A Wearable Sensor Network for Human Locomotion Data Capture

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Abstract. A new wearable data capture system for gait analysis is being developed. It consists of a pantyhose with embedded conductive yarns interconnecting customized sensing electronic devices that capture inertial and electromyographic signals and sends aggregated information to a personal computer through a wireless link. The use of conductive yarns to build the myoelectric electrodes and the interconnections of the wired sensors network, as well as the topology and functionality of the sensor modules are presented.

Keywords: Human gait analysis, Technical fabrics, Body sensor network.

Introduction

Human motion capture systems have been explored as objective instrumented means to help clinicians detecting and identifying mobility impairments, diagnosing early stages of pathologies that can cause or be caused by them, selecting orthotics or prosthetics, as well as to evaluate the effectiveness of surgical or rehabilitation interventions [1,2].

Different techniques have been developed and proposed to observe and capture locomotion data. Vision based technologies employ cameras to capture the spatial location of targets fastened to the lower limbs. Other systems have been developed based on the acquisition of kinematic variables using accelerometers and gyroscopes fastened to body segments. Additionally, electromyography capture systems employing surface electrodes glued to the skin over muscles locations allow assessing myoelectric activity in the lower limbs. However, current instruments and methods for gait analysis are still expensive and complex, difficult to apply by healthcare staff, difficult to use and uncomfortable for the patient, and require a very high level of expertise for data gathering, analysis and interpretation.

A new wearable locomotion data capture system for gait analysis is being developed with the purpose of measuring human locomotion parameters in a practical and non-invasive way, even for people with strong impairments or disabilities. This system includes, in a single infrastructure, the means to capture inertial and surface electromyographic signals (sEMG) of the lower limbs, and is meant to allow for capturing data for prolonged periods of time of typical movement activities under everyday living conditions, without interference or discomfort to the patient. This

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infrastructure realizes a body sensor network that communicates with a personal computer through a wireless link.

For this purpose, accelerometers, gyroscopes and sEMG sensors are organized in sensor nodes (SN) placed two per thigh and two per leg. The SNs capture typical kinematic quantities of the lower limbs, namely linear and angular movement (in a six-degrees-of-freedom inertial system) of thighs and shanks, as well as sEMG signals of the muscles that are most important for locomotion. The collected data is then sent to a central processing module (CPM) attached to the patient's belt. Wired communication among SNs was selected for being power efficient and embeddable into the fabric unnoticed, since the wires are part of the textile itself.

This paper continues with the description of the textile garment substrate and the technology being used to integrate the myoelectric electrodes in the fabrics. Section 2 addresses issues raised by the use of conductive yarns to build the wired sensor network, namely frequency constrains and reliability. Section 3 presents the architecture of the sensor modules and preliminary data capture results obtained with the first prototypes. Section 4 discusses data processing approaches being considered and section 5 highlights the main conclusions.

1. The Technical Fabrics Substrate

The ProLimb project aims at developing a new electronic instrument to capture human locomotion parameters in the most practical and non-invasive possible way, even for persons with strong impairments or disabilities. It is deployed as a comfortable wearable pair of stockings or pantyhose, incorporating electronic components in the textile fabrics, including wired intercommunication performed by suitable conductive yarns woven into technical textile.

Although several yarns exist that present good electrical properties, specific physical characteristics are required for use in textile production equipment: rigidity, friction and mechanical resistance. Yarns must bend easily, present a low dynamic friction coefficient, and have an acceptable mechanical resistance, since they will be submitted to high traction forces during the production process. Yarns made of pure copper present excellent electrical conductivity, however the resulting fabric, if possible to be produced, results rigid and uncomfortable. Often, these yarns break during production or cut other yarns built in the surrounding structure.

In order to successfully produce fabrics with conductive yarns, and particularly to build the sEMG electrodes, two types presenting relatively good electrical properties have been used: A) spun yarns made with a mixture of a non-natural fiber, like polyester, and stainless steel fibers; B) yarns made with twisted filaments, each one a polymeric filament covered by a very thin layer of conductive material, generally silver.

Previous research [3] has shown that it is possible to measure electric potentials using conductive fibers or yarns instead of conventional (dry and wet) electrodes. The fundamental assumptions of this project demand a fabric made from weft knit due to its inherent properties, such as elasticity, body fit and comfort. There are weft knitting machines that allow for producing fabrics specially conceived for body size, being the seamless technology one of the most used ones. The capabilities of modern textile machines allow designing textile-based electrodes with the most adequate shape, as well choosing the most convenient position. This is achieved by selecting a proper structure, and by inserting and removing the conductive yarns in the fabric, by exchanging with a base yarn or simply by adding the conductive yarn to the base yarn already being used in the fabric's production.

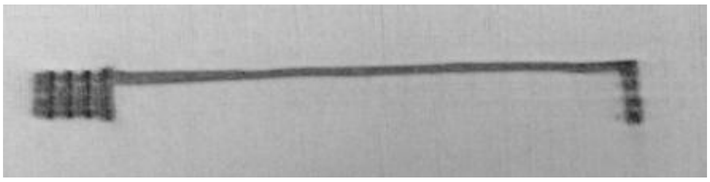

Figure 1. Detail of a sEMG electrode and interconnection line, both embedded in the knitted fabric.

Figure 1 illustrates an electrode and conductive track, both embedded in the knitted fabric. The electrode is seen in the far left side of Figure 1 and presents an area of 1x1 cm^2. The interconnection line comprises six consecutive rows of the same conductive yarn. The vertical line on the far right side of Figure 1 comprises six columns of conductive yarn. Figure 2.a) illustrates how the electrodes are presented in a finished piece of garment. Figure 2.b) shows the waveform of a sEMG signal captured with these electrodes. Comparing to signals obtained with conventional electrodes it was observed that these signals present some additional noise, which can be reduced by improving the electrode/skin contact impedance and afterwards with signal filtering.

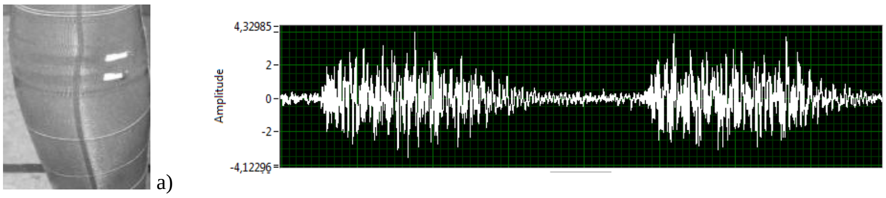

Figure 2. sEMG electrodes placed in a legging and the obtained myoelectric signal.

In order to develop a leggings like garment, with embedded electrodes and conducting tracks for all the sensor nodes, a suitable but complex design of the tracks is necessary to knit the yarns without them crossing each other. This is where the capabilities of the production machines assume a critical importance, justifying the technology that was adopted. Our machine is capable of drawing a pattern where the conductive yarn is carefully selected to be inserted in specific places, thus guarantying that the tracks will not intersect. Other issues will then rise, like isolating the tracks. This matter shall be addressed in a next stage of this project.

2. The Interconnections Infrastructure

The use of conductive yarns in the interconnections raises two issues. On the one hand, the higher impedance (compared with copper conductors) limits communication frequency and, on the other hand, requires that testing facilities are available to evaluate whether the frequency bandwidth has degraded.

The conductive yarn can be modeled as a series R-L impedance. Figure 3 shows the impedance profile of a type A yarn (60 cm length). It can be seen that both resistance and inductance vary with frequency, i. e., $\boldsymbol{Z}(\mathrm{f}) = r(\mathrm{f}) + j2\pi\omega l(\mathrm{f})$. Table 1 shows that impedance also varies when stretching or relaxing the yarn.

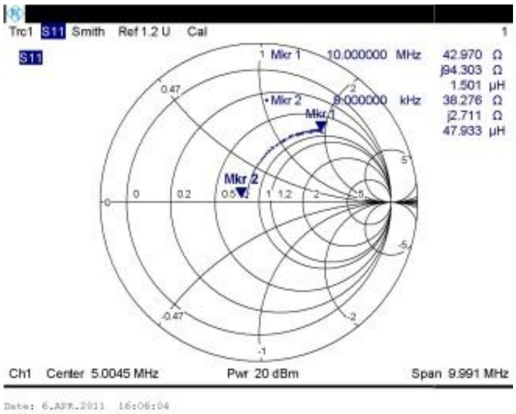

Figure 3. Impedance of a single yarn (60 cm long) as a function of frequency.

This electrical behaviour requires using several yarns in parallel in order to obtain a suitable communication frequency. The yarn impedance together with circuits' output and input capacitances create a π interconnection whose step response presents a rise time given by $t_r \approx 2.2RC + 0.6\sqrt{LC}$.

Table 1 – Yarn per unit length impedance.

Yarn	Relaxed (natural length)		Stretched (1.5 natural length)	
	Ω/cm	nH/cm	Ω/cm	nH/cm
1	0.65	16.4	0.47	6.68
2	6.76	35	4.43	33

A mesh like network is being used to interconnect the sensor nodes (Figure 4). The worst case interconnection impedance is that of the path seen between the CPM, to be placed in the user's belt and one of the SNs placed in the shank. Considering a voltage defined signal, it was found that each track should be made with a minimum of 4 yarns to ensure a transmission frequency of 10 MHz with rise and falling times shorter than 12 ns – this corresponds to a bandwidth of approximately 30 MHz. Nevertheless, tracks with six yarns were adopted.

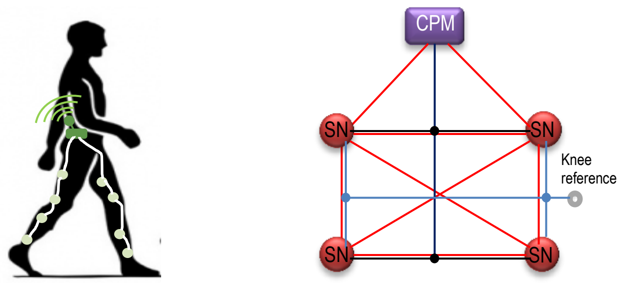

Figure 4. Interconnection topology of the mesh sensors network.

The interconnections reliability raises two issues. One concerns the yarn impedance variability with stretching, washing and aging and the other the quality of the interface between yarn and electronics. A specific interconnections test methodology is being developed to assess the conformity of the link between two SNs and to detect signal integrity violations. This test can be performed on-line or off-line, that is, using mission signals or dedicated pseudo-random signals, respectively [4].

Another critical aspect concerns power management. The SNs may be powered by small batteries or by energy distributed from the CPM to the whole network through the conductive yarns. In the first prototype each sensor has its own power battery, but the final objective is to have each SN harvesting power from the mesh network.

3. Data Acquisition

The prototype sensor network under development comprises one CPM and eight SNs – four per leg. The developed networking protocol allows the number of SNs to scale up to a maximum of 255. Figure 5 illustrates the deployment of one SN connected directly to the CPM module.

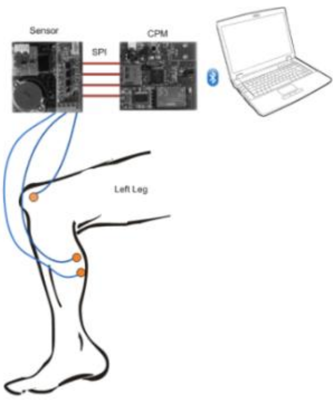

Figure 5. Overview of sensor network deployment.

Although each sensed quantity could have been associated to its own SN, it was decided to integrate each sEMG and inertial signals associated with the same limb segment in one SN for a more accurate time alignment. The CPM gathers information from all the nodes, performs some local processing, and sends aggregated data remotely, immediately or later, via a wireless link to a personal computer for further processing.

The communication among SNs is performed over a single signal line, all links being bidirectional: each SN can simultaneously send data to a neighboring node and receive data from another neighbor. In fact, in each SN transmitting and receiving functions are independent.

In order to prevent communication breakdowns, namely due to accidental yarn breaking, a mesh topology was chosen for the network. It adds redundancy and robustness to the overall network. Also, as wireless-based systems are prone to be affected by interferences, in order to improve data communication reliability **Erro! A origem da referência não foi encontrada.**the CPM module is also equipped with a USB port and a MicroSD card to save and transfer data whenever the wireless communication fails.

Energy efficiency and integration of systems are considered fundamental milestones for the proposed body-area network. The system should last for long periods of operation, especially during prolonged monitoring. Thus, a reactive, energy-efficient routing protocol, described in [5], was developed and adopted for the network data layer. This protocol does not require each node to possess global information about the network, but still ensures that all data communication uses minimum cost paths. It also handles link and node failures gracefully. Simulation results show that this protocol provides better performance than the standard minimum-cost forwarding protocol [6]. Results also indicate higher throughput and less energy dissipation, leading to increased network lifetime.

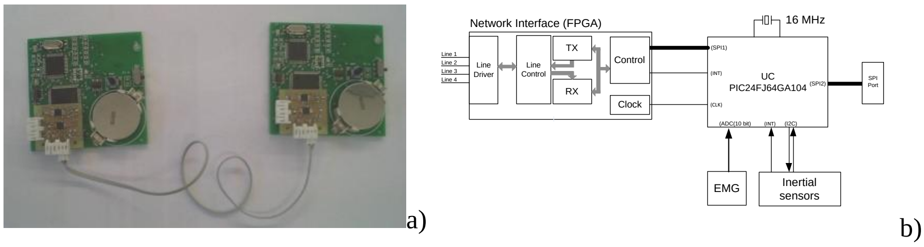

Figure 6. a) Two sensor node prototypes connected to each other. b) Block diagram of the sensor node prototype.

The first hardware prototypes for the SN and the CPM have been designed and fabricated (Figure 6.a) for proof of concept purposes. Figure 6.b) shows the block diagram of a sensor node. The network interface (physical and data link layer) is implemented in a low-power FPGA (Actel AGLN125) operating at 16 MHz. The physical layer employs baseband communication using the NRZI (non-return-to-zero, inverted) line code, with 0 V and 1.5 V signal levels.

The PIC24 16-bit microcontroller used in the SN implements the routing protocol, performs sEMG signal acquisition using the built-in 10-bit A/D converter, and uses the I2C bus to acquire acceleration and angular movement data. Future plans include the miniaturization of the sensor node, so that it can be attached to the garment.

4. Data Processing

Surface EMG signals captured from muscles that are essential for locomotion (quadriceps femoris, biceps femoris, tibialis anterior and gastrocnemius medialis) simultaneously reveal activation patterns for different motor actions, such as stepping, walking, climbing stairs or even sitting down [7].

Figure 7 shows an example of acceleration, angular movement and sEMG signals (of the gastrocnemius muscle) captured with one SN, while the test subject executed three steps, and later transferred from the CPM to a PC through Bluetooth. The sampling frequency of the accelerometer is 50 Hz and that of the sEMG signal is 1 kHz. These bandwidths were chosen assuming a maximum gait frequency of 10 Hz and an EMG frequency bandwidth of 500 Hz.

The muscle activity is clearly identifiable in the sEMG signal. In these preliminary experiments wet electrodes were used. Notice that after instant 6500 ms there is no acceleration or angular activity but still sEMG activity is detected due to muscle contraction in standing position. Notice also the delay between kinematic and sEMG signals. As it can be seen, combining and correlating sEMG with kinematic data allows easier exposition of movement abnormalities, as it would be the case with, e. g.

hemiplegic, Parkinson disease, and cerebral palsy. Signal processing methods include the real-time calculation of the average rectified value and standard root mean square of sEMG signals, providing the onset and offset of muscle activity above a customized preconfigured threshold. Further developments are taking place to include methods to characterize muscle fiber properties and muscle fatigue, which are relevant for rehabilitation and training [8].

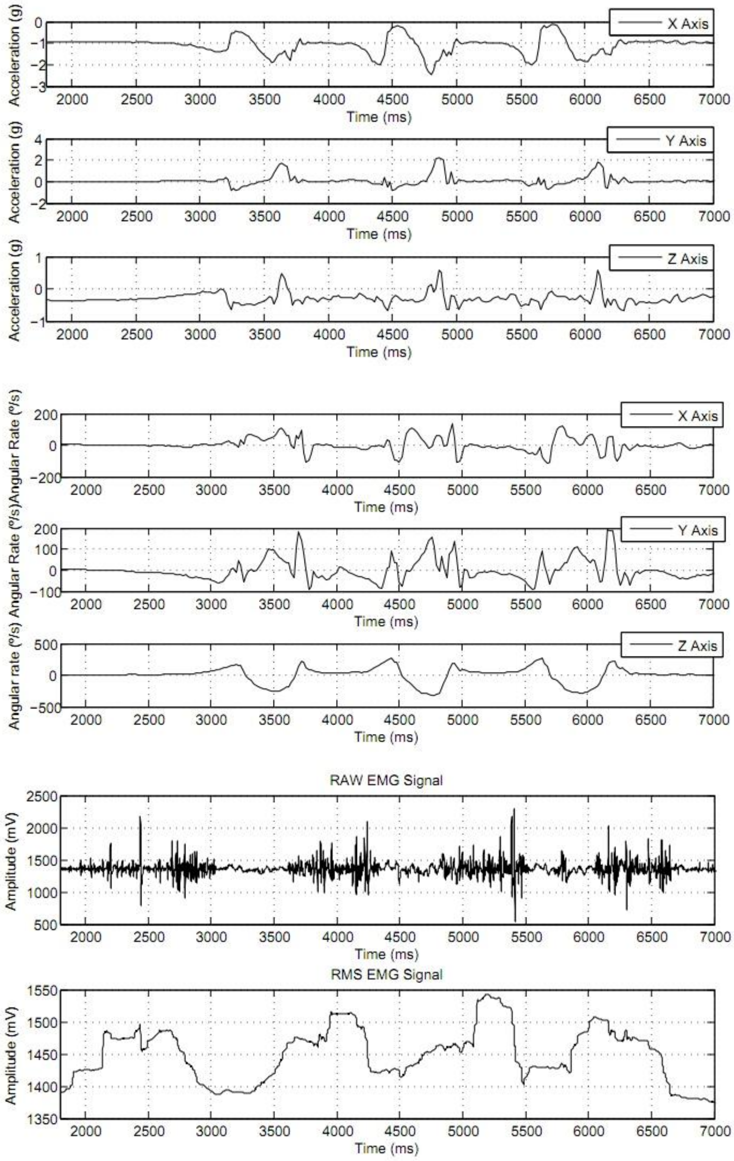

Figure 7. Acceleration, angular movement and sEMG signals captured by a sensor node prototype, corresponding to a subject's march during 3 steps.

5. Conclusions

A wearable body sensor network is being developed to be used as a human locomotion data capture system for gait analysis. This system explores technical fabrics to build a more comfortable and easier to manipulate wearable human locomotion data capture system and conductive yarns to wire-up sensor nodes which capture inertial and surface electromyographic signals. This paper describes how conductive yarns are being used to integrate myoelectric electrodes in the technical fabrics as well as how limitations raised by their electrical characteristics are being addressed to build a reliable wired sensors network. New circuits, communication protocol, and data processing solutions are being developed. The physical and link layers of the communication among sensor nodes have been tested and shown operating as expected. Further work is going-on to develop more compact sensor nodes and signal processing algorithms to extract relevant data for rehabilitation and physiotherapy.

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