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Clinical Applications of Wearable Technology

Paolo Bonato, PhD, *Senior Member, IEEE*

Abstract — **An important factor contributing to the process involved in choosing a rehabilitation intervention is the assessment of its impact on the real life of patients. Therapists and physicians have to infer the effectiveness of rehabilitation approaches from observations performed in the clinical setting and from patients' feedback. Recent advances in wearable technology have provided means to supplement the information gathered using tools based on patient's direct observation as well as interviews and questionnaires. A new generation of wearable sensors and systems has recently become available thus providing clinical personnel with a "window of observation" in the home and community settings. These tools allow one to capture patients' activity level and exercise compliance, facilitate titration of medications in chronic patients, and provide means to assess the ability of patients to perform specific motor activities. In this paper, we review recent advances in the field of wearable technology and provide examples of application of this technology in rehabilitation.**

I. Introduction

Recent advances in the development of technologies such as sensing and communication have opened new possibilities for individual health monitoring. Several wearable systems are available today and the field is witnessing a dramatic increase in investments and new solutions proposed by researchers and manufacturers to achieve long-term monitoring of patient status. We believe that wearable technology is bound to provide clinicians with new tools to manage a number of medical conditions by relying on observations gathered in the home and community settings [1].

Wearable devices can be divided into two categories: 1) garments with embedded sensors and 2) body sensor networks. Embedding sensors into garments is an idea that was first pursued by the research team led by Dr. Sundaresan Jayaraman at Georgia Institute of Technology [2]. Research work by this team eventually led to a wearable system referred to as the *Smart Shirt*. Several companies and research groups took inspiration from the seminal work achieved by the research team at Georgia Institute of Technology and pursued the development of garments with embedded sensors. This approach appears to be ideal for very long-term monitoring (i.e. months to years) of individuals in the home and community settings. However, the use of miniature wireless sensors seems to be more practical when monitoring needs to be achieved over shorter periods of time (i.e. a few days to a week).

Pioneer work in the area of wearable wireless sensors was performed at the NASA's Jet Propulsion Laboratory, Pasadena CA in the late 90's. Researchers attempted to implement prototypes of sensor patches to record physiological data over extended periods of time. These sensors were miniature biotelemetric units similar to bandages. Several companies took inspiration from the seminal work achieved by researchers at NASA's Jet Propulsion Laboratory and developed body sensor networks that eventually made it into the market.

A fundamental limitation of available systems is that they are only suitable for collecting data at a sampling rate of a few Hz. The sampling rate required for applications in rehabilitation often ranges from 100 Hz (e.g. for biomechanical data) to 1 kHz (e.g. for surface EMG data). The first two research groups that achieved this goal are the one led by Dr. Emil Jovanov at University of Alabama [3] and the one led by Dr. Matt Welsh at Harvard University [4]. They both developed body sensor networks that provide adequate performance for application in rehabilitation. Their work focused on developing complex data management architectures with buffering and data transmission occurring both in real time and offline to meet the above-mentioned specifications.

Researchers and clinicians with a focus on rehabilitation are showing a growing interest for the adoption of wearable technology. Data gathered in the home and community settings have the potential to allow clinical personnel to optimize outcomes of rehabilitation interventions. Three major application areas are emerging: 1) monitoring motor activities via pedometers or body sensor networks with the ability of detecting complex motor activities; 2) monitoring symptoms to facilitate medication titration and, more generally, applications in which clinicians intend to gather information to adjust interventions accordingly; and 3) assessing the outcomes of therapeutic interventions (i.e. physical and occupational therapy) with goal of adjusting the intensity and modality of therapeutic exercises to maximize patient benefits. In the following sections, we discuss how wearable technology could be of great benefit to the management of three medical conditions: chronic obstructive pulmonary disease (COPD), Parkinson's disease, and stroke.

II. Chronic Obstructive Pulmonary Disease

Chronic obstructive pulmonary disease (COPD) is the fourth leading cause of death in the world [5]. Disability,

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Paolo Bonato is with the Dept. of Physical Medicine and Rehabilitation, Harvard Medical School, Spaulding Rehabilitation Hospital, Boston, MA (corresponding author, phone: 617-573-2770; fax: 617-573-2769; e-mail: pbonato@partners.org).

hospitalizations, and medication costs associated with this disease account for 15 billion dollars in lost revenues and health care expenditures annually. Unfortunately, there has been very limited progress in our ability to monitor and manage patients with COPD. Existing measures that could be potentially adopted in the field appear to be inadequate to implement strategies of effective clinical management of these patients. For instance, the forced expiratory volume in 1 s (FEV_1) takes too long to change to be a meaningful measure to monitor patient status and assess when an intervention is needed. Recent work by our team [6] and others [7] has focused on the hypothesis that measures of physical activity in the patient's home environment combined with heart rate, respiratory rate, and oxygen saturation can provide improved monitoring of COPD patients.

In recent work by our team [6], we studied 6 males and 6 females, mean age 68 $\pm$ 11 years, with severe COPD. Mean $\pm$ s.d. FEV1 was 0.96 $\pm$ 0.51 L (34 $\pm$ 17% predicted) and FVC 2.57 $\pm$ 0.91 L (70 $\pm$ 18% predicted). The average six-minute walking distance in these patients was 1170 $\pm$ 304 feet. The primary aim of the study was to automatically identify from recordings performed using wearable sensors the performance of three exercises that were part of the aerobic portion of the pulmonary rehabilitation program the patients participated into: walking on a treadmill, cycling on a stationary bike, and cycling of the upper extremities on an arm ergometer. We designed a neural network to achieve identification of these motor tasks. We demonstrated that identification of the exercise activities could be achieved with high reliability, thus allowing us to monitor patients' compliance. For misclassification equal to 5%, the sensitivity of the neural network ranged from 93% to 98% across subjects. Details concerning the study are provided in Sherrill et al [8] and Moy et al [9].

A secondary aim of the study was to test whether wearable sensors could allow us to detect the performance of motor activities such as climbing stairs, walking indoors, doing household chores, etc. Identifying these motor activities could provide a means to measure patients' overall mobility. We recorded data while patients followed a script as described in Sherrill et al [6]. The number of features derived from the accelerometer data largely exceeded the number of data segments utilized for the analyses. Therefore, we did not attempt to assess feasibility of patient monitoring via implementation of a classifier. Rather, we envisioned that in the future we will gather data from a large group of patients and will perform identifications of motor tasks based on an existing database of data collected during performance of such motor tasks. This approach would require that the variability across tasks exceeds the variability within tasks across individuals. Therefore, we sought ways to visualize the clusters of data points corresponding to the conditions of interest as a way to demonstrate feasibility of the proposed approach. For this purpose, we combined principal components analysis (PCA) and Sammon's mapping. A PCA transformation was applied first. Fifteen components (accounting for 90% of the total variance) were retained. The Sammon's map of the feature space obtained from the PCA transformation was the computed. Results showed a clear division among feature sets pertaining to different motor tasks. The "quality" of the clusters was assessed as reported in Sherrill et al [6], thus allowing us to determine that motor activities related to patients' overall mobility can be identified based on features derived from accelerometer data positioned on the upper and lower extremities.

III. PARKINSON'S DISEASE

Parkinson's disease affects about 3% of the population over the age of 65 years and more than 500,000 US residents. The disease is marked by characteristics motor symptoms such as tremor, bradykinesia (i.e. slowness of movement), rigidity (i.e. resistance to externally imposed movements), and impairment of postural balance. Therapy to manage Parkinsonian symptoms is based on augmentation or replacement of dopamine, using levodopa or other drugs that activate dopamine receptors [10]. These therapies are often effective in the early stages of the disease, but most patients eventually develop motor complications [11], namely wearing off (i.e. the abrupt loss of efficacy at the end of each dosing interval) and dyskinesias (i.e. involuntary hyperkinetic movements typically associated with the performance of a fine motor control task with the contralateral side of the body). Wearing off and dyskinesias are associated with disability and compromise the effectiveness of the therapy [12, 13].

Available tools for monitoring and managing motor fluctuations are very limited [14]. Information about motor fluctuations is often obtained by clinicians by asking patients to recall the duration of ON (i.e. when medications effectively attenuate tremor) and OFF time (i.e. when medications are not effective). This approach is unfortunately prone to perceptual bias and recall bias. Another approach is the use of patient diaries. Diaries are preferable to patient interviews as they allow one to achieve higher reliability as symptoms are recorded as they occur. However, diaries do not capture many motor features that are useful in clinical decision-making because patients do not have an objective perception of their own motor status.

Motivated by these considerations, our team [15] and others [16] have developed methods that rely on wearable technology to monitor longitudinal changes in the severity of symptoms and motor complications in patients with Parkinson's disease. In the first of such studies carried out by our team, we recruited twelve individuals 46 to 75 years old with a diagnosis of idiopathic Parkinson's disease (Hoehn & Yahr stage 2.5 to 3) [17]. We tested subjects in a "practically-defined OFF" state, namely subjects delayed their first medication intake for their baseline assessment.

Subjects performed a series of motor tasks commonly utilized in evaluating patients with Parkinson's disease such as tapping with the index finger and thumb, performing repetitive pronation/supination movements of both forearms, opening and closing both hands. While subjects performed these motor tasks, we recorded accelerometer data using sensors positioned on the upper and lower extremities. The study focused on estimating the severity of tremor, bradykinesia, and dyskinesia based on features derived from accelerometer data. Accelerometer data was high-pass filtered (1 Hz cutoff frequency) to remove gross changes in the orientation of body segments. An additional filter was applied to isolate the frequency components of interest with different settings for each symptom or motor complication. Specifically, we applied a band-pass filter with bandwidth 3-8 Hz for the analysis of tremor, and a low-pass filter (3 Hz cut-off frequency) for the analysis of bradykinesia and dyskinesia. A rectangular window randomly positioned throughout the recordings was used to segment the data. Features were extracted from 30 such data segments from recordings for each motor task. Five different types of features were estimated from the accelerometer data. The features were chosen to represent characteristics such as intensity, modulation, rate, periodicity, and coordination of movement. A Support Vector Machines approach was adopted to predict clinical scores of the severity of Parkinsonian symptoms and motor complications. The results of this study show that the severity of symptoms and motor complications can be reliably estimated via processing data recorded using accelerometers during performance of motor tasks commonly associated with the clinical assessment of patients with Parkinson's disease. The prediction error we obtained did not exceed on average just a few percentage points. Specifically, we observed average prediction error values of 3.5 % for tremor, 5.1 % for bradykinesia, and 1.9 % for dyskinesia [18].

IV. STROKE

More than 700,000 people suffer a stroke each year in the United States [19]. The long-term effects of a stroke include a person's cognitive, language, perceptual, sensory, and motor abilities. More than a million Americans who suffered a stroke have reported significant functional limitations. The process of recovering from a stroke continues after discharge from the hospital inpatient unit stay. Rehabilitation is guided by clinical assessments of motor abilities, which are expected to improve over time in response to the therapeutic intervention. Therefore, researchers and clinicians have recently started to focus on telerehabilitation as a means to facilitate extending therapy and assessment capabilities beyond the clinical setting.

Achieving accurate assessment of motor abilities is essential toward optimizing clinical outcomes of therapeutic interventions. These assessments are based on observations of subjects' motor abilities using clinical rating scales. Wearable sensors could be used to provide accurate measures of motor abilities in the home and community settings. Their use could tremendously facilitate the implementation of telerehabilitation protocols. In recent studies, we have explored the use of wearable sensors (accelerometers) and of an e-textile sensorized glove to monitor movement and allow one to implement physical therapy via an interactive gaming approach.

Our work showed that it is possible to predict Wolf Functional Ability Score (FAS) values by collecting and processing accelerometer data during performance of the Wolf Motor Performance Test [20]. The Wolf FAS provides a measure of the subject's quality of movement and captures aspects of the observed movement patterns related to smoothness, speed, ease of movement, and amplitude of the compensatory movements. We recruited 23 subjects who had a stroke. Accelerometers were positioned on the sternum and the hemiparetic arm. Subjects performed multiple repetitions of motor tasks including reaching and prehension movements that we selected from the Wolf Motor Performance Test. The selected motor tasks included reaching to close and distant objects, placing the hand or forearm from lap to a table, pushing and pulling a weight across a table, drinking from a beverage can, lifting a pencil, flipping a card, and turning a key. Features were derived from the accelerometer data to capture different aspects of movement that we expected to be associated with the Wolf FAS. Such features were fed to a classifier built using a Random Forest. The Random Forest approach is based on an ensemble of decision trees and was found to be suitable for datasets with low feature-to-instance ratio. We derived estimates of the prediction error values for each motor task and found such values to range between about 1 % and 13 %. This result suggests that FAS scores can be estimated by using accelerometers to monitor motor tasks performed by patients in the home and community settings.

In another study, we explored the use of a sensorized glove to implement motor therapies based on an interactive gaming approach. The glove was utilized to implement grasp and release in the video game "environment". We defined "hand aperture" as the size of the virtual object held by the subject. Calibration of the glove was achieved by asking individuals to hold a wooden cone-shaped object with diameter ranging from 1 cm to 11.8 cm. The output of the glove sensors was used to estimate the diameter of the section of the cone-shaped object corresponding to the point held by the subject. We then utilized a linear regression model to estimate "hand aperture" (dependent variable) using the sensorized glove outputs as independent variables. We achieved an estimation error smaller than 1.5 cm. This result is satisfactory in the context of the application of interest and justified further studies in which the sensorized glove is leveraged upon to implement therapeutic exercises. These studies are ongoing and we anticipate that results will be available in the near future.

V. CONCLUSIONS

The application of wearable systems to the three medical conditions that were the focus of the studies summarized above provides evidence of the tremendous potential value of wearable technology in the context of managing long-term clinical conditions. These medical conditions have in common the fact that they do not require continuous hospitalization of patients, namely that clinical management of such conditions occurs mostly in the home setting. Besides, these are conditions that require an intervention in such environment to avoid worsening of patient's status (e.g. to avoid missing symptoms associated with early stages of an exacerbation episode in patients with COPD), to optimize the management of symptoms (e.g. to facilitate medication titration in patients with late stage Parkinson's disease), and to facilitate the assessment and administration of therapy in the home environment (e.g. to track functional scores in patients post stroke, to provide a means to enhance available therapeutic interventions). Experimenting with available systems to pursue actual clinical applications provides one with a unique perspective on shortcomings of the technology. For instance, the level of obtrusiveness of available systems is such that difficulties are encountered in donning/doffing the technology. The "life" of these systems (i.e. how long the system can collect data without requiring that one recharges or replaces the battery package) is still rather limited thus causing some problems if one intends to deploy such systems in the home setting. Despite these shortcomings of available wearable systems, the clinical benefits associated with home monitoring of patients with certain conditions (such as the one herein presented) are very significant and justify deployment of the technology with its current limitations and further work to optimize wearable systems for actual clinical applications in real-world conditions.

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