W2M2: WIRELESS WEARABLE MODULAR MONITOR
A Multifunctional Monitoring System for Rehabilitation

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Abstract: Wearable/portable biometric/physiological monitoring devices are rapidly becoming a recognized alternative in medicine, rehabilitation and sports. Developments in sensors, energy harvesting, embedded technology, smart textile, to mention a few, are driving the field to more seamless and complex solutions, sometimes part of pervasive strategies for activity monitoring. Additionally, the number of sensors forming part of wearable solutions seems to be incrementing thanks to miniaturization and lowering components cost. Consequently medical and rehabilitation protocols and standards are undergoing the slow process required for adaptation to such emerging trends. This article presents a simple, modular, low-cost, wearable device originally intended for rehabilitation data gathering. Such device was based on commercially available components which can be assembled and managed by physicians, therapist and other healthcare personnel through a proposed platform. The objective is the familiarization and even active inclusion of healthcare personnel in the technological development process and, more importantly, the incorporation of electronic data acquisition in their procedures.

1 INTRODUCTION

Rehabilitation, healthcare and sports share a natural affinity, especially in this age when healthcare management seems to focus more on healthy lifestyles and prevention. Such affinity is not limited to the upkeep of a healthy condition through exercise or the recuperation of an injury through rehabilitation, but also at a technological level. Nowadays, technology is providing new tools to all three fields and entering within the individual's home at times. Wireless sensor networks, implantable devices, textile integrated circuitry and other achievements have allowed for designs that require less energy and remain on site for longer periods of time. Some systems are appearing now on the market capable of human movement analysis and for physiotherapy assistance. However, their institutional oriented approach makes them impractical for widespread usage due to highly technical learning curves and/or required accommodations size and electrical requirements; not to mention prohibitive costs.

An interdisciplinary team was formed in order to design and implement a simple and low-cost data gathering platform, originally focused for the development of quantifiable rehabilitation progress methodologies. Commercially available components were considered with the premise of the final solution being adaptable and maintainable by non-technical proficient persons; thus, high available components and user-friendly solutions were preferred.

1.1 Rehabilitation Protocols and Procedures

The fields of physiotherapy and rehabilitation are rapidly developing areas of health science that covers a wide spectrum of multidisciplinary intervention with several research and clinical subspecialties. Rehabilitation in its broaden sense is becoming a cornerstone of interest for both policy makers and service providers within health and

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social care agencies, mainly due to the expected growing number of elderly people. However, the impact and interweaving of rehabilitation on the daily activities of an individual are not sufficiently emphasized. There exists a need for the investment of resources aimed to promote quality research in order to overcome challenges that both therapists and patients face in real life settings. The rehabilitation process tends to involve and affect a number of interpersonal relations that go beyond the therapist-patient dynamics, shaping communal inter-dynamics at all levels of social structures; from families to governments, as illustrated on Figure 1. Modern technological developments for rehabilitation must consider such inter-dependency complexity, thus favoring low-cost adaptable solutions seeking integration in everyday scenarios as opposed to rigid strategies meant for limited usability.

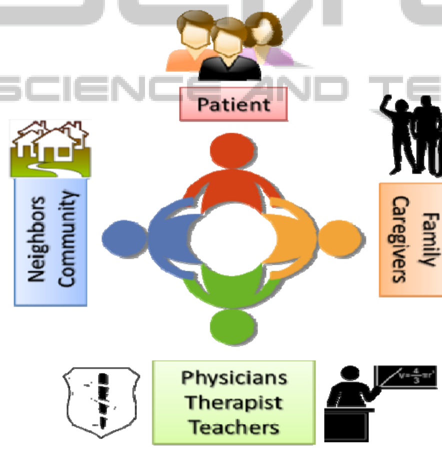


Figure 1: Inter-dynamics of social structures involved in therapy/rehabilitation process.

An in depth understanding of the human body in everyday scenarios, advanced skills in physical assessment, and experience in hands-on management, allow physiotherapists to manage a broad range of conditions, with the fundamental goal of promoting wellness, mobility and independent function, throughout the lifespan of the individual (Tate, 2006). Rehabilitation interventions should specifically address the individual's impairment; be sufficiently difficulty to challenge the motor system and integrate strategies to develop transfer of performance gains from the training situation to everyday life (Cirstea and Levin, 2007). Being this the ideal scenario, an enduring question facing not only rehabilitation as a field, but healthcare in general, is whether and to what extent methodologies and protocols used are effective, and, if so, whether they are efficient (DeJong, Horn, Gassaway, Slavin, Dijkers, 2004). Clearly the answer is dependent on the knowledge of the value of the outcomes, not only for patients, but also for end-payers and society as a whole.

A crucial aspect guiding physiotherapist's clinical reasoning, and thus design of rehabilitation intervention, is the assessment of motor performance; in fact, according to Paten et al. (2010) implementing therapeutically programs require accurate clinical and field measurements based on motor pattern identification not readily available from traditional tools. Standardized clinical motor assessments rely on physiotherapists observational skills, which although may be considered useful, remains insufficient for reliable measurement of certain quantitative features (e.g., intersegmental coordination, quality of movement and smoothness). Moreover observation-based assessment is subject to observer induced error, resulting from poor training (thus mostly confined to more experienced professionals), personal bias, limited capacity of human visual perception, just to mention some. The Rivermean motor assesment (RMA), Fugl-Meyer motor assessment (FMA), postural assesment scale for stroke patient (PASS) and the reach performance scale (RPS) are examples of viable and reliable measurement instrument commonly used in physiotherapy. In what refers to evaluation instrumentation encountered in the laboratory environment, relevant to the field at hand, one can refer to EMG, force platforms and complex image/video analysis systems, that introduce a degree of objectivity in the interpretation of events, augmenting the therapist/physician perspectives in what refers to functional and motor characterization. However, such resources accessibility in clinical environment is scarce or null, restricting their routinely usage from clinical rehabilitation practices.

Physiotherapists clinical practice reality concerning data gathering and recording is far from being effective, despite general guidelines concerning this matter. In fact this important step of the overall rehabilitation process is many times absent and when present tends to be mainly subjective and qualitative, based on the therapist opinions and patient's provided information, regarding movement restoration and overall progress. Such recordkeeping varies from institution to institution, from therapist to therapist, and are not necessarily updated at each session; therefore a progressive evaluation based on such records remains subjective to the experience and interpretation of the reader, which clearly contributes to a chain-cycle of deteriorating results, both in progress and outcomes. Quantitative data records provide a means for efficient and expedient analysis of the effectiveness of a therapy on a patient's progress, safeguarding from negative activities that can go unnoticed and unrecorded. Such approach strengthens and streamlines internal technological platforms, expanding their coverage and added-value; promoting the formulation of standards and protocols for patient progress monitoring, thus compensating current guidelines.

2 W2M2 ARCHITECTURE

The system hereby presented was originally intended to address post-stroke upper limb rehabilitation monitoring. Post-stroke rehabilitation reality within Portugal (and in most parts of the world for that matter) is far from being ideal or even effective, from both the clinically and economical point of view. In fact, given the growing number of stroke victims in recent years (portuguese statistical data reported a mortality rate due to cerebrovascular diseases per 100.000 inhabitants of 133.9, in 2009 (Portuguese Official Statistics, 2009)) this clinical condition is considered a major burden on the healthcare system. Despite the elevated related cost, there is a general agreement of the importance of addressing the *sequelas* of stroke, both due to acute and sub-acute scenarios, albeit the long-term nature of the chronic phase. In spite of the well establish beneficial effects of timely and continuous managed rehabilitation, there is a clear need to improve its quantity, quality and overall effectiveness.

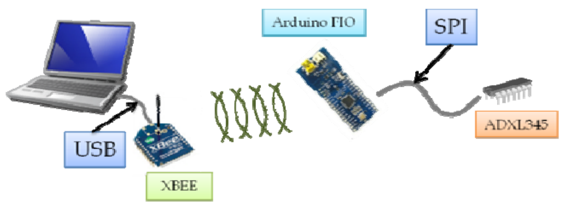


Figure 2: Component view of first W2M2 prototype.

At the request of physiotherapists pursuing alternative therapies for home-based rehabilitation for post-stroke individuals, a simple inertial monitoring device was design and implement. The device was based on commercially available components that could be assembled in a fast manner, without extensive knowledge of electronics; seeking to reduce overdependence on collaborating engineers. The system concept seen on Figure 2 is based on a modular approach and almost out-of-box ready-to-use.

The module's main component, the Arduino® FIO, is accessible at low cost and can be programmed with a reduced learning curve; while its numerous features such as communication protocols (IIC, SPI), external interrupts and a number of analog and digital I/O pins, provide design flexibility. Additionally, a large amount of open source resources are available for fast-paced prototyping and when combined with an XBEE® based wireless interface, transforms the module in a portable, wireless adaptable resource. The XBEE® modules can be readily purchased and are offered with varying ranges and antennas versions. A number of inertial and physiological sensors can be combined with the module, both digital and analog in nature. Common communication protocols, such as the IIC and SPI, can be used to chain a number of modern sensors. The ADXL345 3-axis accelerometers break-out board was used in this case for initial testing, permitting data gathering for upper limb reach based rehabilitation exercises that seek to generate inertial based biomechanical models for compensatory movement determination. The sensor board was encased in a 5.5 x 3 x 2.5 cm standard project box and fastened on the target individual's body through flexible Velcro ended straps (double sized athletic/rehabilitation tape can also be used for awkward positions). Figure 3 illustrates a number of tested sensor positions, utilized for a reach-press-return post-stroke patient study.

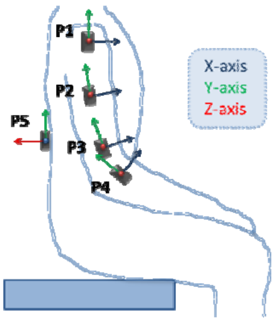
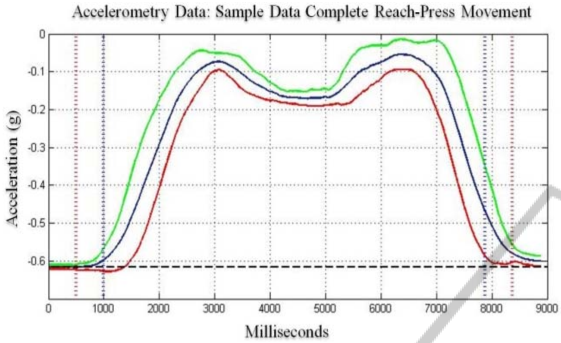
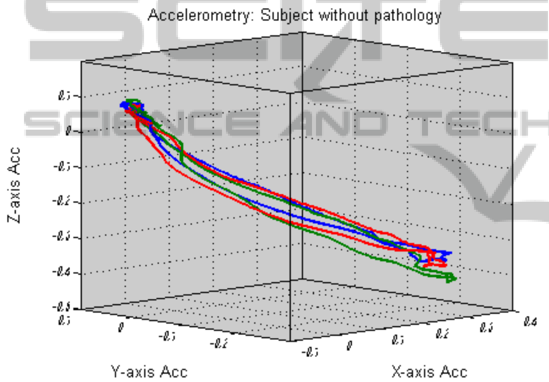


Figure 3: Sensor locations.

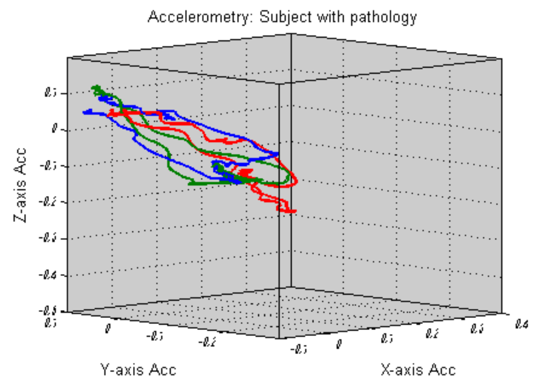
The 3-axis accelerometers data was captured at a frequency of approximately 100 Hz, which was then buffered and transmitted wirelessly. After package format verification, the data was processed in Matlab by applying a simple smoothing strategy and an auto movement start/end determination based on a window differentiation function. Supplementary lines were added for signal stability referencing as can be observed on Figure 4 a). An example of the processed data illustrating the difference between three independent reach-press.return trials by a subject without pathology and a subject with pathology can be seen on Figure 4Figure 4 b) and c) respectively.



(a)



(b)



(c)

Figure 4: Sample accelerometry data a) single axis complete reach-press-return; three independent accelerometry for reach-press-return b) subject without pathology c) subject with pathology.

Field usage of the prototype generated a number of requests by physiotherapist and patients, not to mention an improved appreciation of the undergone therapy process. Such gain understanding translated into a conceptual idea for a modular solution which allows for an integration of different sensor modules according to the needs of specific rehabilitation methodologies. The improved concept considered multiple modules, either through digital or analog communication, which could be connected to the processing unit transforming the original W2M2 into a multi-purpose monitoring system. Due to the number of current available sensors, the advantage to incorporate modules provides a flexibility which permits the system to adapt to the therapist and patient on a needs-basis.

At this stage, the W2M2 allows the interconnection of accelerometer and gyroscope boards, electrodes, capacitive and galvanic sensors and also an On/Off sensor, nonetheless the use of standard communication protocols such as IIC and SPI permit interconnect to a wide variety of commercially available sensors which may be added to address a particular purpose (see Figure 5).

Although, emphasis has been on sensor interconnection for data gathering, feedback modules have been considered since the preliminary stages of the project in order to address home-based or remote rehabilitation assistance. Digital pre-processing previous to signal transmission allows for dataset reduction and optimization for data fusion, pattern recognition, event detection and feature extraction strategies; not to mention auto-feedback response for specific situations as compensatory movement determination or fall scenarios.

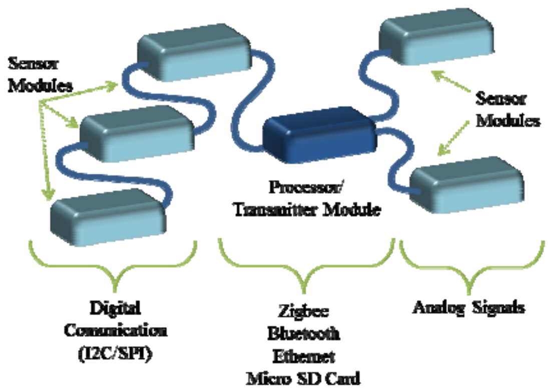


Figure 5: Modular approach of the W2M2.

From a user interface side a number of alternatives exist for development, such as visual studio based application, java based application, scripting languages, even data processing application such as Excel, Matlab and Labview. Initial data gathering and visualization was performed using Processing, an open source programming language which permits interfacing with Arduino® based boards with a minimal learning curve. The language permits for fast application implementing and can serve for a number of specific objectives. In order to provide a more complete solution, which maintained an organized database of demographic data and clinical scores in conjunction with the gathered data, that said, a VB2010 based application for database management, data visualization and ease of user interfacing and control was developed. However, due to the wireless interfacing through an XBEE® based USB to serial unit base, software counterparts can be developed in a wide number of platforms as mentioned previously. The possibility also exist to use Bluetooth based XBEE® modules in order to interface with mobile technology such as cell phones, or directly with most laptops, tablets and other devices.

Table 1: Main module and PC interface cost.

Item	*Cost per Item*	*Total*
Arduino FIO	20	20
XBEE modules	30	60
USB – XBEE interface	25	25
Rechargeable Battery	10	10
Misc. (cases, cables, etc)	20	20
Total	-	135

Misc.: miscellaneous

Table 2: Sensor cost examples.

Sensor boards	*Cost*
ADXL 345 3-axis accelerometers	22
IDG500 Dual gyroscopes	34
ITG3200/ADXL345 3-axis acc. & gyr. combo	50
HMC5843 3-axis magnetometer	18
MPR121 12-electrode capacitive touch	9

Acc.: accelerometer; Gyr.: gyroscope

From a cost perspective the W2M2 system is a low-cost solution, especially when compared to other physiological and biological signal monitoring devices available in the market. Devices such as Biopac, Plux, Biodex and video based solutions from Qualysis and Viacom are just some examples of system being used today in rehabilitation and medical research. These systems retail from thousands to hundreds of thousands Euros, and tend to require equally expensive add-ons. In contrast, the W2M2 can be constructed under 150 Euros and the sensor components tend to cost less than 50 Euros, as presented on Table 1 and Table 2. In order to insure good connectivity and measurement reliability a printed circuit board (PCB) can be designed for interconnecting the sensor board with the chosen connector, and sent for manufacturing to a number of online sites; however such process tends to cost upwards of 50 Euros for a limited number of boards. Prototyping boards can offer a low-cost alternative, especially during initial trials. Custom sensor solutions, such as electromyography (EMG) or bioimpedance, can be constructed using battery based instrumentation amplifiers and operational amplifiers, and the analog I/O pins of the main module.

The W2M2 is the key part of a more global data gathering platform that can be used for home-based rehabilitation monitoring and as a portable data acquisition system, as illustrated on Figure 6, which permits the generation of databases that can be shared and analyzed for an increase understanding of human responses to their surroundings under a number of scenarios (in this case rehabilitation progress monitoring). There exist a number of options for remote monitoring interfacing, be it by periodic data uploading for remote progress analysis, or real-time one-on-one physiotherapist-patient sessions. Such interfacing can be achieved through custom made applications programmed in free software such as PHP or Visual Basic; or by utilizing chat applications that allowed for file sharing and video conferencing.

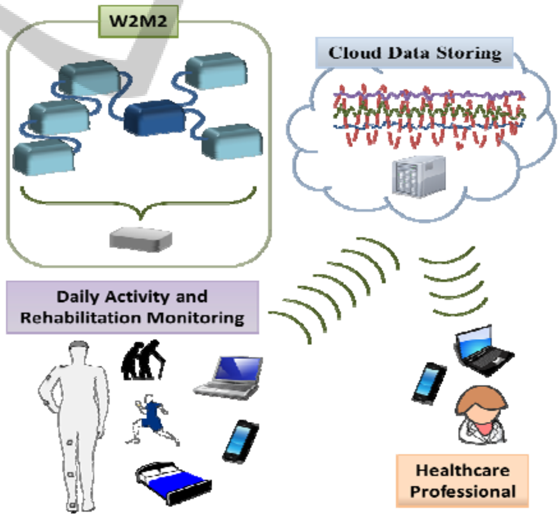


Figure 6: Complete data acquisition system overview.

3 DISCUSSION

A number of factors have contributed to the fast-paced development of wearable monitoring technology of the past decade, where interdisciplinary collaboration is a factor of paramount importance. medical/rehabilitation professionals combining efforts with scientist/engineers has become commonplace, advancing areas which traditionally were slow to adapt. Some systems are now appearing capable of human movement analyze and for physiotherapy assistance (Zhou and Hu, 2007; Pérez et al., 2010); however, their institutional oriented approach makes them impractical for widespread usage due to highly technical learning curves and/or required accommodations size and electrical requirements; not to mention prohibitive costs. The system presented seeks to ease the data gathering process by offering an adaptable low cost alternative that can be used and modified by physician, therapist and even patients (for home-based and/or remote solutions). Its portability allows for data gathering in a number of diverse scenarios including home-based rehabilitation, or even daily-activity, monitoring; altering the therapist-patient dynamics by extending the rehabilitation process.

Currently, visually based biomechanical models seem to dominate the field, probably due to traditional appreciation methodologies for patient progression; however, inertial, chemical, electrical sensors are broadening the perceptual capacities of current rehabilitation practices, introducing the need for new approaches and models. Through data gathering practices by physicians, therapist and even patients, a body of comparable datasets can be generated for the formulation of statistical and analytical methods that can reveal quantifiable methods that can contribute in the diagnosis, treatment and follow-up of numerous conditions.

4 CONCLUSIONS

A data acquisition system was designed and developed as a low-cost, fast implementable alternative for rehabilitation monitoring. Although the device was originally thought for post-stroke upper limb rehabilitation monitoring, its flexibility and adaptability allowed usage in a number of monitoring objectives. The device seeks to ease the data gathering process by therapist and others, in order to facilitate the development of quantifiable methodologies and protocols.

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