Analysis of Skeletal Muscles Contractility Using Smart SEMG-Based Socks

Lucia Giampetruzzi, Gabriele Rescio, Alessandro Leone, and Pietro Siciliano

Abstract Surface electromyography increasingly plays an important role for prevention, diagnosis and rehabilitation in healthcare field. In this context, the continuous monitoring of the electrical potentials produced by muscles appears to be effective to detect abnormal events. The recent progresses in surface electromyography technologies have allowed for the development of low invasive and reliable wearable devices. These devices promote long-term monitoring; however, they are often very expensive and not easy to be positioned appropriately. Moreover, they use disposable pre-gelled electrodes that can cause skin redness. In this work, to overcome these issues, a prototype of new smart socks has been realized, implementing reusable and high biocompatible hybrid polymer electrolytes. These electrodes provide a comfortable lower limb long-term monitoring avoiding a difficult daily repositioning by users. The realized socks are lightweight and integrates all electronic components for the pre-elaboration and the wireless data sending. The Gastrocnemius-Tibialis muscles were selected and analyzed due to their relevance for assessment of age-related changes in gait, sarcopenia pathology, postural anomalies, fall risk, etc. In particular, in this paper an evaluation on the risk of falling detection by the system was considered as a case of study.

Keywords Wearable device · Surface electromyography · Hybrid polymer electrodes · Smart socks

L. Giampetruzzi (✉) · G. Rescio · A. Leone · P. Siciliano
Institute for Microelectronics and Microsystems, National Research Council of Italy, Via Monteroni c/o Campus Ecotekne, Palazzina A3, Lecce, Italy
e-mail: lucia.giampetruzzi@le.imm.cnr.it

G. Rescio
e-mail: gabriele.rescio@cnr.it

A. Leone
e-mail: alessandro.leone@cnr.it

P. Siciliano
e-mail: pietro.siciliano@le.imm.cnr.it

A. Monteriù et al. (eds.), *Ambient Assisted Living*, Lecture Notes in Electrical Engineering 725, https://doi.org/10.1007/978-3-030-63107-9_4

1 Introduction

Recently, bio-signal measurements among which electromyography (EMG) and electroencephalography (EEG) have been increasingly demanded. In particular, EMG is a medical procedure that provide the acquisition of the electric potentials produced by the voluntary contraction of the skeletal muscle fibers. These potentials are bio-electric signals, acquired from the human body and then filtered to reduce the noise produced by other electrical activities of the body or inappropriate contact of the sensors, namely artifacts. Then the signals are processed in a control system to acquire information regarding the anatomical and physiological muscles' characteristics and to make a diagnosis.

The surface EMG (sEMG) can acquire signals by no invasive electrodes placed on the surface of skin, compared to the intramuscular technique. The sEMG signals are considered most useful as electrophysiological, for application in medicine as the assessment of age-related changes in gait, for diagnosis in Sarcopenia Pathology (SP), Amyotrophic Lateral Sclerosis (ALS) and Multiple Sclerosis (MS) or other neuropathies, postural anomalies, fall risk, etc. [8, 16, 17]. The effects of these diseases are mainly monitored through the response of EMG on the muscle strength/power performance in the lower limbs using medical wired stations or portable and wearable technologies [29]. Wearable devices have recently gained increased importance due to their reliability and no-invasive monitoring of health parameters, exercise activity, but also for the early detection of illnesses and/or disorders or to prevent dangerous events in the elderly healthcare [15].

Considering fall events among elderly, several automatic integrated wearable devices and ambient sensor devices capable of fall detection have been constructed [1, 3, 5, 20, 27]. Although these devices are remarkable, they are not able to prevent injuries resulting from the impact on the floor. To overcome this limitation advanced technologies should be developed on the timely recognition of imbalance and fall event, activating an impact protection system. The current solutions are oriented to evaluate the patient physical instability, primarily monitoring the users' body movements and their muscle behaviors [2, 6, 11, 17]. These studies suggest that the lack of balance causes a sudden modification on the EMG patterns brought about by reactive/corrective neuromuscular response. So, the imbalance detection systems based on EMG signals may represent a very responsive and effective strategy for fall prevention. In these kinds of analysis, generally, the wired probes or wireless devices integrate the gold standard for sEMG analysis: Silver/Silver Chloride (Ag/AgCl) wet (hydrogel) electrodes. These electrodes consist of a silver disc layer surrounded by a silver chloride hydrogel layer that improves the signal quality by lowering the impedance between the electrode and skin. However, these electrodes are unsuitable for a long-term monitoring because they cause skin irritation and they also dehydrate, producing high impedance and so providing the loss of signal quality [19] and consequently a high incidence of motion artifacts and noise. They are also relatively expensive depending on the cost of silver. Although the fabrication of comfortable and stable textile electrodes for long-term monitoring still represents an open research issue. Recently, several companies have developed electrodes that address hydrogel dehydration designing new electrodes made of new materials and polymer by combining viscoelastic polymeric adhesive to address the limitations of traditional electrodes, aiming to adhere and conform the electrodes to the skin [4].

In the paper, new wireless smart socks for the surface EMG signals acquisition were developed to increase the users' level of usability and acceptability. This aim was achieved with the integration into the device of all electronics components and biocompatible hybrid polymer electrolyte (HPe)-based electrodes for the EMG data acquisition and transmission. The device was designed to monitor the Gastrocnemius Lateralis (GL) and Tibialis Anterior (TA) muscles contractions. A low computational cost and low invasive hardware-software system for the lack of human balance detection is described by using the realized socks, suitable for the fall risk evaluation.

The hardware was realized customizing commercial devices for that purpose and a low computational cost machine learning paradigm was chosen for the evaluation of imbalance events.

2 Materials

To acquire the electromyography data coming from the GL and TA muscles a sensorized sock was realized. The device is mainly made of (a) hybrid polymer electrolytes (HPe) electrodes to contact the skin, (b) an electronic interface unit to read the signals coming from the electrodes, (c) an elaboration and wireless transmission unit. In Fig. 1 the overview of the smart socks it is reported.

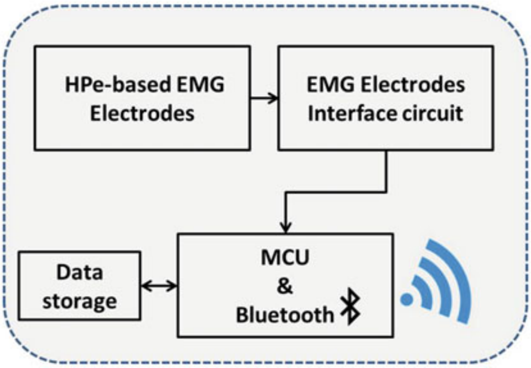

Fig. 1 Overview of the socks' hardware architecture

Fig. 2 HPe-based electrodes have been casting incorporating the clips, in the site where the Myoware Muscle Sensor board is placed

2.1 HPe-Based Electrodes Preparation and Implementation

The electrodes have been realized adopting the blending technique with a solution of Polyvinyl Alcohol (PVA) into a Carboxymethyl cellulose (CMC) solution. The two solutions were mixed at different ratio: 20:80, 40:60 and 50:50; while the best ratio has been resulted the 20:80 (PVA: CMC) as reported in literature [23, 24]. The polymer solutions were complexed with a 30 wt% of NH_4NO_3 in order to increase the biopolymer conductivity [25]. The CMC/PVA hybrid (80/20 wt%) as host solid biopolymer electrolytes complexed with NH_4NO_3 was casted into a mold containing the socks fabric and after the drying process, as described in literature [24], they resulted embedded into socks. An example of the system: socks-clip-HPe (made of 80:20 CMC/PVA blended) are shown in Fig. 2. The new electrodes made of CMC/PVA HPe could enhance the mechanical properties and the biological compatibility of the sensor system. In particular, CMC has been used in various medical applications including tissue engineering, drug delivery and wound dressings, as well as PVA has been employed in many medical fields [7, 22, 28]. The blending of CMC with PVA could result in highly effective hydrogen-affinity membranes reducing skin irritation and improving the signal detection [26, 31]. In the work a preliminary study was accomplished with the developed electrodes. Through the read-out circuit described in the following section, good signals quality was obtained. Further analyses will be needed for the electrodes mechanical and electrical characterization to realize reliable and robust electrodes adapt for long-term monitoring.

2.2 Data Acquisition and Transmission System

To read and amplify the signals coming from the HPe electrodes, the Myoware Muscle Sensor board interface, shown in Fig. 3, was sewed on the socks [13].

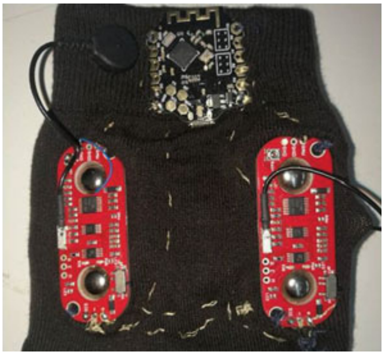

Fig. 3 Prototype of the smart socks

Myoware Muscle sensors are equipped with three electrodes; two of them must be placed on skin in the measured muscle area, and one on skin outside the muscle area, which is used as the ground point. Myoware device normally uses disposable pre-gelled electrodes, but through the variable gain of Myoware interface and the pre-elaboration step, described in the following section, it has been possible to obtain a high signal quality with the new realized electrodes. The Myoware Muscle Sensor can be polarized through a single voltage and it was designed for wearable devices. For the data transmission and elaboration unit the Bluno Beetle board was used [14]. It is lightweight, compact and integrates the low energy Bluetooth 4.0 transmission module. The board was sewed on the socks and connected to the Myoware device through conductive wires. Whereas, the whole system was supplied with a rechargeable Lipo battery of 3.7 V of 320 mA with dimension 26.5 × 25 × 4 mm and weight of 4 gr. It was placed and glued in the rear part of the Beetle board. In Fig. 3 is shown the realized prototype. Each electronic component was insulated through an Acrylic resin lacquer; in the future no-invasive packaging will be provided to make system washable. The total current consumption was measured to evaluate the lifetime of the 3.7 V battery. Based on the results the whole system consumes about 40 mA in data transmission mode. So, considering the used battery the system is able to monitor the lower limb muscles and to send data to a smartphone/embedded PC for about 8 h. Future improvements should be addressed to increase the system autonomy, optimizing the hardware and their power management logics. The prototype was realized by using an elastic sock to enhance the adhesion between the electrodes and the skin. The sensors were located on the socks in correspondence of the antagonist GL-TA Muscles. The algorithmic framework for the elaboration of the EMG signals, coming from the sensorized socks, was located and tested on an embedded PC, equipped with a Bluetooth connection.

3 Preliminary Results

To evaluate the electromyography signals coming from the device, five young healthy subjects of different ages (28.7 ± 7.1 years), weight (67.3 ± 8.5 kg), height (1.73 ± 0.3 m) and sex (3 males and 2 females) have simulated Activities Daily Livings (ADLs) and unbalance events, in controlled conditions. To acquire data, the socks were located so that the GL and TA muscles can be monitored, as shown in Fig. 4. In the zone where the probes were placed, the skin had been shaved and cleaned using an isopropyl alcohol swab to reduce impedance. Each actor performed about 40 simulated ADLs and 10 falls for a total of 211 ADLs and 54 falls. The acquired sEMG signals were sent to an embedded PC through the Bluetooth connection, for the data analysis. The imbalance events were simulated with the use of a movable platform designed and built to induce imbalance conditions until to the actors' fall. So, the data acquired have been used to develop and to test the computational framework of the system. In the primary phase of the data elaboration, the noise caused by movement artifacts were reduced through the band-pass filtering within a frequency range of [20–450] Hz. Moreover, for EMG-tension comparison, the signals were processed by generating their full wave rectification and their linear envelope [9]. The calibration was necessary to calculate the baseline of the signals and to reduce the inter-individual variability of sEMG signals between different users. The calibration phase was performed by users after the sEMG device is placed on the subject and through the calculation of Maximum Voluntary isometric Contraction (MVC) values for TA and GL muscles [17]. For the purpose of fall risk assessment, attention was focused on several low computational cost features, commonly used in the analysis of the lower-limb muscle activities [12, 18]. Based on the experimental results, the muscle Co-Contraction Indices (CCI) showed higher degree of discrimination using a sliding window of 100 ms. The CCI give an estimation about the simultaneous activation of the pair of muscles for each data point of the pre-processed data [12].

For the evaluation of performance and for the classification of the fall risk event, the low computationally cost Linear Discriminant Analysis (LDA) classifier was selected [10]. To assess the performance of the system the CCI features have been calculated for all ADLs and unbalance events simulated during the aforementioned acquisition

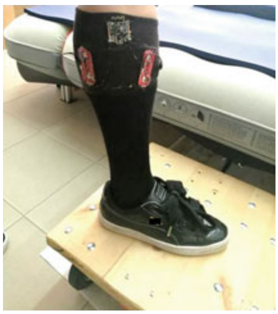

Fig. 4 The sEMG sensors mounting setup

campaign. The 70% of dataset was used to train the classifier, while the remain part was used to measure the performance in terms of sensitivity and specificity [30]. The measured values of the sensitivity and specificity are respectively 82.3% and 81.7%. These results were obtained considering 125 Hz sample rate. To evaluate the detection time, the average period between the moment when the unbalance condition is identified until the impact on the mat was analyzed. Based on the obtained results the system appears able to detect the fall risk about 750 ms before the impact on the mat. These results are close to those obtained from a similar analysis in which commercial, not very comfortable devices, were used [21]. This demonstrates the effectiveness of the realized wearable EMG-based system to detect fall in very fast way.

4 Conclusions

The paper deals with a preliminary study about a new and low invasive surface Electromyography-based smart socks for the monitoring of the antagonist GL-TA muscles. The system is suitable for the evaluation of several diseases related to the lower limb movements and activities such as age-related changes in gait, fall risk, sarcopenia pathology, amyotrophic lateral sclerosis and other peripheral neuropathies. To test the effectiveness of the system, the fall risk assessment was examined as a case of study. The classification has been performed through a low computational cost machine learning approach. Based on the results, relevant performance in terms of detection time, sensitivity and specificity have been monitored in controlled condition. The described analysis was carried out involving young healthy subjects, future work will be addressed to evaluate the system performance testing the socks with elderly subjects.

References

1. Andò B, Baglio S, Lombardo CO, Marletta V (2016) A Multi-sensor data fusion approach for ADL and fall classification. IEEE Trans Instrum Meas 65(9):1960–1967
2. Andò B, Baglio S, Marletta V (2016) A Inertial microsensors based wearable solution for the assessment of postural instability, ISOCS-MiNaB-ICT-MNBS, Otranto, Lecce, 25 29 June, 2016.
3. Andò B, Baglio S, Marletta V (2017) A neurofuzzy approach for fall detection. In: 23rd ICE/IEEE ITMC conference, Madeira Island, Portugal, 27–29 June 2017
4. Ansari SP, Anis A (2018) Conducting polymer hydrogels. Polym Gels. 2018. 467–486.
5. Bagalà F, Becker C, Cappello A, Chiari L, Aminian K, Hausdorff JM, Zijlstra W, Klenk J (2012) Evaluation of accelerometer-based fall detection algorithms on real-world falls. PLoS ONE 7:e37062
6. Blenkinsop GM, Pain MT, Hiley MJ (2017) Balance control strategies during perturbed and unperturbed balance in standing and handstand. Royal Soc Open Sci 4(7):161018

7. Capanema NSV, Mansur AAP, De Jesus AC, Carvalho SM, De Oliveira LC, Mansur HS (2018) Superabsorbent crosslinked carboxymethyl cellulose-PEG hydrogels for potential wound dressing applications. Int J Biol Macromol 106:1218–1234
8. Chung T, Prasad K, Lloyd TE (2013) Peripheral neuropathy: clinical and electrophysiological considerations. Neuroimaging Clin N Am 24(1):49–65
9. De Luca CJ, Gilmore LD, Kuznetsov M, Roy SH (2010) Filtering the surface EMG signal: movement artifact and baseline noise contamination. J Biomech 43(8):1573–1579
10. Englehart K, Hudgins B (2013) A robust, real-time control scheme for multifunction myoelectric control. IEEE Trans Biomed Eng 50(7):848–854
11. Galeano D, Brunetti F, Torricelli D, Piazza S, Pons JL (2014) A tool for balance control training using muscle synergies and multimodal interfaces. BioMed Res Int, 565370
12. Horsak B et al (2015) Muscle co-contraction around the knee when walking with unstable shoes. J Electromyogr Kinesiol 25
13. https://www.advancertechnologies.com
14. https://www.dfrobot.com
15. Kamišalić A, Fister I Jr, Turkanović M, Karakatič S (2018) Sensors and functionalities of non-invasive wrist-wearable devices: a review. Sensors (Basel, Switzerland) 18(6):1714
16. Joyce NC, Gregory GT (2013) Electrodiagnosis in persons with amyotrophic lateral sclerosis. PM & R: The J Inj, Funct, Rehabil 5(5 Suppl):S89-95
17. Leone A, Rescio G, Caroppo A, Siciliano P (2015) A Wearable EMG-based system pre-fall detector. Procedia Eng 120:455–458
18. Phinyomark A, Chujit G, Phukpattaranont P, Limsakul C, Huosheng H (2012) A preliminary study assessing time-domain EMG features of classifying exercises in preventing falls in the elderly. In: 2012 9th International conference on electrical engineering/electronics, computer, telecommunications and information technology (ECTI-CON), pp 1–4, 16–18 May (2012)
19. Posada-Quintero H, Rood R, Burnham K, Pennace J, Chon K (2016) Assessment of carbon/salt/adhesive electrodes for surface electromyography measurements. IEEE J Transl Eng Health Med 4, 2100209
20. Rescio G, Leone A, Siciliano P (2013) Supervised expert system for wearable MEMS accelerometer-based fall detector. J Sens 2013, Article ID 254629, 11 pages
21. Rescio G, Leone A, Siciliano P (2018) Supervised machine learning scheme for electromyography-based pre-fall detection system. Expert Syst Appl 100:95–105
22. Reza AT, Nicoll SB (2010) Characterization of novel photocrosslinked carboxymethylcellulose hydrogels for encapsulation of nucleus pulposus cells. Acta Biomater. 6:179–186
23. Roy N, Saha N, Kitano T, Saha P (2010) Novel hydrogels of PVP–CMC and their swelling effect on viscoelastic properties. J Appl Polym Sci 117(3), 1703–1710
24. Saadiah MA, Samsudin AS (2018) Electrical study on Carboxymethyl Cellulose-Polyvinyl alcohol based bio-polymer blend electrolytes. In: IOP conference series: materials science and engineering, vol 342, no 1. IOP Publishing
25. Saadiah MA, Samsudin AS (2018) Study on ionic conduction of solid bio-polymer hybrid electrolytes based carboxymethyl cellulose (CMC)/polyvinyl alcohol (PVA) doped NH_4NO_3. AIP Conf Proc 2030(1). AIP Publishing
26. Scilingo EP, Gemignani A, Paradiso R, Taccini N, Ghelarducci B, De Rossi D (2005) Performance evaluation of sensing fabrics for monitoring physiological and biomechanical variables. IEEE Trans Inf Technol Biomed 9(3):345–352
27. Siciliano P et al (2009) A networked multisensor system for ambient assisted living application. In: Advances in sensors and interfaces. IWASI, pp 139–143
28. Thomas LV, Arun U, Remya S, Nair PD (2009) A Biodegradable and biocompatible PVA–citric acid polyester with potential applications as matrix for vascular tissue. Eng J Mater Sci Mater Med 20:259–269
29. Wei Y, Liu Y, Peng PCQ (2007) Age-related sarcopenia: an electromyographic and mechanomyographic study. I: ISBS-conference proceedings archive, vol 1, no 1

30. Wu G, Xue S (2018) Portable preimpact fall detector with inertial sensors. IEEE Trans Neural Syst Rehabil Eng 16(2):178–183
31. Yang L et al (2019) Construction of porous sponge-like PVA-CMC-PEG hydrogels with pH-sensitivity via phase separation for wound dressing. Int J Polym Mater Polym Biomater. https://doi.org/10.1080/00914037.2019.1581200