An Architecture to Manage Motor Disorders in Parkinson's Disease

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***Abstract*—Telemedicine systems for remote monitoring are gaining importance given the increase in aging population. Possible limitations to their diffusion in daily living situations can lay on usability and social acceptability barriers. In this work we propose an architecture for remote monitoring and management of motor disorders applied on Parkinsonian patients suffering of Freezing of Gait (FoG). The architecture is composed of a smartphone app, a database (DB) and a web app, hence it uses only technologies that are well known and diffuse among society. The smartphone app monitors gait parameters and provide acoustic feedback (cues) to the patient when it detects a FoG episode. Furthermore the app stores all the informations collected in a local DB and periodically sends them to the central DB when Internet connection is available. The web app provides graphic user interfaces to query the DB to observe FoG monitoring data and to remotely adjust patient's rehabilitation and pharmacological therapies. The architecture was tested on 6 Parkinsonian patients, results about FoG detection accuracy and cues effectiveness are reported.**

***Keywords*-Smartphone; Web App; Database; Parkinson's Disease;**

I. INTRODUCTION

Recent increase in aging population led to important challenges for society and the health care system such as an increase of neurodegenerative pathologies, an increase in health care costs, shortage of caregivers, dependency. Technological innovations, especially in wearable sensors and wireless communication can help to face these problems. A number of wireless body area networks have been proposed to monitor the body function for sporting, health, entertainment and emergency applications [1]. These systems are generally three-tiers architectures composed of wearable sensors that communicate (preferably wirelessly) with a personal server and subsequently through the Internet with a remote medical database server [2], [3], [4], [5], [6]. For instance, Kanthoc [5] proposed a system architecture for the monitoring of physiological parameters. The system is composed of a body sensor unit with Bluetooth connection, a gateway to forward data to a remote clinical server. The system proposed by Otto et al. [2] performs real-time analysis of sensor's data, provides real-time feedback to the user, and forwards the user's information to a telemedicine server. Jamthe et al. [4] described a solution for continuous monitoring of Parkinsonian patients in their home environment, embedding wireless sensors in patient's vicinity. Sensors motes are placed in patient's room and also shoes to monitor him from early fall detection and freezing of gait events. Data collected must be sent to a base station located in patient's home.

Unfortunately, patients (specially elderly patients) tend to do not accept the kind of solution described above, since it uses additional, not common and unknown technology for the patient (such as the body sensor network). As a consequence usability and acceptability requirements are not satisfied [7]. On the other hand, embedding sensors at home is considered costly and intrusive. Finally, a wireless connection with a server at home is not enough flexible to support the patient when she/he is not at home.

The objective of the paper is the description of a system for the management and treating of Parkinsonian patients' motor symptoms. The system architecture was chosen in order to be low cost (it uses sensors on board a smartphone), flexible (it can be used when the patient is not at home) and less intrusive with respect to systems described above.

More in depth, the system was applied to a motor disorder called Freezing of Gait (FoG). FoG is a motor block that manifests as a sudden and transient inability to generate effective stepping despite the intention to walk [8]. Unluckily FoG is resistant to standard pharmacological treatments, but clinicians suggest the use of external rhythmic stimuli (cues) to alleviate this gait block [9]. In order to be acceptable and effective the rhythmic cue should be contextual to FoG episode. Another problem related to FoG is its mysterious nature and hence poor clinical knowledge about the phenomenon. Such issue arises from the episodic nature of FoG, which is difficult to observe in a laboratory setting [10]. Our architecture aims to face both the above problems: on the one hand the system supports the patients by means of a mobile app on board the smartphone able to automatically detect FoG and generate a rhythmic auditory sound, when a FoG is detected; on the other hand the system supports clinicians by means of gathering FoG data and providing a web app which allows them to consult all the information about FoG episodes.

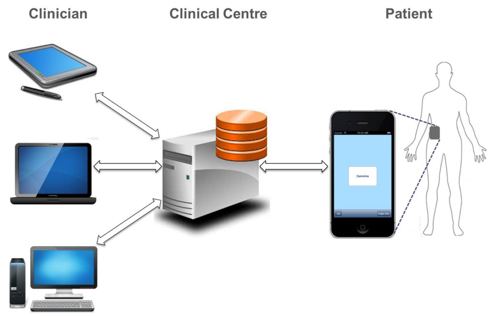

Figure 1. Architecture components: smartphone app, DB at the clinical center, clients interacting with DB through the web app.

II. Materials and Methods

The proposed architecture is composed of a smartphone app, a database (DB) and a web app. In Fig. 1 there is a graphical overview of the architecture.

The smartphone app performs the following actions:

- monitoring gait parameters;
- detecting FoG;
- providing rhythmic acoustic stimuli in response to a FoG;
- saving gait parameters trend and FoG episodes in a local DB;
- periodically uploading to the central DB all the information stored in the local DB.

The app monitors the following gait parameters: step length, step frequency, freeze index [11], energy [12]. Step length is estimated according to the inverted pendulum model [13], as explained in detail in [14]. Step frequency is evaluated as two times the foundamental harmonic of acceleration signal. Freeze index is the ratio between the integral of power spectrum in the band $3-8$ Hz and in the band $0.5-3$ Hz [11], while energy is the sum of the two quantities [12]. Gait parameters are computed from the signal measured by the onboard tri-axial accelerometer (100 Hz sample frequency). A sliding window of 256 samples flows over the acceleration signal with a step of 40 samples. On each window gait parameters are computed and then sent as input in a Mamdani fuzzy inference system, which decides whether a FoG is happening or not. If so, the app plays a rhythmic sound. Fuzzy logic has the advantages of interpretability and the possibility to exploit a priori knowledge about a phenomenon. In fact, clinicians' expertise about relationships between gait parameters and FoG occurrences can be translated in the form of *if...then* rules and hence used for FoG detection. Trapezoidal membership functions were chosen for variables involved in the fuzzy inference system. The trapezoidal fuzzy set A in the the real line $\mathbf{R}$ with the membership function μ_A is parameterized by four real scalar parameters: (a, b, c, d) with $a < b \leq c < d$. This representation can be mathematically written as follows:

Table I
Considered fuzzy sets for the input variables: linguistic terms and their corresponding trapezoidal fuzzy sets.

Input variables	Linguistic terms	Fuzzy sets (a, b, c, d)
Freeze Index	Low	0 , 0 , 0.25 , 0.5
	Medium	0.3 , 0.5 , 0.7 , 0.9
	High	0.75 , 1.0 , 1.25 , 1.5
	Very High	1.25 , 1.5 , $+inf$, $+inf$
Energy	Low	0 , 0 , 0.25 , 0.5
	Medium	0.3 , 0.5 , 0.7 , 0.9
	High	0.7 , 1.0 , 1.25 , 1.5
	Very High	1.25 , 1.5 , $+inf$, $+inf$
Step Length	Low	0 , 0 , 0.7 , 0.9
	Medium	0.8 , 1.0, 1.7 , 1.9
	High	1.8 , 2 , $+inf$, $+inf$
Step Cadence	Low	0 , 0 , 0.7 , 0.9
	Medium	0.8 , 1.0, 1.7 , 1.9
	High	1.8 , 2 , $+inf$, $+inf$

$$\mu_A(x) = \begin{cases} 0\,, & x < a \\ \frac{x-a}{b-a}\,, & a < x < b \\ 1\,, & b < x < c \\ \frac{d-x}{d-c}\,, & c < x < d \\ 0\,, & x > d \end{cases} \quad (1)$$

Values chosen for the fuzzy sets are reported in Table I and a graphical sample is shown in Fig. 2.

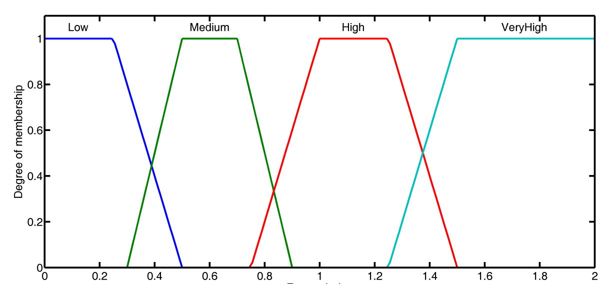

Figure 2. Fuzzy sets for the input variable $FreezeIndex$. The x-axis is the ratio between the actual $FreezeIndex$ computed and a baseline value measured during upright stance.

The output of the fuzzy inference system is the $FOGLikelihood$ and fuzzy sets are: Low, Medium, High, Very High, as shown in Fig. 3. After the defuzzyfication process we determined a FoG episode when the $FOGLikelihood$ has a value greater than 0.75.

The reader can refer to [15] for further details about the adopted fuzzy logic algorithm. The smartphone app was developed for iOS and Android platforms.

The DB at the clinical server stores the following information: web app users' personal details, patients' monitoring

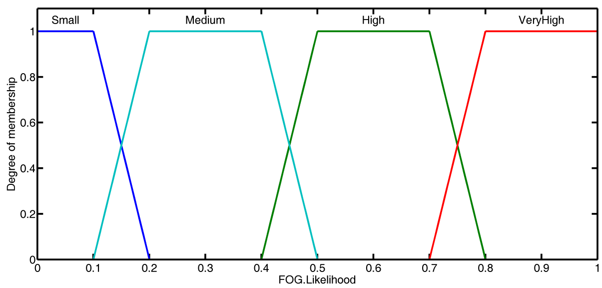

Figure 3. Fuzzy sets for the output variable $FOGLikelihood$.

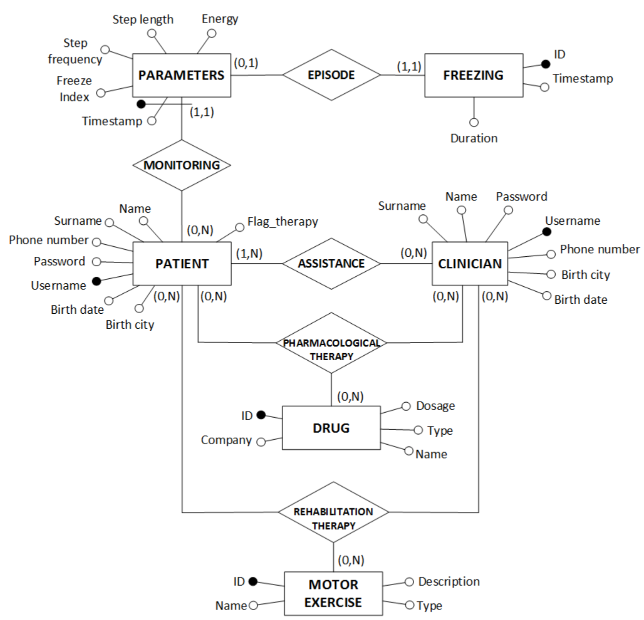

Figure 4. Entity-relationship model of the central DB.

data from the smartphone app, pharmacological and rehabilitation therapies assigned by clinicians to patients. The entity-relationship model of the DB is shown in Fig. 4. We used MySQL to create and manage the DB.

The web app allows users to communicate with the central DB and to consult information of interest through dedicated graphic interfaces. Web app users can be clinicians or patients, each of them has dedicated areas protected by authentication. Clinicians area offers the consultation of FoG monitoring data, for example requesting the number of FoG episodes in a given time interval or parameters trend during a FoG. In particular the search can be filtered by time interval, FoG duration, parameter values (equal, grater or less than a specified value or comprise to specified values). Furthermore the app can display search results in dedicated graphic plots. Each clinicians is allowed to consult only data of her/his own patients. Figure 5 shows some screenshots about clinicians area.

Figure 5. Web app clinician area.

Other functions in the clinicians area are the possibility to remotely update patients' pharmacological and rehabilitation therapies. In this way, if the clinician perceives important changes in the health status of her/his patients, she/he can change their therapies without the need to wait for the next medical examination. Patient's area allows her/him to see the actual pharmacological and rehabilitation therapy. A message alerts the patient as soon as a change involving any therapy has happened. The message appears after each login until the patient visualizes the changes.

III. Experimental Set Up

We tested our architecture on 6 Parkinsonian patients. They wore the smartphone with the application running during several motor exercises designed to elicit FoG. Each patient performed 9 walking trials: 3 standard Time Up and Go (TUG) tests, 3 TUG with cognitive task (execute simple mathematical operation while walking), 3 TUG with manual task (bear a tray with two glasses during the trial). Patients repeated the 9 trials two times: ones with the auditory cue turned off and the other with the auditory cue turn on. Patients executed the two experimental sessions (with and without cues) in a random order. Each trial was video-recorded for further analysis.

The smartphone app performance was evaluated through sensitivity and specificity of FoG detection. In particular, FoG episodes detected by the application were compared with FoG episodes visually identified by clinicians from video recordings. Sensitivity is described as follows:

$$Se = tp/(tp + fn) \tag{2}$$

Where true positives (tp) were the windows correctly classified as FoG and false negatives (fn) the windows classified as non-FoG despite the patient manifests the symptom in that time instant. For what concerns specificity, we defined true negatives (tn) the windows correctly classified as non-FOG and false positives (fp) the windows wrongly classified as FOG despite its absence. Based on these definitions specificity was calculated as:

$$Sp = tn/(tn + fp) \tag{3}$$

In order to evaluate the effectiveness of auditory cues provided by the smartphone app we compared time of execution and percentage of time frozen (the percentage of time the patient was freezing with respect to the total duration of the trial) between trials with and without cues.

Since an important task of the architecture is executed on a mobile platform, we evaluated energy consumption by measuring the battery life reduction with the app turned on. To this purpose, we annotated the battery life time of the smartphone with the wifi turned on (since our app requires wifi) but without doing anything else. Then, we measured the battery life time of the smartphone with the app always turned on. Finally, we evaluated the percentage battery life time reduction due to our app with the next formula:

$$\%cdr = \frac{t_{off} - t_{on}}{t_{off}} \tag{4}$$

where t_{off} and t_{on} are the battery life times respectively doing nothing and with the app turned on.

The web app usability is currently under testing phase, in fact clinicians are now using the app to analyse the data collected during the experimental sessions. Unluckily usability results are not yet available, because we need a longer period of clinical experimentation.

IV. Results

We observed a total of 81 FoG episods during all the trials. Table II shows sensitivity and specificity scores for each patient, while the last row reports a mean sensitivity of 93.08% and specificity of 90.98% over all the patients.

Table II
Sensitivity and specificity of FoG detection

Patient	FoG	Sensitivity	Specificity
1	4	100%	84.36%
2	35	81.78%	86.88%
3	18	87.89%	94.94%
4	4	94.52%	84.78%
5	8	99.17%	97.72%
6	12	95.13%	97.21%
TOT	81	93.08%	90.98%

Results for cue effectiveness are reported in Table III. Both time of execution and percentage of time frozen are grouped for trials type (TUG stands for the standard TUG test, CG for the TUG test with cognitive task and MA for TUG test with manual task), because different exercises have different cognitive and motor effects on the patient and hence they can affect in a different way cue effectiveness. The values reported in the table are the mean over the 3 trials of the same type. When percentage of time frozen is 0.0% means that in those trials the patient did not manifest FoG.

For what concerns energy consumption we found that a 12.15% decrease of battery life with the app turned on.

V. Discussion

The smartphone app showed a high performance in real time FoG detection (mean sensitivity of 93.08% and mean specificity of 90.98%) with respect to previous works in the literature [11], [12], [16] which uses simple binary rules. Hence results confirmed our previous findings concerning the use of a fuzzy logic based detection algorithm [15], where we found that increasing the intelligence of the FoG detection algorithm will result in higher accuracies.

For patients 1,4,5 and 6 cue effectiveness results reported in Table III revealed a general decrease in the execution time and percentage time frozen when the system provided rhythmic auditory feedback after FoG detection. The only exception is patient 1 that was frozen for 2.9% of the TUG tests execution time when the cue feedback was available, with respect to a 0% of time frozen when the cue was not available. However the small amount of frozen time demonstrates the benefit of auditory cue to resume gait (in fact Table II shows a sensitivity of 100% for subject 1, indicating that the system immediately recognized FoG episodes and gave the feedback). Instead performance got worst in patients 2 and 3 when the system provided auditory cues after FoG detection. A possible explanation of this difference in cue effectiveness may reside in the amount of gait impairment manifested by those patients. In fact, as it can be seen from the number of FoG reported in Table II, patients 2 and 3 performed trials with greater difficulties in gait with respect to the other patients. Hence it is possible that rhythmic auditory cues lose or decrease their effectiveness when they act on patients with important cognitive or motor difficulties. Another possibility can be the need to customize the cues on the basis of patient characteristics. In fact the application uses the same acoustic stimulus for all the patients: a metronome ticking at 1 Hz frequency, but probably both cue frequency and melody should be adapted to patient's step frequency and musical preferences (as it happens for ringtones) in order to be more effective.

VI. Conclusion

In this work we presented an architecture for the management of motor disorders in Parkinsonian patients. In particular it carries out the following main functions: real time assistance during the gait through a smartphone app,

Table III
CUE EFFECTIVENESS RESULTS

Patient	Execution Time (s)						Frozen Time (%)					
	TUG		CG		MA		TUG		CG		MA	
	no cue	cue	no cue	cue	no cue	cue	no cue	cue	no cue	cue	no cue	cue
1	19.3	19.3	35.3	28.7	34.7	26.7	0.0	2.9	7.2	0.0	0.0	0.0
2	25.5	29.6	48.3	46.3	46.1	45.7	22.4	44.7	62.9	63.3	50.7	62.8
3	13.5	16.3	30.3	38.1	18.7	20.7	0.0	0.0	17.3	45.7	12.7	22.7
4	16.0	14.5	18.3	16.5	24.0	21.5	0.0	0.0	11.2	0.0	0.0	0.0
5	13.6	13.2	18.5	17.0	16.2	16.0	11.6	11.1	22.2	10.3	0.0	0.0
6	26.0	20.0	30.1	22.5	26.3	20.7	10.5	0.0	13.8	0.0	21.6	9.2

remote consultation of monitoring data and management of pharmacological and rehabilitation therapies through a web app. The major strength of our architecture is the good tradeoff reached between powerful computational capabilities, high performance, simple hardware, and low cost.

For what concerns the smartphone app, it was employed to FoG detection on 6 Parkinsonian patients reaching 93.08% of sensitivity and 90.98% of specificity. The application was also able to provide auditory cues when a FoG was detected, in order to help the patient to resume walk. We found that the cue effectiveness was greater in patients with less gait impairment, suggesting a possible decrement in cues effect when the patient manifests important motor or cognitive difficulties. The other possible explanation may be the necessity to customize auditory cues on the basis of patient's step frequency or musical taste, in order to increase patient attention and hence cue effectiveness. However the number of subject is too much low to validate any hypothesis. Web app usability is currently under investigation, but we do not yet have results.

The high performance reached in FoG detection joined with the ease of use and social acceptability of the architecture revealed the potential of the system to be applied in a daily living situation. Furthermore the entire architecture could be easily applied to other similar clinical scenarios.

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