ORIGINAL PAPER

Journal of Textile Engineering (2013), Vol. 59, No. 6, 153 – 158

E-Legging for Monitoring the Human Locomotion Patterns

CATARINO André [a], ROCHA Ana Maria [a], ABREU Maria José [a], DEROGARIAN Fardin [b], DA SILVA José [b,c]
FERREIRA João [b,c], TAVARES Vitor [b,c], CORREIA Miguel [b,c], DIAS Ruben [c]

[a] *Centre for Textile Science and Technology, University of Minho, Guimar.es 4800–058, Portugal*
[b] *Faculty of Engineering - FEUP, University of Porto, Portugal*
[c] *INESC TEC, University of Porto, Portugal*

Received 7 January 2013 ; accepted for publication 8 August 2013

Abstract

Human motion capture systems help clinicians to detect and identify mobility impairments, early stages of pathologies and evaluate the effectiveness of surgical or rehabilitation intervention. Although there is a considerable number of solutions presently available, these systems are often expensive, complex, difficult to wear, and uncomfortable for the patient. With the purpose of solving the formerly mentioned problems, a new wearable locomotion data capture system for gait analysis is being developed. This system will allow the measurement of several locomotion-related parameters in a practical and non-invasive way, also reusable, that can be used by patients from light to severe impairments or disabilities.

Key Words : Wearable electronics, E-legging, Body sensor network

1. Introduction

Different techniques have been developed on the recent past to capture and analyze locomotion data. One technology, based on Vision makes use of cameras to capture the spatial location of special marks attached to the lower limbs. Other approaches involve systems based on recording kinematic variables, such as accelerometers and gyroscopes fastened to body segments. Additionally electromyography allows assessing surface myoelectric activity (sEMG) or specified muscles activity in the lower limbs. These systems are expensive and complex, difficult to apply by healthcare staff, difficult to use and uncomfortable for the patient.

This paper presents the work under development in the ProLimb project with the objective of developing a new proposal of an autonomous, real time monitoring wearable body sensor network for human locomotion data capture. This approach is intended to be dressed by the patient, with the adequate comfort, with the purpose of acquiring several human locomotion parameters in a non-invasive way, even for people with strong impairments or disabilities.

The system involves capturing inertial and electromyographic signals of the lower limbs for long time periods involving typical movement activities under everyday living conditions. Capturing sEMG signals of muscles essential for locomotion (quadriceps femoris, biceps femoris, tibialis anterior and gastrocnemius medialis) simultaneously reveals activation patterns for different motor actions, such as stepping, walking, climbing stairs or even sitting down, and can be combined and correlated with the kinematic data to more easily expose movement abnormalities, e. g. hemiplegic, Parkinson disease, and cerebral palsy [1].

The next section describes the body sensor network and its building blocks. The following section addresses the e-legging and its construction issues. Section 4 discusses the problem of using textile conductive yarns as paths for signal and power transmission, and the final section draws some conclusions.

2. E-legging Data System Description

This section briefly describes how the body sensor network is organized. The system is based on a legging with elastic properties, which allows the correct positioning of the sensors and electronics. This legging is equipped with different sensors that involve the measurement of kinematic quantities of the lower limbs, such as linear movement of thighs and shanks, and surface

---

* Corresponding author : E-mail : whiteman@det.uminho.pt, Tel : +351 964 122 020, Fax : +351 253 510 293

electromyography (sEMG) of several muscles (*quadriceps femoris, biceps femoris, tibialis anterior and gastrocnemius medialis*). The sensors communicate by means of sensor nodes (SN) to the central processing module (CPM), which on its turn sends the information by wireless communication. The analogue signals measured with the sensors are immediately converted to digital signals in the sensor nodes (SN), in order to reduce as much as possible the presence of artifacts. These sensor nodes (SN) are placed nearby the sensors and connected to them using special conductive textile yarns, made of polyamide filaments covered with silver. The central processing module (CPM) is placed on the waist, while the sensor nodes are distributed on the garment (Fig. 1). These sensor nodes share paths between them with the purpose of having alternative paths to send the data collected by the sensors. Using this approach, the system can select the most favorable path or have alternatives in case of damage on one of the paths. It is important to note that the sensor nodes (SN) do not communicate wirelessly with the central processing module (CPM), rather than communicate through wires, in this case textile conductive wires that build these paths.

The prototype sensor network under development comprises one CPM and eight SN, although capable to be extended to 255 SNs.

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, immediately or later, via a wireless link to a personal computer for further processing.

The communication among SN is performed over a single signal line. Also, as wireless-based systems are prone to be affected by interferences, in order to improve data communication reliability the CPM module is also equipped with a USB port and a MicroSD card to save and transfer data whenever the wireless communication fails. Fig. 2 illustrates two sensor nodes developed for this project, connected through hard wire during the test period. This first version boards had the approximate dimensions of 50 mm × 50 mm and a height of 25 mm. The final version of these sensor nodes will include all the hardware in one single card, with 30 × 30 mm and 5 to 8 mm height. The weight will be of 30 g.

Energy efficiency and integration of systems are considered fundamental milestones for the proposed body-area network. The system should work for long periods of time, especially during prolonged monitoring. Thus, a reactive, energy-efficient routing protocol, described in [3], 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

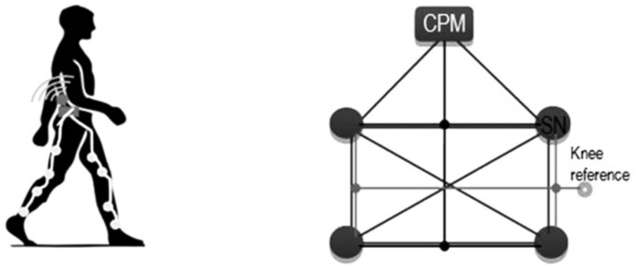

Fig. 1 Interconnection topology of the mesh sensors network.

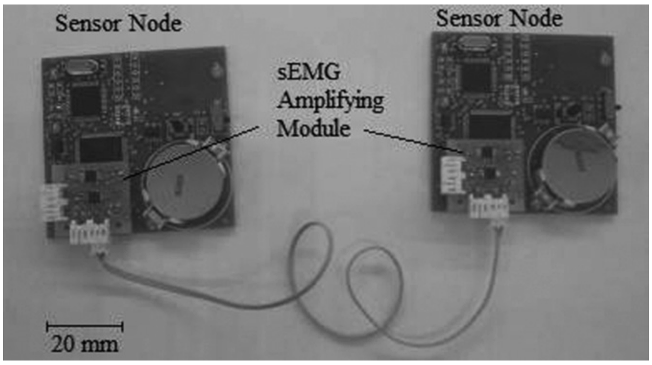

Fig. 2 Two sensor node prototypes connected to each other.

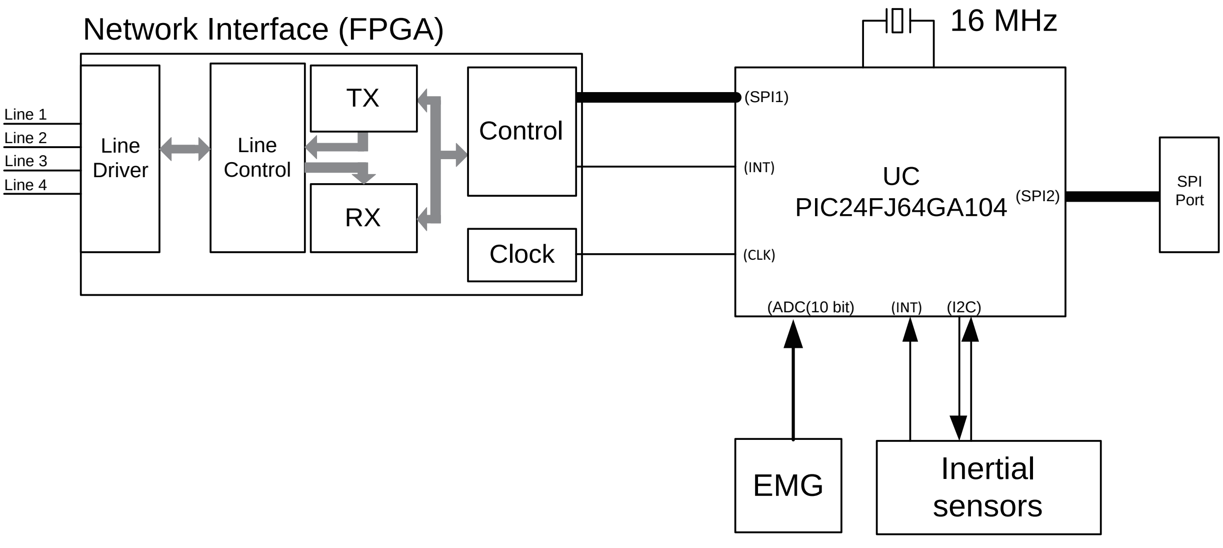

Fig. 3 Block diagram of the sensor node prototype.

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 [4]. Results also indicate higher throughput and less energy dissipation, leading to increased network lifetime. Fig. 2 illustrates the sensor nodes.

The first hardware prototypes for the SN and the CPM have been designed and fabricated (Fig. 3), for proof of concept purposes. Fig. 3 shows the block diagram of a sensor node (SN). 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. Future plans include the miniaturization of the sensor node, so that it can be attached to the garment.

The PIC24 16-bit microcontroller 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.

Fig. 4 shows an example of accelerometer signal captured with this setup while the test subject executed three steps, and transferred from the CPM to a PC through Bluetooth.

Signal processing methods will include the real-time calculation of the average rectified value (AVR) 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 [5].

3. Textile based sensors in the E-legging

A wearable garment meant to be comfortable implies an adequate combination of materials, compression effect and preferably with electronic components incorporated in the textile and interconnected with data and power tracks, if possible made with conductive yarns embedded in the fabrics. This solution would allow an easy to dress piece of garment, reusable and usual methods for cleaning and maintenance.

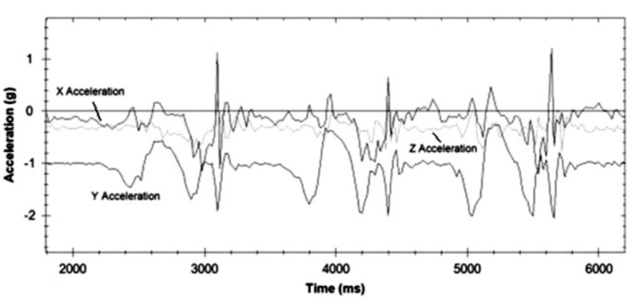

Fig. 4 Accelerometer signal captured by the sensor node prototype, corresponding to muscle activity during 3 steps.

Regarding the sensors to be embedded in the E-legging, the biopotential parameters are the ones that are more successful in terms of reliability. For that reason sEMG electrodes were embedded in the knitted fabric, making use of the technology available on weft knitting. Although several yarns exist that present good electrical properties, specific physical characteristics are required in order to being used in textile production equipment: rigidity, friction and mechanical resistance. Yarns must bent easily, present a low dynamic friction coefficient, and have an acceptable mechanical resistance, since they will be submitted to high traction forces during the knitting production process.

As mentioned above, previous research [6] has shown that it is possible to measure electric potentials using electrically conductive fibers or yarns instead of conventional electrodes, being possible to measure biopotentials using dry or wet textile based electrodes. Regarding the raw material to be used as conductive element, yarns made of pure copper present excellent electrical conductivity and are cost effective, however the resulting fabric, if possible to be produced, usually results rigid and uncomfortable. Moreover, these yarns break during production or cut the other yarns built in the surrounding structure, which constitute the support of the electrodes. Thus, these yarns may not be used directly in knitted fabric, unless they are covered with a smoother surface that at the same time offers a mechanical behavior more adjusted to weft knitting.

In order to successfully produce fabrics with conductive yarns, and particularly to build textile sensors, namely sEMG electrodes, two types presenting relatively good electrical properties have been used: A) spun yarns with a mixture of polyester, and stainless steel fibers with linear resistances of 350 Ohm/m; B) and yarns made with twisted filaments, each one a polymeric filament covered with silver with linear resistances of about 30-40 Ohm/m.

The fundamental assumptions of this project demand for 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 producing fabrics specially conceived for body size, being the seamless technology one of the most used ones. The capabilities of modern textile machines also permit 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. The knitting machine used has one single needle system, gauge E28, it is a full jacquard machine with eight feeding and cam systems. The yarns are supplied into the knitting zone with storage feeders and electronic feeders whenever elastane is used. The yarns are selected through one of seven yarn guides of each stripper and cut when not needed.

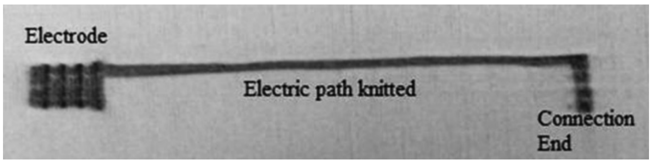

Fig. 5 Detail of an electrode (left side) and its track for signal transport into the sensor node (center and right).

Fig. 5 illustrates an electrode and conductive track, both embedded in the knitted fabric. The electrode can be seen in far left side of Fig. 5 and presents an area of 1 × 1 cm^2, knitted with a special structure that improves the contact with skin and thus reduces the skin to electrode impedance. The interconnection line comprises six consecutive rows of the same conductive yarn. The vertical line on the far right side of Fig. 5 is also made with six columns of conductive yarn.

Fig. 6 illustrates how the electrodes are presented in a finished piece of garment and a Fig. 7 shows the resulting waveform for a sEMG signal captured with these electrodes.

Comparing to the 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. There is a similar behavior between the signal patterns obtained with conventional and textile electrodes [6].

In order to develop a legging-like garment, with embedded electrodes and conducting tracks for all the sensor nodes, a suitable but complex design of the tracks is necessary in order to knit the yarns without 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.

Fig. 8 illustrates a version of the program used to produce the tracks and electrodes. Although the resulting tube represents a 3D shape, it is necessary to transform the legging into a 2D shape, considering that the first column of pixels at the left side of the drawing will be the same as the column that is more far away, on the right side. The number of columns in the drawing represents the number of needles in the knitting machine, in this case 1152 needles. The letter A represents an area where two pairs of electrodes are knitted, and B shows where the hip will be. The two coarser light grey vertical lines that are nearby B are the place where the tube will be cut and later sewed in order to produce the two legs. Several lines are displayed in Fig. 8. Regarding the horizontal stripes, the thinner ones represent fixed distances in order to better place the electrodes during design and also as orientation for the user. The coarser horizontal bands coincide with the regions where the electrodes are knitted, which demand for a

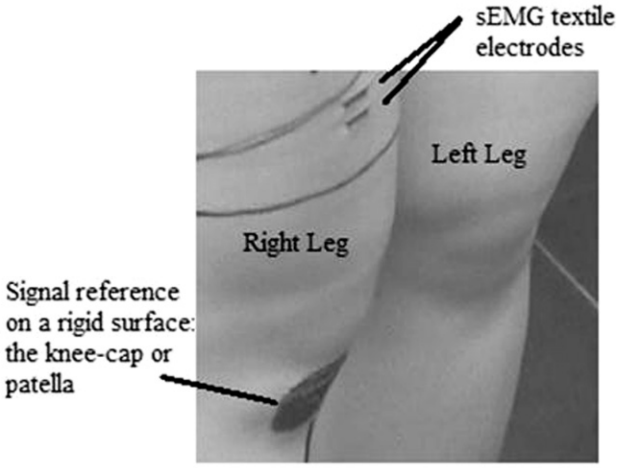

Fig. 6 sEMG electrodes placed in a legging and the obtained myoelectric signal.

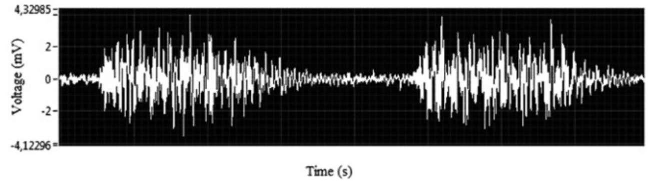

Fig. 7 sEMG signal obtained with the electrodes presented in Fig. 6.

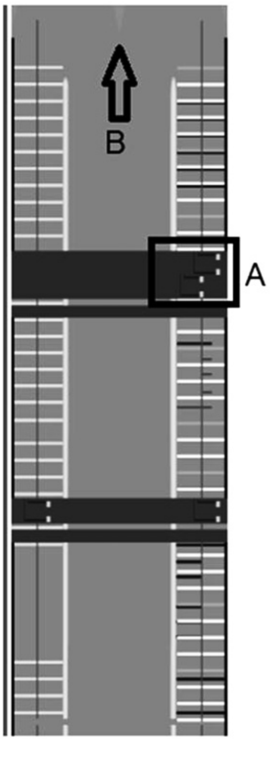

Fig. 8 Drawing of the e-legging, using the knitting machine's CAD system.

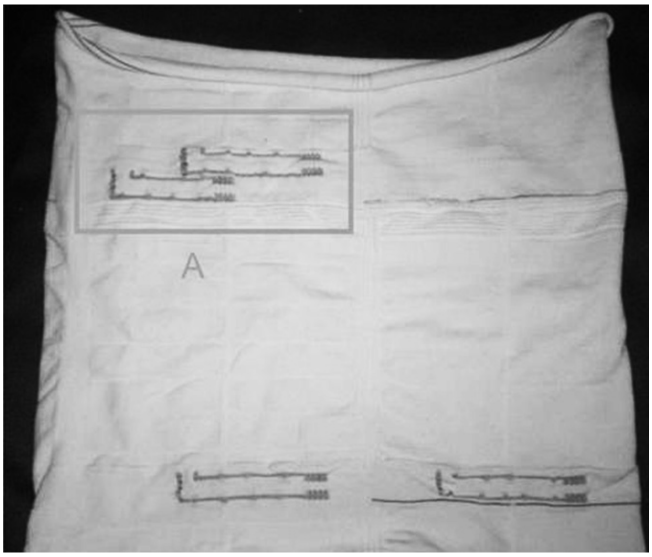

Fig. 9　Fabric produced based on the drawing made on the knitting machine's CAD system.

more elastic and stronger structure, able to better sustain the electrodes in place. The vertical lines are made with different colors and are used both to provide an orientation to the user for a correct positioning of the electrodes. Fig. 9 illustrates the resulting fabric, where one can observe the electrodes and corresponding tracks in region A. The different loop length on different zones like A, the knitted structure and elastane provide the means for a correct legging adjustment to user's body.

This version does not consider the interconnection paths between SNs, since it is under development.

Another issue of major concern is the compression. The compression is obtained by combining the raw material, the presence of elastane, the structure that is knitted, and the loop length. The compression needs to high enough to maintain the sensors in place, but not too high in order to avoid discomfort and difficulty to dress the e-legging. Studies are being conducted with the purpose of determining the proper compression to satisfy both conditions.

4. The interconnection paths made with conductive textile yarns

The use of conductive yarns in the interconnections raises an important issue: the higher impedance (comparing to pure copper conductors) will limit the communication frequency, and consequently the available bandwidth. The conductive yarn can be modeled as series RL impedance. It can be seen that both resistance and inductance vary with frequency, i.e. $Z = f(\mathrm{f}) = r(\mathrm{f}) + j2\pi\omega l(\mathrm{f})$. Table 1 shows that impedance also varies when stretching or relaxing the yarn. The yarns presented are a 235 dtex/f34 polymer covered with silver as number 1 and a 200 dtex yarn spun with polyester and stainless steel as number 2.

Table 1　Thickness and density of onion sheet.

Yarn	Relaxed		Stretched 50%	
	Ω/cm	nH/cm	Ω/cm	nH/cm
1	0.65	16.4	0.47	6.68
2	6.76	35	4.43	33

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

A mesh like network is being used for the interconnected sensor nodes. The worst case interconnection impedance is that of the path between the central processing unit (CPM), to be placed in the user's belt, and one of the SN 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. Nevertheless, tracks with six yarns were adopted.

The interconnections reliability raises two issues. One concerns the yarn impedance variability 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 SN, 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 [6].

Another critical aspect concerns power management. SN may be powered by small batteries, or power may be distributed to the whole network by the CPM 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.

5. Conclusions

This paper presented a research that is being developed with the objective of proposing a e-legging for monitoring lower limb movements and help technicians to assess the severity of diseases or accidents on human locomotion. Several issues were presented like the body sensor network, which will be built using conductive yarn, the electrodes embedded in the knitted fabric, as well as the communication and energy path made with textile conductive yarn. Generally, one can say that it is possible to transmit signal at the adequate time rate and measure muscle activity with textile based sensors. Several improvements are currently under development in order to achieve the most flexible and reliable system.

6. Acknowledgements

The authors wish to thank National Funding Agency (FCT) by financing this project PTDC/ EEA–ELC/ 103683/ 2008.

References

[1] Iezzoni L, O'Day B (2005) More than Ramps: A Guide to Improving Health Care Quality and Access for People With Disabilities, Oxford University Press, Oxford

[2] Yuting, Z, Markovic S, Sapir L, Wagenaar R, Little T (2011) 5th International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth), 370–373

[3] Derogarian F, Ferreira J, Tavares V (2011) SENSORCOMM 2011, The Fifth International Conference on Sensor Technologies and Applications, 85–90

[4] Ye F, Chen A, Lu S, Zhang L (2001) Proceedings of the Tenth International Conference on Computer Communications and Networks, 304–309

[5] Vila-Chã C (2012) Electrophysiological assessment of neuromuscular adaptations to training, PhD thesis in Biomedical engineering, University of Porto, Faculty of Engineering, http://hdl.handle.net/10198/6908

[6] Barros L, Dias M, Carvalho H, Catarino A (2011) 4º Congresso Nacional de Biomecânica, Coimbra, Portugal, 671-676

[7] Zambrano A, da Silva J (2012) 18th International Mixed-Signals, Sensors, and Systems Test Workshop, 79–84