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Using Wearable Sensor Systems for Objective Assessment of Parkinson's Disease

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***Abstract* – This paper presents a novel wearable sensor system based on the integration of miniaturised IMUs for fine hand movement analysis. The system, named SensHand V1, is composed of full 9-axis inertial sensors, placed on the fingers and wrist, which are managed by a cortex-M3 microcontroller. The acquired data are sent to a data logger through the use of Bluetooth communication. In this paper, the system is used for the objective diagnosis of Parkinson's disease, which is commonly assessed by neurologists through visual examination of motor tasks and semi-quantitative rating scales. Here, these motor tasks are also assessed using the SensHand V1, and then compared with the subjective metrics. Results demonstrate that the system is adequate to support neurologists in diagnostic procedures and allows for an objective evaluation of the disease.**

I. INTRODUCTION

Parkinson's disease (PD) is the second most common neurodegenerative disorder. It presents with characteristic and disabling motor symptoms, such as tremors, muscular rigidity, postural instability, bradykinesia and hypokinesia, caused by a loss of brain dopaminergic neurons. Approximately one million Americans and more than 1.2 million Europeans [1] suffer from it, with this number forecasted to double by 2030 [2]. Parkinson's has an estimated annual cost for the European community of about 13.9 billion euro [1].

Currently, for the assessment of movement disorders, the neurologist uses a visual examination of motor tasks and semi-quantitative rating scales, such as the Hoehn-Yahr (HY) Scale [3] and the Movement Disorder Society - Unified Parkinson's Disease Rating Scale (MDS-UPDRS) [4]. Previous studies [5–6] demonstrated a five years latency time between the beginning of the process and the appearance of the typical symptoms of PD, which is diagnosed when the neurodegenerative process has yet compromised wide brain areas. Moreover, the best objective testing for PD consists of specific brain scanning techniques (e.g. SPECT DATSCAN) that can measure the dopamine system and brain metabolism. However, these examinations are invasive, very expensive and require specialised imaging centres and specially trained and dedicated staff.

The opportunity to objectify and to hasten the diagnostic process could be a major milestone in the management of the disease: 1) minimising both intra-rater and inter-rater variability due to neurologist subjectivity; 2) slowing down the disease progression, with a greater effectiveness in addressing the biochemical imbalance that determines the illness and its worsening [7]; 3) reducing the economic impact of the disease; and 4) favouring a better Quality of Life (QoL) for patients for longer period of time.

The system proposed in the paper, called SensHand V1, provides an objective and quantitative analysis of the movements of the upper limbs through an inertial measurement unit (IMU) which is low-cost, low-power, non-invasive, small in size, lightweight, wireless and easy to use. Such a system can be used to support early clinical diagnosis, as well as to periodically monitor patients' motor performances over time, providing detailed information for each patient about disease course and therapy effectiveness.

Prototypes and commercial products based on wearable devices are mainly glove-shaped [8–9], developed to faithfully reproduce the movement of the hand and are generally based on flex sensors [10], inertial sensors [11–13] or their combination. Applications vary from virtual reality management to biomedical applications, including the study of PD and assistance for patients with movement disorders [14]. However, the proposed solutions show limitations, especially in size, wearability, modularity and adaptability. The technological advantages of the SensHand V1 [15–16] can be synthesised in the following properties.

•Physical properties: 1) miniaturisation, integration and

reduced weight for full wearability; 2) independence from the physical constitution of the subject wearing it; 3) independence of artefacts caused by the movement; 4) wireless communication.
•Properties of measurement: 1) a complete inertial system; 2) repeatability and endurance of the sensors not affected by deterioration problems or drift conditions; 3) infrequent calibration required thanks to an intrinsic compensation typical of 3-axial systems.
•Additional properties: low-cost components, low-power consumption.

II. INSTRUMENTS

The SensHand V1 wearable device (Fig. 1) was developed using inertial sensors (gyroscopes and accelerometers) integrated into four INEMO-M1 boards (size: 4x5x1.1 mm), based on MEMS sensors and equipped with dedicated STM32F103RE microcontrollers (ARM 32-bit Cortex™-M3 CPU, STMicroelectronics, Italy).

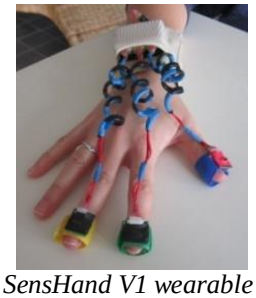

Fig. 1. SensHand V1 wearable device.

Each module includes LSM303DLHC (6-axis geomagnetic module, dynamically user-selectable full scale acceleration range of ±2 g/±4 g/±8 g/±16 g and a magnetic field full-scale of ±1.3÷±8.1 gauss) and L3G4200D (3-axis digital gyroscope, user-selectable angular rate full-scale of ±250/±500/±2000 deg/s), I^2C digital output. As a result, each board is able to measure metrics and parameters related to the human hand by means of the complete 9-axis sensor system on board, guaranteeing a three-dimensional mapping of motion. Module coordination and data synchronisation are implemented through the Controller Area Network (CAN) standard. The module, placed on the forearm, is the coordinator of the system, collecting data at frequency of 100 Hz (f_s) and transmitting them towards a generic control station through a wireless communication based on the ESD 210 (Parani) Bluetooth serial device. The other modules are positioned on the distal phalanges of the thumb, index and middle fingers. A small, rechargeable and light polymer lithium battery, integrated into the coordinator module, supplies the system.

A. Sensor Unit Calibration

The sensor unit is adequately calibrated, both in static and dynamic states, in order to calculate the offset and sensitivity that affect measurements and correct them. For gyroscope calibration, output mean value ω_i is calculated in static conditions and represents the gyroscope offsets on *i*-axis (O_ω_i). Calibrated data from the gyroscopes are computed as follows:

$$\omega_i = \omega_i - O\_\omega_i \ (i = x, y, z) \quad (1)$$

Calibration of the accelerometers requires two static acquisitions in order to calculate the sensor's sensitivity and three static ones in order to define the offset for each axis. Sensitivity Sv_a for each *i*-axis is defined as:

$$Sv_{a_i} = \frac{(max(a_i) - min(a_i))}{2} \quad (2)$$

where max(a_i) is the maximum value of a_i at the '1g' condition ('g' is acceleration due to gravity), while min(a_i) is the minimum value of a_i at '-1g' condition. To calculate the offset for *i*-axis (O_a_i), the mean value of a_i output was calculated with *i*-axis at '0g' condition. Finally, the calibrated data from the accelerometers are calculated as follows:

$$a_i = a_i \cdot Sv_{a_i} - O\_a_i \quad (3)$$

III. METHODOLOGY

A preliminary experimentation at the Neurology Operative Unit of Carrara Hospital was conducted to show the feasibility and scientific/technical effectiveness of the proposed system in distinguishing PD patients from healthy subjects, and supporting the diagnosis of Parkinson's disease.

A. Participants

Fifteen patients with a diagnosis of PD (nine male and six female, mean age ± SD: 69.4 ± 4.5 years) and six healthy controls (HC) (two male and four female, mean age ± SD: 63.3 ± 8.2 years,) were included in the study. All patients were on medication before and during the experiments. Exclusion criteria included impairments or diseases other than PD that could affect the performance of daily activities. The study procedures received the approval of the ASL1 Massa and Carrara Ethics Committee (n°1148/ 12.10.10).

B. Clinical Assessment

Patients attending the study were first evaluated by a neurologist by means of clinical scales typically used for PD assessment as reported in Table 1.

Table 1. Scores assigned to PD patients in relation to the clinical evaluation scales

Clinical Features of PD Patients	Mean±SD	N°
–Disease stage (HY):	2.6±1.0	15
Very early (HY 1)		3
Early (HY 2)		2
Moderate (HY 3)		8
Advanced (HY 4)		2
–Activity limitation (S&E%) [17]	76.0±18.1	15
–Disease severity: UPDRS (total)	37.9±18.7	15
MDS-UPDRS III (Motor Section)	19.2±10.9	15

C. Experimental Protocol

According to the neurologist and to the motor section of the MDS-UPDRS, an experimental protocol comprised of three exercises (performed three times, both hands), such *Thumb-Forefinger Tapping* (*THFF*), *Forearm Pronation/Supination* (*PSUP*) and *Hand Opening/Closing* (*OPCL*), has been proposed to analyse the motor skills of the upper limbs of the subjects in this study. In addition, every subject attended a short preliminary training to try all of the required movements.

D. Exercises Description

During the trial session, subjects assumed a comfortable and standardised sitting posture. For each exercise, an initial specific fixed position was established to permit a static acquisition in order to calibrate each trial. The exercises had to be performed for 10 seconds, as quickly and widely as possible. The descriptions of the exercises are as follows:

THFF: The subject was directed to keep the hand fixed on the desk, so that the plane between the thumb and forefinger joined together was parallel to the table. In the starting position, the thumb and the forefinger were in contact, and then the subject tapped the forefinger against the thumb.

PSUP: The subject was asked to put his sensorised arm outstretched in front of him/herself, with the wrist stable and the hand in prone position. The prono/supinations had to be performed in parallel to the floor.

OPCL: The subject was directed to flex the arm that was fixed on the table at the elbow, keeping the palm of the hand in front of him/herself. The subject had to alternatively open and close his/her sensorised hand, holding the forearm and the wrist fixed.

E. Extracted Features

For exercises performed by subjects using the SensHand V1, some biomechanical parameters, such as frequency, amplitude and velocity were measured (Table 2).

Table 2. Extracted biomechanical features

Ex.	Biomechanical Features
THFF	–Number of taps and frequency (taps/s) –Amplitude (deg) of index finger movement –Opening and closing velocity (deg/s) of the forefinger –Energy expenditure
PSUP	–Number of rotations and frequency (rotations/s) –Amplitude (deg) of the movement –Velocity (deg/s) in supination and pronation movements –Energy expenditure
OPCL	–Number of movements and frequency (movements/s) –Amplitude (deg) of the movement –Opening and closing hand velocity (deg/s) –Energy expenditure

The tasks proposed by the MDS-UPDRS can thus be evaluated in an objective way by means of the assessment of these features, overcoming the issues related to the subjectivity of medical judgment.

IV. DATA PROCESSING

The inertial data acquired with the SensHand V1 were stored on the PC and processed offline using Matlab®. All of the measured parameters were obtained from the acceleration and angular rate data supplied by the accelerometers and gyroscopes. A fourth-order low-pass digital Butterworth filter was applied with a 5 Hz cut-off frequency (f_c) in order to eliminate high-frequency noise and tremor frequency bands. In the analysis conducted in the spatio-temporal domain, the appropriate algorithms of segmentation were implemented in order to identify the characteristic times of the typical phases for each exercise. Angular rates were integrated using the trapezoidal rule, with sub-intervals of integration equal to the inverse of the sensor-sampling rate (Δt=100 ms), in order to calculate the movement amplitude. For finger tapping exercises, it was hypothesised that movement occurred only at the metacarpo-phalangeal joint and that the finger was a rigid segment.

A. Events Detection

The function to gather information about the different phases in all exercises was performed by the gyroscope signal of the axis orthogonal to the plane of the movement. The segmentation procedure used threshold algorithms that divided acquired signals into some phases, depending on the complexity of each exercise. It was assumed that the initial condition for the angle was null (θ_{init}=0). To improve the accuracy of the measures, a nulling algorithm was applied to the gyroscope signal: it provided the offset reckoning, averaging the angular velocity from N gyroscope samples (N=100) collected in

the static phase:

$$\omega_i = \omega_i - \frac{1}{N} \cdot \sum_{j=1}^{N} \omega_i(j) \quad (4)$$

For the movement exercises, θ angles covered during the movements were calculated. The outcome measures of the performances were computed from the angular rate and from the amplitude calculated through the integration of it and representing the θ angles covered during the movements. To remove sensor drift in the analysis of data, the "Zero Velocity Update" technique [18] was applied to remove cumulative effects in order to obtain accurate integration results.

Examples of events detection and signal processing are reported in Figure 2, where angular velocity and angular displacement of the forefinger in the THFF for both a PD patient and a healthy control are represented. The control subject clearly shows higher frequency, velocity and amplitude of movement than does the PD patient.

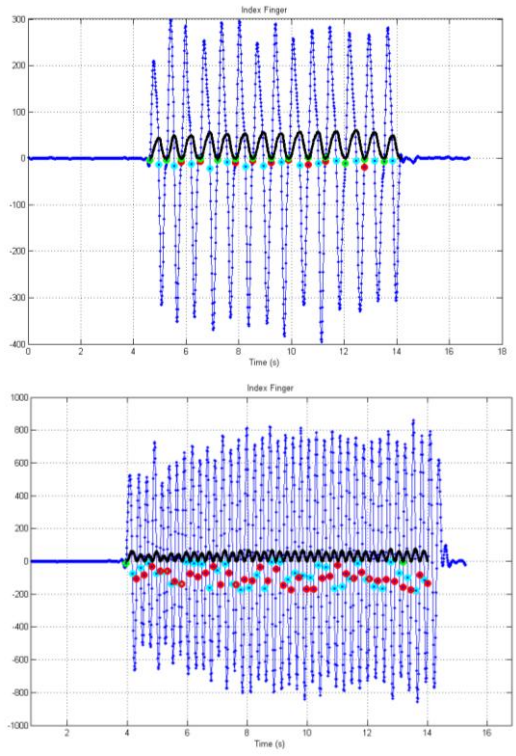

Fig. 2. A signal-processing example: thumb-forefinger tapping for a PD patient (top) and for a healthy control (bottom). Angular velocity (blue), angular displacement (black) and characteristic times (T_{start} in green, T_{TF} in cyan and T_{end} in red) are represented. T_{start} is the time that the movement starts; T_{TF} is the time in which the thumb and the forefinger are at the maximum distance, T_{end} is the time that the movement ends and the thumb and the forefinger are in contact again.

V. RESULTS AND DISCUSSIONS

A. Biomechanical Assessment

A statistical analysis was conducted of the biomechanical features that were extracted. An univariate ANOVA analysis (p-value<0.01), combined with a further comparative analysis (Pearson's correlation coefficient) permitted only four parameters to be selected in order to distinguish the group of PD patients from the healthy controls (Fig. 3).

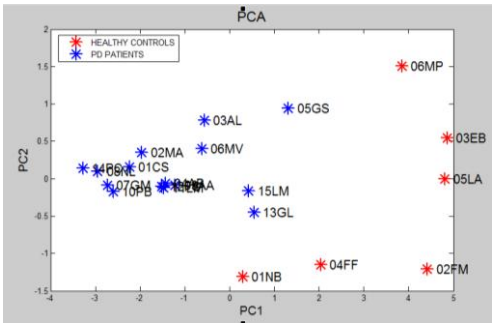

Fig. 3: Results regarding the motor performances of the two examined groups were summarised through the principal component analysis (PCA).

The four resulting parameters that best described the existing differences between the two examined groups were: number of pronosupination (num_PS), pronation velocity (ω_sp), number of hand opening/closing movements (num_OC) and energy expenditure (IAV_OC). The mean values and standard deviations for these parameters are reported in Table 3 for both the right hand (RH) and the left hand (LH).

Table 3. Mean values and standard deviations of significant parameters.

Parameter	PD (mean±SD)	HC (mean±SD)
num_PS_RH	11.4±4.1	22.8±11.4
num_PS_LH	11.5±6.3	23.8±10.1
ω_sp_RH	276.6±98.0	477.7±188.8
ω_sp_LH	254.2±130.8	499.8±106.0
num_OC_RH	16.0±5.4	33.4±5.5
num_OC_LH	15.1±7.3	35.4±4.4
IAV_OC_RH	124.3±21.5	233.9±68.6
IAV_OC_LH	137.8±45.2	287.9±59.7

B. Correlation to Clinical Assessment

The statistical correlation between the clinical scores that were subjectively assigned to PD patients by the neurologist and the quantitative outcome measures obtained from the patients' motor performances was evaluated through the use of a multiple linear regression,

as reported in Table 4. The multiple R was high for all of the scales, ranging between 0.86 to 0.95, meaning that the system is able to assess patients with Parkinson's disease in the various stages of development.

Table 4. Correlation to clinical scales.

Clinical Scales	Multiple R
MDS-UPDRS III	0.87
MDS-UPDRS I-IV	0.95
HY	0.92
Schwab & England	0.86

VI. CONCLUSIONS

This work demonstrates the technical effectiveness of a wearable sensor system for hand fine motor skills analysis and its usefulness in the assessment of objective metrics in the diagnostic procedures for PD, as demonstrated by the preliminary experimentation. More complete protocols to assess the subjects' motor performances can support a PD diagnosis with increasing accuracy in the early stages of pathology. The SensHand V1 device opens several possibilities in the applications of future customised healthcare programmes, not only in healthcare facilities, but also in domestic environments. Indeed, being easy to use, low-cost, and easily connectable in cloud platform, it is particularly adequate for empowering patients to manage their diseases, and thus allows professionals and patients to design new personalised healthcare services in the patient's home.

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