Philosophiae Doctor Doctoral Dissertation
Doctoral Program in Bioengineering and Medical-Surgical Sciences (Cycle XXXI)

A Wearable and Modular System for Neuromuscular System Assessment and Motor Rehabilitation

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Summary

In the last decades, neuromuscular disorders and pathologies replaced viruses, bacteria infections and nutritional deficiencies among the main causes of death and disabilities in industrialized countries. Wearable sensors for the assessment of movement and of the neuromuscular system in either healthy and pathological subjects are gaining increasing attention and are going to be used either in clinical, research or tele-medicine contexts. The monitoring of the human movements requires the simultaneous acquisition of kinematics, dynamics and electrophysiological signals.

The aim of this PhD project is to design, develop and test a modular, wireless, and customizable system for the neuromuscular system assessment and motor rehabilitation.

Chapter 1 introduces the basic needs related to the quantitative neuromuscular assessment and describes the State-of-the-Art regarding the technology for the detection of sEMG signals and for neuromuscular electrical stimulation. An analysis on existing commercially available devices and systems described in the literature is reported. Actual needs and open issues are identified and discussed.

Chapter 2 describes the architecture of the whole system consisting of four different wireless, modular and miniaturized sub-systems allowing to i) acquire biomechanical variables; ii) detect bipolar sEMG signals; ii) detect High-Density sEMG signals, and iv) electrically stimulate muscles. All the modules composing the system (Sensor/Stimulation Units) communicate with a Processing Unit (mobile device PC) and can be worn by the subject, creating a Body Area Network (BAN).

Chapter 3 describes the hardware, firmware and software design, implementation and prototyping of the Sensors and Stimulation Units. The design of bipolar sEMG and biomechanical sub-systems were addressed in parallel. Each module composing these sub-systems allow the acquisition, sampling and transmission to the Processing Unit of either two bipolar sEMG, or raw analog

signals, or conditioned analog signals. In order to satisfy the simultaneous needs for high-quality sEMG recordings and minimum encumbrance, a two-electrode analog front-end for the bipolar sEMG acquisition that does not need a reference electrode, using a minimum number of electrical components was designed.

The HD-sEMG Sensor Unit allows the acquisition of 32 monopolar sEMG signals detected by means of electrode grids or arrays. The high miniaturization of the electronic circuit, together with the absence of connecting cables between the detection and acquisition systems allowed obtaining a high rejection to movement artefacts commonly affecting HD-sEMG signals during dynamic tasks.

The Stimulation Unit allows i) programming a custom stimulation pattern in terms of waveform and timing; ii) triggering the stimulation start/stop through signals detected by means of different Sensor Units.

A multi-platform software, running on the Processing Unit, for the acquisition, processing and visualization of signals from the Sensor Units was designed and implemented. The software architecture was designed to be easily expandable through custom plugins developed for the applications described in Chapter 5.

Chapter 4 describes the tests carried out to characterize the functioning and performances of all modules. All Sensor/Stimulation Units were characterized in terms of signal quality, data throughput, and power consumption. An experimental test demonstrating the overall functionality of each module is reported.

Chapter 5 demonstrates the system flexibility throughout the use of different combination of modules in several scenarios. Each application aims to highlight the main features of the system and its potentiality. i) The HD-sEMG Sensor Units were used during highly dynamic tasks to emphasize the system wearability and robustness to movement artefacts; ii) The bipolar sEMG and HD-sEMG Sensor Units were used in an Augmented Reality biofeedback for the monitoring of the muscular activity; iii) The bipolar sEMG and biomechanical Sensor Units were used to demonstrate the flexibility of the implemented architecture, showing the system potentiality in a tele-medicine scenario; iv) The preliminary design of a hand orthosis controlled by sEMG was presented; v) Two electrical stimulator modules were tested in combination with the biomechanical Sensor Unit in a closed-loop FES-Cycling application.

The overall tests confirmed beyond state-of-the art performances of the system in terms of signal quality, flexibility and adaptability to different scenarios and needs. These features allow the development of new applications with a minimal effort in terms of design and development of new devices and software for the neuromuscular system assessment and motor rehabilitation.