecture focusing the acquisition, signal conditioning and stimulation system.

tion block, is responsible to the implementation of the real-time EMG data acquisition functions, namely to collect the muscular information through EMG sensors in each 1 ms. The collected electrode signals will be forward to a signal conditioning block that amplifies the signal to a higher intensity that can be transmitted to avoid losses and to filter the signal to attenuate undesired frequencies and noise. Next, the EMG signal is converted from analogue to digital by using an Analog/Digital Converter (ADC), and finally transmitted to a microcontroller that will store and process locally the data by executing the control rules to implement the stimulation function. These control rules are defined according to the treatment protocol previously established by the physician, and triggered according to the biofeedback from the EMG signal (and in this way closing the loop between the signal acquisition with the stimulation functions).

The commands for the muscle stimulation, provided by the microcontroller, are forward to the eletrical stimulation driver that is responsible to set the amplitude and frequency of the electrical signals injected in the FES electrodes. Closing the loop, the acquisition module will measure the EMG signal that corresponds to the muscle stimulus occasioned by the current flow.

The system also comprises an user-friendly mobile application running in a smartphone, which interface enables the patient to access the clinical data and medical plan stipulated by the physician. With this, the patient is able to start, stop and interrupt the treatment any time, and visualise the EMG and FES signals in real-time. For this purpose, the acquired data from the wearable is transmitted to the mobile application through the BLE wireless protocol, which provides low power consumption and implementation complexity. A microservice architecture capable of communicating with the wearable system to perform treatments at home was developed, ensuring the data security and privacy, mainly using a Single-Sign On (SSO) authentication service (Franco et al., 2021). The data collected during the session and the report provided by the patient at the end of the session are transmitted to a secure cloud database, where the physician can perform the clinical follow-up.

Another important module in this system is the use of AI algorithms running in the cloud that allows to analyse the collected data from the treatment session (and also the previous historical data for that and others patients) and derive new prescriptions for the next treatment sessions according to the patient's profile and response, and type of pathology.

4 DEVELOPMENT OF THE BIOSTIMULATION SYSTEM

Considering the established requirements and the designed system architecture, an integrated biostimulation prototype system was developed as illustrated in Figure 2 (note that the mobile app and the secure cloud including the AI algorithms are not detailed in this paper). The solution comprises the data acquisition and electrical stimulation modules that operate integrated and in real-time, which means that the stimulus are derived from the feedback from the collected EMG signal, and this signal is the response of the muscle to the stimulation.

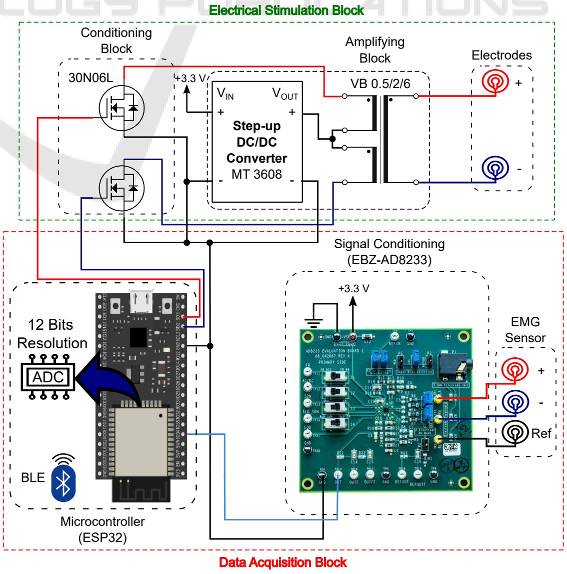

Figure 2: Data acquisition and stimulation practical setup.

4.1 Data Acquisition System

The signal conditioning stage employs the AD8233CB-EBZ board that contains an AD8233 heart rate monitor front end. Originally, the board was designed to acquire ECG signals with a frequency bandwidth of $7-25$ Hz, but to measure EMG signals, a modification in the High-pass filter (HPF) and Low-pass filter (LPF) circuits were necessary to be performed to achieve a new bandwidth of $15-480$ Hz. This allows to acquire and amplify the skeletal muscle signals since the biosignals have low amplitude levels, ranging from µV to a few mV.

The ESP32 Devkit V1 was used as microcontroller due to their low-cost, wireless communication (BLE and Wi-Fi) and capability to operate with dual core. The ESP32 has an ADC with 12 bits of resolution, allowing to address the system requirements, permitting to convert analogue values from 0.8 mV, while e.g., the Arduino only has 10 bits of resolution that only allows to measure a signal from 5 mV. In spite of offering the possibility to communicate using Wi-Fi and BLE wireless protocols, the selection was to use BLE due to the low-power consumption that ensures a longer battery autonomy (note that Wi-Fi is widely employed due to its availability and capacity of streaming but in these applications, the autonomy of the battery is a strong requirement). Furthermore, the dual-core functionality provided by the ESP32 is crucial to guarantee that the acquisition and stimulation can be done separately without delays and interference between the two tasks.

The acquisition system operates with a sampling rate of 1 kHz, respecting the Nyquist theorem, to avoid aliasing. The acquired data is transmitted to the mobile application each 200 ms due to the limitation of the BLE protocol to receive a maximum number of 500 bytes; each transmitted sample occupies 2 bytes, which means that each transmitted package comprise 400 bytes. Finally, the collected data is stored in the cloud database to be available to the physician for clinical follow-up and to the AI algorithms for optimisation of the treatment for the next sessions.

4.2 Electrical Stimulation Module

The electrical stimulation block is responsible to generate the muscle stimulus by applying electrical signals according to the system commands. The commands are two pulses, defined in duration, amplitude and frequency, and produced by the microcontroller to compose the biphasic waveform, necessary to apply the stimulation. The conditioning block receives the pulses and switch them by using a pair of MOSFETs, in this case 30N06L that were chosen due to their low drain-source resistance ($R_{DS} = 0.035$) that allows a higher switching speed.

The amplification power block generates the biphasic wave form and increases the output voltage of the stimulation signal. This stage is composed by a $MT3608$ step-up converter with a $1:20$ conversion ratio, and a transformer VB $0.5/2/6$ with a $6:230$ transformation ratio. The boost converter was chosen due to its low cost and amplification rate, and the transformer due to its small size ($22/22.7/19$ mm) and the disposition of the pins, once it has four pins in the low voltage side which enables the generation of the biphasic pulse while the signal is amplified. These parameters are defined for the treatment applied to the patient, established by the physician and the AI algorithms.

The pulses are applied to both inputs of the low voltage side of the transformer, and the middle points are powered by a constant voltage amplified by the step-up converter to reach a higher output rate. This configuration allows to generate the desired pulse form and reach the necessary amplitude voltage to fulfil the stimulus signal. The output amplitude is controlled by using the Pulse Width Modulation (PWM) technique where the pulses are adjusted in duration and period, being the amplitude directly proportional to the pulse duration.

5 EXPERIMENTAL RESULTS

Several experimental tests were performed in the developed prototype solution to verify the accomplishment with the established requirements. The acquisition experiments were developed with a healthy person, maintaining the same motion pattern during 3 seconds to start the movement, 4 seconds in the maximum muscle contraction and 3 seconds to return to the rest. The stimulation was tested in a load to simulate the skin impedance, being able to evaluate the generated waveform and the module performance.

5.1 Acquisition of the EMG Signal

In order to evaluate the proposed solution, the experimental tests were performed using wet (Ag-AgCl) and two distinct types of dry (Ti and TiCu) electrodes. As shown in Figures 3 and 4, it is possible to note that the signals acquired using the Ti film and the polylactic acid substrate (PLA) exhibit no saturation in the readings and the energy levels were significantly close to those obtained with the wet sensors, presenting a signal-to-noise ratio (SNR) of 17.57 dB while the disposable ones provided a value of 18.15 dB. This shows that the Ti dry electrode is competitive to be used in such solutions since the energy levels were close to those recorded by the Ag-AgCl electrode, simplifying the algorithm to detect the amount and moment of the muscle contractions, as well as to avoid the use of gel that can cause skin irritation and reduces the number of generated waste.

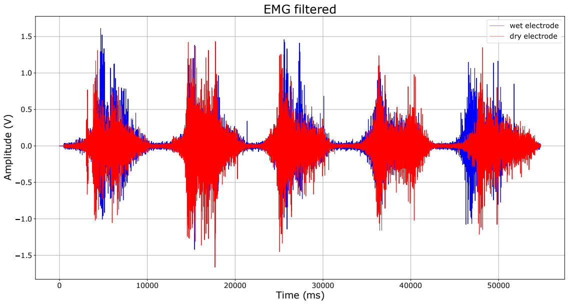

Figure 3: Analysis of filtered reading with Ti and wet electrodes signals.

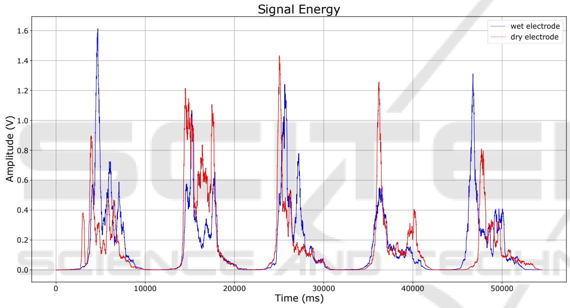

Figure 4: Analysis of the signal energy of Ti and wet electrodes.

In therms of the TiCu electrodes, the reached signal quality is 17.85 dB, which is higher than the one provided by the Ti film 17.57 dB, as illustrated in Figure 5. However, the energy levels, illustrated in Figure 6, were lower compared to the other types of tested sensors which ends up hindering the detection of muscle contractions and the diagnosis of the patient. Therefore, the presence of copper in the sensor improves the quality of the acquired signal by providing an acquisition with a more reasonable level of noise. However, the presence of this material in the film makes the electrode much more susceptible to oxidation and can cause irritation in case of a prolonged period of time in contact with the skin.

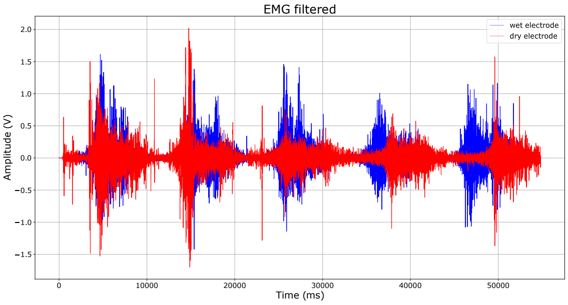

Figure 5: Analysis of filtered reading with TiCu and wet electrodes.

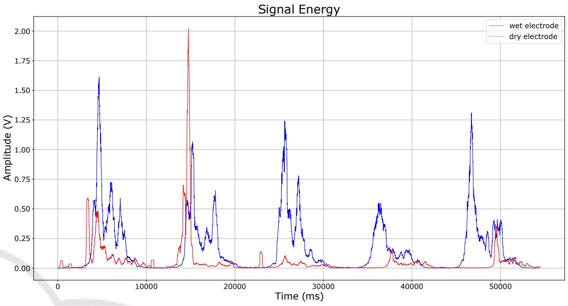

Figure 6: Analysis of the signal energy of TiCu and wet electrodes.

Another critical factor observed during the tests was the electromagnetic noise in the environment, which affects the measurements and turns the system inaccurate. In order to mitigate this effect, it was employed the shielding in the circuit container to isolate the electronics of the environment noise, attenuating possible magnetic coupling and high-frequency interference. Protecting the circuit from these effects allowed to improve the system reliability and to reduce the measurements uncertainty.

In terms of data transmission between the wearable and the smartphone application using BLE, the wearable system in average sends the acquired data each 206 ms, and the mobile application receives the information basically in real-time, with a delay of some µs. This achievement is reasonable since the microcontroller is also performing the signal processing and the generation of the stimulation pulses, and the mobile application is plotting the received signals and running lighter artificial intelligence trained models to adapt the stimulation rules used by the wearable.

5.2 Electrical Stimulation

The experimental tests related to the electrical stimulation were performed to evaluate if a certain stimulation voltage is achieved by adjusting the pulse variables, which are executed according to the control rules defined by the AI algorithms that are continuously updated on the wearable by the mobile application. The amplification block was powered with a voltage of 3.3V, the step-up converter elevates the input voltage to an approximate value of 8.2V, and the transformer generates the biphasic waveform and amplifies the pulses according to the pulse width.

Since the objective was to achieve an output amplitude near 30V, the width of the pulses was adjusted until the amplitude reached the desired value, starting with a width value of 5 µs and increasing the width according to the balance of the pulse. During the modification of the pulses' width, the pulses become unbalanced, i.e. the positive component gradually becomes bigger than the negative component. To correct this issue, the width of the negative component is set with a greater value than the positive one.

According to this, the amplitude of 30V was reached for the values of 360 µs for the positive pulse, 550 µs for the negative pulse, and 80 ms for the period. The pulses produced by the microcontroller, based on the input values explained above, can be observed in Figure 7. These pulses are sent to the transformer that composes the biphasic wave form and amplifies its amplitude.

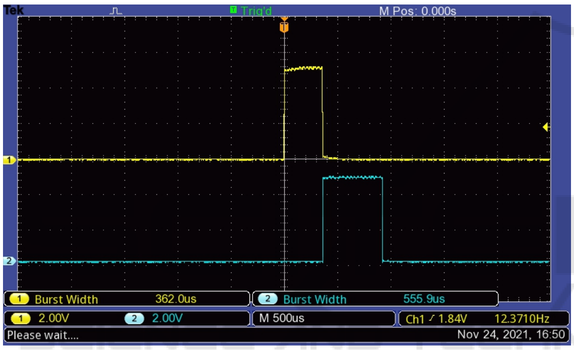

Figure 7: Stimulation pulses produced by the microcontroller.

The resulting waveform for the previous pulses is showed in Figure 8, with the biphasic wave signal having approximately 30V of amplitude. The resulting signal is close to the expected, presenting the desired output voltage and a balanced shape, with the negative component bigger than the positive component according to the width values previously established for the input pulses.

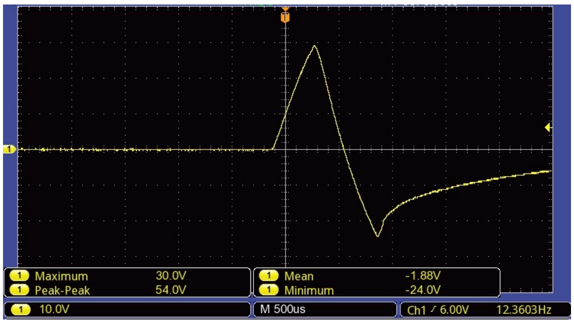

Figure 8: Experimental stimulation signal with approximately 30V of amplitude.

6 CONCLUSIONS

Wearable systems have a vast range of applications, e.g., sports and healthcare, representing technological alternatives to assist the execution of rehabilitation treatments and remote monitoring of vital health parameters.

The proposed innovative and low-cost wearable solution considers the use of dry electrodes and an adaptive control of the bio-stimulation based on the sEMG feedback, as well as the use of artificial intelligence algorithms to adapt the treatment protocol according to the pathology and the patient profile. Preliminary experimental tests were carried out and clearly shows that the main system requirements were achieved, mainly in terms of the frequency of sampling the EMG signal and the capability to integrate the data acquisition with the stimulation using dry electrodes. Also the effective transmission of collected data from EMG and FES signals for the mobile application was verified, being the microcontroller capable to manage the signal acquisition and transmission, and to generate the stimulation pulses.

During the experiments, it was also clear the need to fix the electrodes to prevent them from changing their position during the patient's movements and to apply the right pressure as this influences the noise and may cause the EMG sensors to lose the reference signal. The electromagnetic noise of the environment strongly influences the quality of the acquired signal, as well as the system accuracy, which is also affected by the ADC resolution. For this purpose, the circuit container was shielded to isolate the electronics from the electromagnetic noise, with significant results.

Future work is devoted to test the developed solution using dry electrodes with connectors that provide a better electrical and mechanical connection and are more malleable to better adjust to the curvature of the leg. The implementation of the developed solution in a PCB and the integration of AI algorithms to provide adaptive and customised treatments will be also considered as future work.

ACKNOWLEDGEMENTS

This work was supported by the European Regional Development Fund (ERDF) through the Operational Programme for Competitiveness and Internationalization (COMPETE 2020), under Portugal 2020 in the framework of the NanoStim - Nanomaterials for wearable-based integrated biostimulation (POCI-01-0247-FEDER-045908) project.

REFERENCES

Biometrics Ltd (2021). Datalog MWX8. ttp://www.biometricsltd.com/datalog.tm. Accessed: 26.11.2021.

Chen, X.-B., Zhou, Y.-X., Wang, H.-P., Lü, X.-Y., and Wang, Z.-G. (2017). Design of sEMG-detecting Circuit for EMG-Bridge. In *Proc. of 39th Annual Int'l Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pages 382–385.

Chun, S., Kim, J., Pang, C., et al. (2019). A Transparent, Glue-free, Skin-attachable Graphene Pressure Sensor with Micropillars for Skin-elasticity Measurement. *Nanotechnology*, 30(33):335501.

Da Silva, H. P., Guerreiro, J., Lourenço, A., Fred, A., and Martins, R. (2014). BITalino: A Novel Hardware Framework for Physiological Computing. In *PhyCS*, pages 246–253.

Delsys (2021). Trigno Research+. ttps://delsys.com/trigno/researc/. Accessed: 26.11.2021.

Di Flumeri, G., Aricò, P., Borghini, G., Sciaraffa, N., Di Florio, A., and Babiloni, F. (2019). The dry revolution: evaluation of three different eeg dry electrode types in terms of signal spectral features, mental states classification and usability. *Sensors*, 19(6):1365.

Ergeneci, M., Gokcesu, K., Ertan, E., and Kosmas, P. (2018a). An embedded, eight channel, noise canceling, wireless, wearable semg data acquisition system with adaptive muscle contraction detection. *IEEE Transactions on Biomedical Circuits and Systems*, 12(1):68–79.

Ergeneci, M., Gokcesu, K., Ertan, E., and Kosmas, P. (2018b). An embedded, eight channel, noise canceling, wireless, wearable semg data acquisition system with adaptive muscle contraction detection. *IEEE Transactions on Biomedical Circuits and Systems*, 12(1):68–79.

Fayyaz Shahandashti, P., Pourkheyrollah, H., Jahanshahi, A., and Ghafoorifard, H. (2019). Highly conformable stretchable dry electrodes based on inexpensive flex substrate for long-term biopotential (EMG/ECG) monitoring. *Sensors and Actuators A: Physical*, 295:678–686.

Ferraz, R. d. S., Fonseca, R. S. d., Rodrigues, I. T., Silva, C. B. d., et al. (2021). Surface electromyographic signal acquisition system for real time monitoring of upper limbs muscles. *Journal of Computational and Theoretical Nanoscience*, 18(4):1147–1152.

Franco, T., Henriques, P. R., Alves, P., et al. (2021). System Architecture for Home Muscle Rehabilitation Treatment. In *Submitted to the 10th World Conference on Information Systems and Technologies*.

Koh, A., Kang, D., Xue, Y., Lee, S., Pielak, R. M., Kim, J., Hwang, T., Min, S., Banks, A., Bastien, P., et al. (2016). A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat. *Science translational medicine*, 8(366):366ra165–366ra165.

Li, X., Zhou, Z., Ji, M., and Liu, W. (2021). A wearable wireless device designed for surface electromyography acquisition. *Microsystem Technologies*, 27(4):1787–1795.

Lou, Z., Wang, L., Jiang, K., Wei, Z., and Shen, G. (2020). Reviews of wearable healthcare systems: Materials, devices and system integration. *Materials Science and Engineering: R: Reports*, 140:100523.

Lynch, C. L. and Popovic, M. R. (2008). Functional electrical stimulation. *IEEE control systems magazine*, 28(2):40–50.

Park, H.-K., Jung, J., Lee, D.-W., Shin, H. C., Lee, H.-J., and Lee, W.-H. (2021). A wearable electromyography-controlled functional electrical stimulation system improves balance, gait function, and symmetry in older adults. *Technology and Health Care*, (Preprint):1–13.

Peng, H.-L., Jing-Quan Liu, Tian, H.-C., Dong, Y.-Z., Yang, B., Chen, X., and Yang, C.-S. (2016). A novel passive electrode based on porous ti for eeg recording. *Sensors and Actuators B: Chemical*, 226:349–356.

Robertson, D. G. E., Caldwell, G. E., Hamill, J., Kamen, G., and Whittlesey, S. (2013). *Research methods in biomechanics*. Human kinetics.

Rodrigues, M., Fiedler, P., Küchler, N., P. Domingues, R., Lopes, C., Borges, J., Haueisen, J., and Vaz, F. (2020). Dry electrodes for surface electromyography based on architectured titanium thin films. *Materials*, 13(9).

Tallgren, P., Vanhatalo, S., Kaila, K., and Voipio, J. (2005). Evaluation of commercially available electrodes and gels for recording of slow eeg potentials. *Clinical Neurophysiology*, 116(4):799–806.

Trung, T. Q. and Lee, N.-E. (2016). Flexible and stretchable physical sensor integrated platforms for wearable human-activity monitoringand personal healthcare. *Advanced materials*, 28(22):4338–4372.

Zhu, L., Mao, G., Su, H., Zhou, Z., Li, W., Lü, X., and Wang, Z. (2021). A wearable, high-resolution, and wireless system for multichannel surface electromyography detection. *IEEE Sensors Journal*, 21(8):9937–9948.