Wearable Wireless Inertial Sensors for Long-Time Monitoring of Specific Motor Symptoms in Parkinson's Disease

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Abstract: It is proposed an electronic system for the long-time monitoring of specific motor symptoms in patients affected by Parkinson's Disease while being at home and making their usual daily activity. The system is made of a network of non-invasive wireless inertial sensors fixed on the patient body. The muscles activity is contemporarily analysed through the integration of a circuit for the surface electromyography. Post-processing algorithms quantify movements in terms of amplitude and power spectrum. Data are electronically elaborated and wireless transmitted to a receiver in the patient home, to be accessed remotely by doctors. The challenge is the automatic distinction between specific parkinsonian symptoms including resting tremor and freezing of gait and patient's voluntary movements made in daily life. To the aim, the contemporarily analysis of muscle activity becomes necessary in specific situations, as in the case of freezing of gait, where accelerometers signals may be misleading. Goal of this research is the comprehension of all the possible environmental and individual factors which favor worsening of gait disorders during the patient daily life and the customization of the drug therapy, aiming to preventing catastrophic events such as falls. Results shown here refer to upper limb tremor and freezing of gait.

1 INTRODUCTION

The analysis of human movement is of major interest since when, in the last decade, integrated electronic technologies have finally allowed the detection, sort and quantification of kinetic components using the fusion of inertial sensors. Integrated inertial sensor chips are today commercially available with a few dollars cost. They include accelerometers and gyroscopes, an embedded Micro-Controller Unit (MCU), a non-volatile memory, a transmission module, in addition to a battery. Some products devoted to sport training and rehabilitation and consisting in one sensor with a dedicated software are commercial. On the contrary, nothing is available on the market for the long-time home monitoring of the Parkinson's Disease (PD) motor symptoms, although in the last few years research groups have published papers on related topics (Patel, 2009; Pantelopoulos, 2010; Zwartjes, 2010; Patel, 2010; Bächlin, 2010; Schepers, 2010; Gouwanda, 2011; Becq, 2011; Taraldsen, 2011; Niazmand, 2011; Sama, 2012; Caldara, 2014). PD is a chronic neurodegenerative disorder affecting about 2% of the worldwide population over 70. Typical PD motor symptoms include resting tremor, muscle rigidity and bradykinesia (slowness of movements) (Berardelli, 2001). In PD, motor symptoms manifest when dopaminergic denervation induces functional abnormalities in the basal ganglia motor circuits which in turn drives altered motor inputs in cortical motor areas. Among PD motor symptoms, tremor is one the most important and frequently observed in PD patients. It typically appears in only a single arm or leg, becoming bilateral later. Frequency of PD tremor is typically between ~ 4 and ~ 6 hertz. Tremor crucially worsens when PD patients are not under dopaminergic therapy (OFF state), whereas it improves when patients receive their dopaminergic therapy (ON state). Hence, the long-term monitoring of tremor amplitude may help the overall clinical evaluation of PD patients and improve the therapeutic strategies.

Gait disorders frequently occur in advanced PD patients and consist of small shuffling steps, reduced stride length and walking speed during free ambulation while double support duration and

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cadence rate are increased. Freezing of gait (FOG) is typically a transient episode, lasting less than a minute, in which gait is halted and the patient complains that feet are glued to the ground. FOG can be experienced in narrow or tight quarters such as a doorway or in the presence of an obstacle along the path and in stressful situations such as when the telephone or the doorbell rings or when the elevator door opens. During FOG, PD patients undergo trunk fluctuations back and forth, move hazardously the body mass center and load in the forefoot regions, sometimes resulting in stability loss. At an advanced stage of the disease, FOG leads to falls in many instances, in fact, about the 45% of falls of PD patients occurs forward, due to trunk fluctuations back and forth. Very recently, some authors have proposed a IMU based-system which gives an alarm feedback to assistants or relatives in the case of patient's fall (Cabestany, 2013). There are some evidences that audio stimulations may help the patient's to reduce the tendency to undergo FOG. Auditory stimulations are commonly rhythmic cues, sometimes embedded in music, set at or slightly above the patient's usual cadence. An IMU based-system has been recently proposed, which gives an audio feedback to the patient in the case of FOG, to help the subject to overcome the involuntary block and prevent the risk of falls (Cabestany, 2013; Sama, 2013; Rodríguez-Martín, 2013). It is evident that the correct identification of the FOG is crucial, since in this case any misevaluation of the patient behavior can be deleterious. For all these reasons, first of all it is of most relevance to monitor FOG events, unequivocally distinguishing them from any kind of voluntary movement, quantifying the daily frequency, identifying the environmental and the individual conditions which lead that specific patient to manifest FOG, finding correlations with the drug administration and, finally, trying to prevent catastrophic events such as falls. Optimized drug therapy can be very effective, especially at an early stage of the disease. However, drug therapy optimization is difficult since the response of PD patients to drugs may vary according to a number of factors. 24 hours monitoring is the only way to optimize the therapy and prevent worsening of symptoms or catastrophic accidents (as falls) due to incomplete clinical analysis of symptoms during the day and a consequent not-optimized therapy. On the other hand, hospitalization is really exceptional today, due to finance cuts imposed by governments to national health services. The sensing system proposed here has the final topic of making possible the long-time monitoring of specific motor symptoms of PD while the patient is at home. The system is composed by a network of several biosensors disseminated on the patient body which embed units for the direct non-invasive measurement of the muscles activity (*surface electromyography, S-EMG*). It is being used in the real-time detection and analysis of PD motor symptoms. The biosensors are wearable and not invasive, easy to use and do not need any technical skill from the patient side. Clinical advantage lies in the optimization and customization of the drug therapy for each individual patient. Social benefits lye in a better quality of life of the patient and the assisting family.

2 THE SYSTEM

The sensors network system presented in this paper is designed for both collecting movement signals and preliminarily analysing them in real-time. This system is a flexible platform useful for collecting data via a triaxial accelerometer, a gyroscope and a magnetometer, with the possibility to incorporate other information sources in real-time, as the S-EMG which detects the muscle activity. The Flash memory stores all inertial data and a Bluetooth module sends information to other external devices. The system allows *pattern reconstruction* of the kinetic components of movements, discriminates between *voluntary and involuntary* movements, selects only those associated to specific PD symptoms, reconstructs and, finally, quantifies their amplitude and frequency. The great challenge of this work is the automatic association of electronic signals to specific *PD symptoms*, filtering all the signals deriving from voluntary movements. In this work engineers and neurologists are involved contemporarily. The engineers develop the hardware/software system, while the doctors carry on the clinical research. Patients are clinically evaluated and movements classified with standard protocols and compared with voluntary movements of healthy subjects. This step allows identifying specific patterns correlated to PD symptoms and is fundamental for the system calibration. On their side, engineers optimize the hardware (type of inertial sensors, protocol of the wireless communication, entity of the data storage, power consumption, battery, integration of the EMG, other) and develop algorithms for data acquisition and processing. Electrical signals from biosensors are compared with clinical observations, in order to achieve the automatic recognition of the disordered

movements associated to the disease. The experiments with patients are performed in the hospital. A few patients have been studied up to date, but many others will be studied in the next, to make reliable the system. In fact, the final goal of the work is using the system at the patient home, far from the visual inspection of doctors, and enabling doctors to access data remotely by a PC. The real challenge of the research is in the automatic distinction of voluntary and involuntary movements, passing through noise filtering, artefacts filtering, movement reconstruction and the identification of kinematic components of the PD with quantification of tremors (amplitude and frequency) and FOG (duration, trunk fluctuations with associated fall risk). The complete hard-system, represented in Fig.1, is composed by a network of 5 body sensors. Two of them are positioned on the thighs, two on the shins and the last one on the chest. All the sensors are controlled by a PC trough the LabView software. Signals coming from the sensors are acquired through a PC and then they are post-processed and displayed with MATLAB.

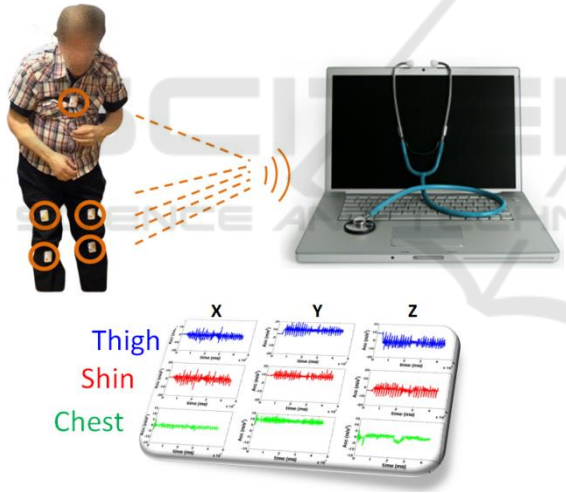

Figure 1: Sketch of the sensing system.

3 EXPERIMENTS

PD patients were recruited at the Movement Disorders outpatient clinic of the Department of Neurology and Psychiatry, Sapienza University of Rome, Italy. All the experiments involving patients have been performed at the Laboratory of Human Motor Control at the same Department. Experiments with patients are still at an early stage, in the sense that only a few patients have been studied to date, and only limb tremors and freezing of gate have been investigated. Nevertheless, although results are preliminary, the system demonstrated its potentiality and versatility in recognizing and quantifying specific disorders associated to the disease.

3.1 Tremor

In this paragraph traces related to tremor are studied. Patient A had an asymmetric symptomatology, in fact while the left hand exhibited a tremor, the right hand did not. A sensor was positioned on the right forearm while another was position on the left one.

The patient was asked to walk for 5" and then turn, for three times. Fig.2a and Fig.2b report the magnitude of resultant accelerations detected while walking. As one can see, the two traces are very different. In fact, in the right sensor it is present only the signal related to arm oscillations during the steps and the turnings, while in the left sensor the oscillation during the steps is reduced with respect to the right one since the left arm was stuck along the body and only the tremor is present.

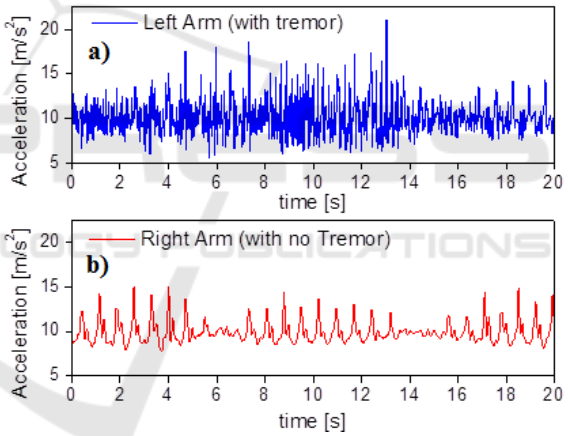

Figure 2: Signals from the y-axis accelerometer while walking: a) Left Arm (tremor), b) Right Arm (no tremor).

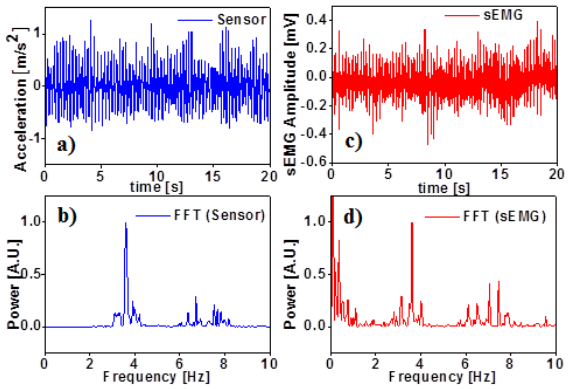

Figure 3: Tremor signals from the accelerometer and S-EMG while sitting a) Tremor; b) FFT; c) sEMG; d) FFT.

Then, the patient was asked to sit with the arms resting on the leg. In this way, the tremor amplitude was detected without any contribution from gait. Results are shown in Fig.3a. The fast Fourier transform (FFT) of the acceleration trace gave its power spectrum, highlighting the expected tremor frequency component around 3.8 Hz (Fig.3b).

The muscle activity during tremor was also detected positioning the S-EMG electrodes on the left arm. As one can see in Fig.3c and 3d the EMG signal and its FFT are of course compatible with the accelerometer traces (the low frequency component in the FFT of the S-EMG trace is not meaningful).

3.2 Freezing of Gait (FOG)

Patients have been asked to execute simple exercises, as the Timed Up and Go test (TUG).

TUG is a simple test used to assess a person's mobility and requires both static and dynamic balance. During the test, the person is expected to wear their regular footwear and use any mobility aids that they would normally require. Patient A was asked to execute the TUG. The exercise included the following movements (see Fig.4): 1) standing-up; 2) motion-less; 3) walking a few meters; 4) turning; 5) walking; 6) sitting down. An obstacle was positioned on the floor, along the walking trajectory.

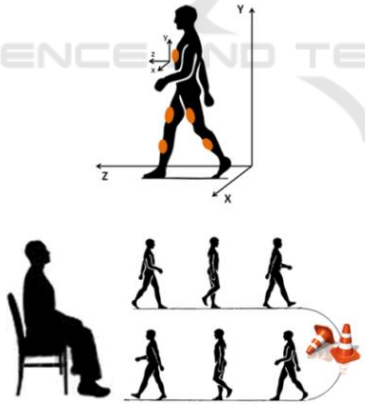

Figure 4: Sketch of the axis orientation and TUG.

Referring to Fig. 4, the patient walking trajectory is along the z-axis, the y-axis being along gravity and the x axis perpendicular to the walking direction, on the same plane.

The main scope of this experiment was the detection of the FOG and therefore results will be discussed in the following showing clearly the occurrence of such an event while walking.

Patient A was asked to execute the TUG. Fig.5a displays traces relative to the linear acceleration

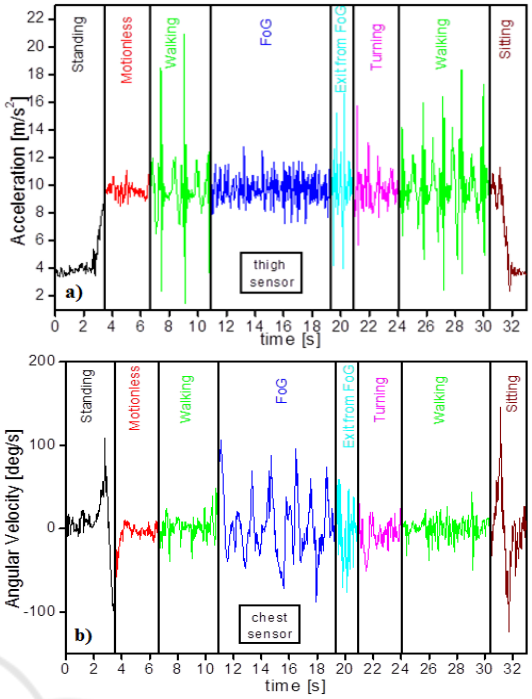

Figure 5: a) acceleration along the y-axis revealed by the sensor on the right thigh; b) angular velocity around the x axis revealed by the sensor on the chest.

along the y-axis revealed by the sensor positioned on the right thigh. Fig.5b displays the signal from the gyroscope of the sensor positioned on the chest and refers to the angular velocity of the trunk around the x axis. The patient starts his TUG from the sitting position. In this condition, gravity is not entirely projected on the y-axis of the thigh sensor, in fact in Fig.5a the y-axis acceleration is lower than 9 m/s^2.

Traces outlines that:

1. STANDING-UP: When the patient stands up, gravity becomes entirely projected on the y-axis of the thigh sensor. This can be seen looking at the black line of Fig.5a, which raises to 9 m/s^2 after 3" approximately from the beginning of the TUG. While standing-up from the sitting position, also the gyroscope positioned on the chest clearly detects the body movement (Fig.5b) and changes its value.
2. MOTIONLESS: the patient is asked to rest for a few seconds, to assess its postural stability (which looks quite upright, corresponding to 0 deg/s from the chest gyroscope and 9 m/s2 from the thigh accelerometer)
3. WALKING: the postural stability keeps on while walking, in fact the angular velocity from the chest sensor is still around zero. The patient makes just three steps starting with the right leg, as clearly shown in Fig.6a, where the very first instants of the green trace indicate that the leg is moved up

(acceleration become greater than gravity) and then moved down for three times. The highest peaks are inertial impacts when the foot falls on the ground.

4. FOG: At a certain point of his walk, the patient encounters the obstacle and experiments a freezing of gait lasting several seconds. In that time interval the patient makes many attempts to walk, oscillating the body essentially back and forth and loading the fore-toes, but he does not make any step as if feet got glued to the ground. This can be seen in Fig.5a, where the characteristic peaks related to steps are absent, but a dense succession of smaller peaks add to the y-axis acceleration trace, whose mean value keeps around 9 m/s^2. At the same time, the chest sensor detects many changes of the angular velocity around the x-axis (perpendicular to the ground, along the walking direction) related to trunk fluctuations (see Fig.5b). These traces are typical of a FoG event, which, in this experiment, was favored by the presence of an obstacle along the walking trajectory.

It is interesting to compare the traces relative to "FOG", to those relative to "motionless", which is voluntary. Signals from the accelerometer are similar, whereas signals from the gyroscope are quite different. Therefore, just looking at the traces from the linear accelerometer it is not possible to distinguish the involuntary FOG from the voluntary resting position. On the contrary, the measurement of angular velocity around the x-axis is a clear indication of trunk fluctuations due to FOG.

We wish to recall that FOG is often the cause of falls, and its definitive identification is absolutely necessary. To the aim, traces from the S-EMG are being analyzed and results will be presented at the conference.

5. OUT OF FoG: Finally, after about eight seconds, the patient makes a step and the signal from the y-accelerometer on the thigh changes its value and exhibits a shape related to a step. At the same time, trunk fluctuations tend to stop.

6. TURNING: the patient turns leftward, with a few small steps. Nothing relevant on the trace.

7. WALKING: the second walking is similar to the first one.

8. SITTING DOWN: The traces relative to sitting-down are complementary to those relative to standing-up. Nothing relevant on the trace.

4 CONCLUSIONS

It was proposed an electronic system for the long-time monitoring of specific motor symptoms of patients affected by Parkinson's Disease while being at home and making their usual daily activity.

The system is made of a network of non-invasive wireless inertial sensors fixed on the patient body. The muscles activity is contemporarily analysed through the integration of a circuit for the surface electromyography. Post-processing algorithms quantify movements in terms of amplitude and power spectrum.

A few patients of the Movement Disorders outpatient clinic of the Department of Neurology and Psychiatry, Sapienza University of Rome were studied up to date, and asymmetric tremor and freezing of gait were analysed.

As a result, starting from signals from the accelerometers signals and the surface-electromyography tremor was unequivocally distinguished respect to voluntary movements, and its amplitude was quantified; the power spectrum revealed a tremor frequency around 3.8 Hz. On the contrary, the freezing of gait was distinguished only thanks to the detection of a gyroscope positioned on the patient chest, since the accelerometers were not able to distinguish unequivocally between voluntary resting in the upright position and the involuntary gait block.

At the conference, results relative to the automatic recognition of the freezing of gait will be presented, obtained on a statistically meaningful number of patients.

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