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Review

Wireless sensor networks for rehabilitation applications: Challenges and opportunities

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ABSTRACT

Rehabilitation supervision has emerged as a new application of wireless sensor networks (WSN), with unique communication, signal processing and hardware design requirements. It is a broad and complex interdisciplinary research area on which more than one hundred papers have been published by several research communities (electronics, bio-mechanical, control and computer science). In this paper, we present WSN for rehabilitation supervision with a focus on key scientific and technical challenges that have been solved as well as interdisciplinary challenges that are still open. We thoroughly review existing projects conducted by several research communities involved in this exciting field. Furthermore, we discuss the open research issues and give directions for future research works. Our aim is to gather information that encourage engineers, clinicians and computer scientists to work together in this field to tackle the arising challenges. We believe that bridging researchers with different scientific backgrounds could have a significant impact on the development of WSN for rehabilitation and could improve the way rehabilitation is provided today.

Contents

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1. Introduction

Rehabilitation is a therapy where the patient performs various physical exercises and activities to achieve a physical functioning level that allows him to return to his initial motor capabilities after an accident, a stroke or a surgery. Studies show that intensive rehabilitation decreases the recovery time and achieves optimal rehabilitation outcomes (Kwakkel et al., 2004). Furthermore, physical therapists should continuously monitor and rectify patients during rehabilitation to avoid improperly exercising. Continuous supervision of patients during long term rehabilitation therapy increases the load for physical therapists and medical staff and cost too much for patients. At a time of such challenges, new solutions arise from the need to develop effective, low-cost and easy to use rehabilitation supervision systems suitable for ambulatory or home settings.

Human Motion Tracking systems attracted significant interest in the last two decades due to their potential in rehabilitation supervision (Zhou and Hu, 2008). Several human motion tracking systems have been proposed both in industry and academic research. They can be classified as either visual or non-visual systems as depicted in Fig. 1. Visual human motion tracking systems (Moeslund and Granum, 2001) conduct 3D localization of the patient's body and limbs by combining data of several cameras recording the patient from different perspectives. Marker-free systems (Gonzalez-Ortega et al., 2010) track the boundaries of human body while marker-based systems, such as CODA (http://www.codamotion.com) or Qualisys (http://www.qualisys.com/), track either light reflective markers (passive markers) or light-emitting diodes (active markers) attached to the patient. Such systems have shown promising performance in rehabilitation supervision due to their accurate localization (error around 1 mm Zhou and Hu, 2008). However, they are expensive, invasive and suffer from occlusion and line-of-sight problems.

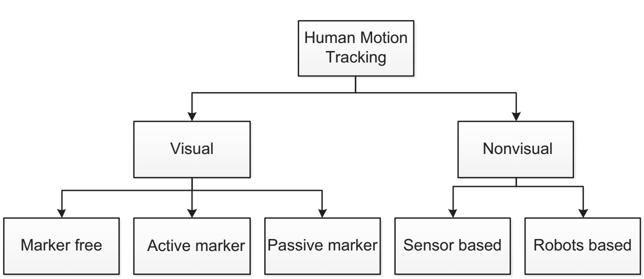

Fig. 1. Taxonomy of human motion tracking systems.

In robot-based solutions (Yoon et al., 2010), the patient installs his limbs on a robot to perform several movement patterns. The robot moves, guides or just disturbs the movement of the limb while measuring kinematic values such as velocity, acceleration and force (Duschau-Wicke et al., 2010). Such systems are recommended for patients with severe disabilities which make them unable to perform exercises by themselves. However, they are expensive, cumbersome and cannot be used in ambulatory or home rehabilitation settings.

Sensors have been used in motion tracking (Wong et al., 2007) to avoid problems inherent to visual systems such as occlusion and line-of-sight problems (Zhou and Hu, 2008). In sensor based systems, the patient wears several small nodes able to assess human movement without interfering with his natural behaviors. These nodes form a network which unobtrusively gathers information regarding position, motion, direction and physiological state. As depicted in Fig. 2, a node is composed of several sensors for data collection, a microcontroller with memory for data processing, a radio transceiver for data transmission and a battery for powering all circuits in the device. Using sensors dramatically reduces the cost and size of rehabilitation supervision systems and opens new opportunities.

Researchers from biomedical, biomechanical and computer science communities have been working toward the development of wireless sensor networks that bring a wave of breakthroughs in providing rehabilitation. Many teams have successfully developed working systems and early clinical results have been already obtained. Indeed, wireless sensor networks have been used in several rehabilitation applications such as stroke rehabilitation, balance training, parkinson's disease and telerehabilitation. The excitement for this technology is motivated by the several benefits associated to long-term monitoring, low cost, rapid deployment, self organization and flexibility features of WSN.

In this paper, we present WSN for rehabilitation supervision with focus on key scientific and technical challenges and design considerations. We thoroughly survey, analyze and discuss works

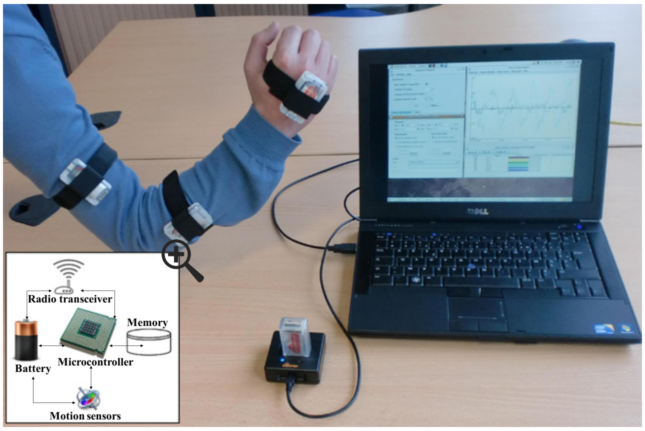

Fig. 2. Node architecture: this picture shows a prototype of WSN for rehabilitation that we have developed in a previous project (Hadjidj et al., 2011b). It is consisting of a set of motion sensor nodes which measure acceleration and angular velocity of each segment of the supervised arm. Collected data is then sent to a central station for data storage and processing.

conducted by several research communities involved in this exciting field, namely, electronics, bio-mechanical and computer science communities. Our aim is to gather information that encourage engineers, clinicians and computer scientists to work together in this field. Furthermore, we present interdisciplinary challenges and issues that are still open and give potential directions for future research works.

The remainder of this paper is organized as follows: In Section 2, we present related works. In Section 3, we propose a classification of different clinical applications of wireless sensor networks for rehabilitation supervision and we present their benefits and their intrinsic characteristics. In Section 4, we discuss the design considerations and the challenges that govern these systems. In Section 5, we survey existing works on wireless sensor networks for rehabilitation. In Section 6, we address open research challenges and give directions for future works. Finally, we conclude the paper in Section 7.

2. Related works

There are several surveys covering human motion tracking systems for rehabilitation (Zhou and Hu, 2008). These surveys reviewed existing vision-based human motion tracking systems (Moeslund and Granum, 2001) as well as the possible applications of sensors in human posture and movement analysis (Wong et al., 2007). However, none of them has considered wireless sensor network technology.

Authors in Pantelopoulos and Bourbakis (2010), reviewed wearable bio-sensors for health monitoring. Similarly, Hao and Foster (2008) provided a comprehensive review of development in wireless sensor networks for human physiological monitoring. A recent work (Ko et al., 2010) has described several promising WSN healthcare applications and highlighted the key technical challenges that WSN face in healthcare. Alemdar and Ersoy (2010) organized existing WSN for healthcare into five categories: *activity of daily living monitoring, fall and movement detection, location tracking, medication intake monitoring and medical status monitoring*. All these works covered a wide range of healthcare applications but they did not consider WSN for rehabilitation.

Rehabilitation supervision may seem as a special case of healthcare supervision. However, traditional WSN for healthcare do not tackle the specific challenges associated with the intrinsic application requirements of rehabilitation (see Section 3.2.1). In fact, sensor diversification, multi-sensor data fusion, real-time feedback for patients and virtual reality integration are examples of features that make WSN for rehabilitation a specific research area with unique hardware, software, communication and architecture design considerations. A recent review paper (Patel et al., 2012) summarized clinical applications of wearable technology in the general field of rehabilitation. Applications described in this review paper include health and wellness, safety, home rehabilitation, assessment of treatment efficacy and early detection of disorders. However, authors presented works currently undergoing assessment without studying previous works. Furthermore, they did not present the scientific and technical challenges of rehabilitation supervision.

Body Area Networks (BAN) is a specific support of WSN for healthcare applications. Although there are several recent surveys on BAN (Chen et al., 2011; Cao et al., 2009; Latré et al., 2011; Ullah et al., 2010), they are mainly focused on hardware and physical layer (antennas, body-network interferences, signal propagation modeling).

The contributions of our work are manifolds. First, we present WSN for rehabilitation supervision and explain the unique characteristics that differentiate it from legacy WSN for healthcare. Second, we identify the design considerations and the challenges that govern these systems. Third, we review existing works on WSN for rehabilitation and discuss their design objectives. Fourth, we identify open research issues and give several directions for future works.

3. Wireless sensor networks for rehabilitation

WSN for rehabilitation have been used in several clinical applications. In this section, we present these different applications and propose a corresponding taxonomy. Also, we highlight the benefits that this technology bring. Finally, we describe unique characteristics that make WSN for rehabilitation different from traditional WSN for healthcare.

3.1. Classification of clinical applications

The main goal of WSN for rehabilitation is to capture movements and postures of patients for monitoring his motor activities during rehabilitation therapy. Possible clinical applications include cognitive rehabilitation such as cognitive impairment or brain injury treatments, as well as motor rehabilitation such as post-stroke rehabilitation, post-surgery rehabilitation, post-accident rehabilitation or post-disease rehabilitation.

Classifying WSN for rehabilitation is a tough task because of the important number of existing works and the wide range of covered applications. A classification following the clinical applications, like traditionally presented in review papers, is not interesting in rehabilitation case. Indeed, the same architecture can be successfully used in different rehabilitation applications. To avoid such a meaningless taxonomy, we classified existing solutions from a process point of view and we divided them into two main classes that we illustrate in Fig. 3. The first class includes WSN designed to measure the patient's movements and activities. In this category, data is continuously collected and recorded in order to be analyzed by specialists. The recorded data can be raw sensors data such as acceleration and velocity or processed data such as limb joints, angles and positions. The second class includes WSN designed to classify the patient movements. In this category, the system extracts features from the collected data and matches them to well known motor patterns in order to answer the question: "what is the action being performed by the user ?".

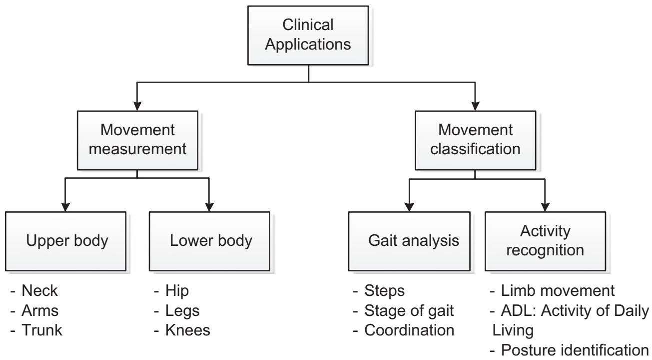

Fig. 3. Taxonomy of WSN clinical rehabilitation applications.

WSN for upper body movement measurement have been mainly developed for arms and trunk supervision. In Jung et al. (2010), authors proposed a network of six motion sensor nodes to track the upper body movement in 3D space at real-time. These sensors collect kinematic data in order to measure elbow, shoulder and waist right/left joints. These measured joints were used to animate a 3D human upper body model consisting of a trunk and two limbs. In Perez et al. (2010), authors defined a kinematic model to accurately track 3D upper limb motion in rehabilitation of brain injury patients. Furthermore, they developed a methodology based on sensor nodes for calculating six degree of freedom, namely, orientation (roll, pitch and yaw), acceleration, angular velocity and magnetic north.

WSN have also been used to monitor the movement of lower body parts such as knees, legs and hips. The Telefonica's I+D Rehabitic project (Olivares et al., 2011) is a knee telerehabilitation project that offer real-time 3D animation of the movement being performed by the patient. Rehabitic fusions data from heterogeneous sensors (accelerometer, gyroscope and magnetometer) to achieve accurate 3D localization of monitored foot. The HipGuard project (Soini et al., 2008) is a wireless sensor network for patient recovery from hip surgery. HipGuard is based on a set of wireless modules with accelerometer, magnetic and capacitive insole sensors to measure hip/leg position and rotation as well as the force between the foot and the shoe.

Gait analysis is an emerging application of WSN for rehabilitation. Hanson et al. (2009) used a wireless sensor node for shuffle/normal gait classification. They proposed a signal processing algorithm for data normalization, features extraction and wavelets pre-processing. Many studies used a wireless sensor network to identify several limb injuries such as osseous, muscular, degenerative and nervous injuries (Olivares et al., 2011). Ying et al. (2011) developed a WSN for detecting steps and respiration phases during treatment of Parkinson's Disease patients. Furthermore, they quantified the degree of the locomotion-respiration coordination using the statistic Kuiper's test (Press et al., 1992) in order to determine the stage of the disease and to re-learn coordination.

Activity of Daily Living (ADL) recognition is a promising rehabilitation application. Guraliuc et al. (2010) presented a WSN for arm movements detection. They implemented an algorithm based on the RSSI (Received Signal Strength Indicator) to identify and classify the rehabilitation activities. They used a max-win voting strategy to classify seven features derived from the RSSI to characterize the patient movements. Alhamid et al. (2011) used a 3 axis-accelerometer sensor network attached to different body segments in order to identify the patient posture (walking, standing, sitting, lying down or falling). They applied a K-Nearest Neighbor (KNN) (Holmes and Adams, 2002) classifier to distinguish between features computed by each sensor separately. Later, they merged the different sensors/classifiers data using a Bayesian network (http://www.cs.ubc.ca/murphyk/Bayes/bnintro.html) in order to identify the patient activity.

Besides motion monitoring, WSN have been used as a research tool for assessment of treatment efficacy, comparison of different treatment protocols, evaluation of recovery and identification of pathological postures and movements. Furthermore, WSN can be used as a support system to improve the efficiency of the rehabilitation process. For instance, the Ubiquitous Rehabilitation Center (Jarochowski et al., 2007) uses a WSN to manage all aspects of a rehabilitation center. It allows specialists to assign prescriptions to patients, to configure rehabilitation machines for patient's particular prescription (i.e. setting resistance, duration and frequency) and to record patient activity while they are carrying out their prescriptions. Bravo et al. (2011) proposed a mobile system to monitor frailty of elderly people during rehabilitation. Their solution computes a frailty index based on balance, mobility, endurance and physical activity of the patient and triggers an alarm if the index reaches a defined threshold.

3.2. Benefits

WSN and visual motion tracking systems have different characteristics that we summarize in Table 1. Consequently, using WSN for rehabilitation supervision brings the following benefits.

Table 1
Comparison between visual motion tracking and WSN based solution for rehabilitation supervision.

Characteristic	Visual motion tracking	WSN based solutions
Cost	High	Low
Accuracy	High	Good
Complexity	High	Low
Automation	Moderate	High
Feedback	High	Moderate
Mobility	Low	High
Comfort	High	Good
Multi modality	NA	High

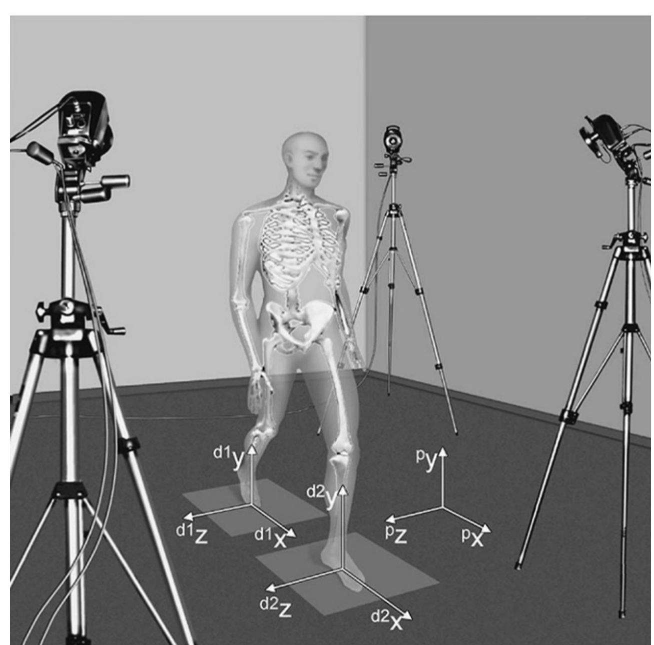

Fig. 4. Camera-based monitoring system (Cappozzo et al., 2005).

3.2.1. Cost effectiveness

Health care cost has been rising for several years and will continue to rise even more rapidly in the future. From a cost perspective, the key challenge today is to move healthcare from where it is expensive (hospitals, clinics ...) to where it costs less (patient's home). This situation is more challenging for rehabilitation because it is a long-term time consuming therapy. Wireless sensor networks, a low cost technology, is then a key to the successful implementation of telerehabilitation services which can replace the traditional face-to-face services and hence improve the cost effectiveness. Moreover, they reduce the stress on rehabilitation providers as well as improve the quality of life for patients.

3.2.2. Installation easiness

Traditional rehabilitation supervision solutions have been proven effective but limited to well equipped laboratories because of their cost and complexity. For example, using a camera-based monitoring system requires installing several cameras to cover different perspectives like illustrated in Fig. 4. In addition, these cameras need to be calibrated and correlated to make possible an accurate 3D localization. This example clearly demonstrates that such system is complicated and cannot be used at home by non-technical and a fortiori by disabled persons. Wireless sensor networks for rehabilitation enable the development of user-friendly easy to use monitoring solutions. Indeed, WSN are easily deployable systems where the patient wears several sensors and starts data collection through a simple user interface. WSN are often based on frameworks that support service discovery, dynamic network construction and configuration as well as sensor node management. All these features improve the system usability and make it suitable for everyday use.

3.2.3. Care access improvement

Restoration of functions is a slow process that requires prolonged courses and regular visits to rehabilitation providers. Commuting to a hospital is expensive and troublesome because of patient disabilities and inadequate transportation. In addition, the patient often needs another person to bring him to the therapy center. Consequently, tele-rehabilitation from a remote location is important for the patient. Wireless sensor networks are ideal for developing at-home rehabilitation solutions able to save time and travel overhead for both patients and care providers. Indeed, the patient can perform their exercises at home and receive automatic real-time feedback from the monitoring system. Furthermore, recording and sending patient's sessions to the hospital gives the therapists more data for deeper analysis and feedback.

3.2.4. Patient mobility

One major benefit of wireless sensor networks for rehabilitation is extended mobility. Namely, lack of wires, small form factor and light weight sensor nodes enable patients to move freely while performing their exercises. A typical scenario of mobility is a patient using a wireless sensor network to do his exercises in a public park. Data is collected at the patient's mobile and relayed to the hospital databases through a 3G connection.

3.2.5. Increasing motivation

Psychological aspect of rehabilitation is of a primary importance. Patients, often affected by post event depression, need to be motivated and encouraged to adhere to long term medical therapies. Rehabilitation exercises are usually considered boring for patients because of their repetitive nature. Wireless sensor networks coupled to other technologies such as video gaming (Burdea et al., 2010) and virtual reality (Cameirao et al., 2010; Alamri et al., 2010) are able to tackle the lack of motivation problem. An interesting system would be a combination of a WSN and a *serious game*, incorporating both pedagogical and entertainment elements, with increasingly difficult levels to make the patient feel the challenge and to increase its involvement in the rehabilitation process.

3.2.6. Multi-modal sensing

People concerned by rehabilitation are mainly elderly, post-stroke or post-surgery patients who may have a critical health status. Consequently, the global physiological state of these high risk patients needs to be monitored during rehabilitation sessions. Wireless sensor networks have the capacity to monitor different vital signals in addition to motion signals. They enable the use of heterogeneous sensors on a common architecture. This feature leads to the development of multi-modal WSN for *safe rehabilitation supervision*. A wireless sensor network for rehabilitation can incorporate an ECG (Electrocardiogram sensor) to monitor heart activity of weak heart patient to avoid over-exercising during rehabilitation sessions. This solution can generate an alarm when the heart rate of the patient reaches a threshold to avoid heart attacks.

3.3. Specificities

WSN for rehabilitation may seem as a special case of healthcare supervision. However, traditional WSN for healthcare do not tackle the unique challenges associated with rehabilitation. In typical medical applications of WSN, a single sensor node is used per vital parameter. Furthermore, positions of sensors are not of a primary importance and can be chosen approximatively. Since limbs are composed of segments jointed together, several sensor nodes are required to monitor the same limb during rehabilitation which increase the number of used nodes. These nodes are carefully placed and accurately localized. Furthermore, they measure several signals (acceleration, angular velocity, muscle activation ...) to capture different characteristics of the movement (displacements, positions, joint angles ...). With several nodes monitoring the same limb, information from one node become highly correlated with other nodes information. Thus, multi-sensor data fusion is used to

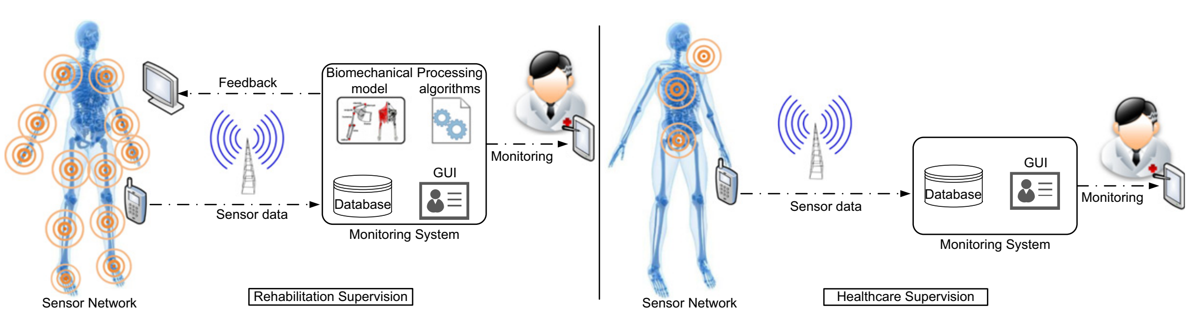

Fig. 5. Rehabilitation supervision VS healthcare supervision.

combine information from different nodes and sensors to produce clinically relevant information.

Another key difference between legacy healthcare supervision and rehabilitation is feedback delivery. In healthcare supervision, the information collected by the sensor network is only used by caregivers to monitor the patient health at real-time (Kulkarni and Ozturk, 2011). In rehabilitation supervision, the information is used by both caregivers and patients. On one hand, doctors view the summative kinematic data to assess the progress of the patient and adjust the therapy accordingly. On the other hand, the collected data is processed and provided as feedback to the patient to allow him to adjust his movements at real-time. Feedback can have different forms such as on-screen 3D avatar showing the patient's movement compared to the correct movement. Virtual reality and video games are also emerging as a new visual feedback technics specific to rehabilitation.

Unique characteristics of rehabilitation supervision have an impact on the hardware, software and communication protocol design. First of all, the architecture of WSN for rehabilitation is different as we illustrate in Fig. 5. At the software layer, new services are introduced for multi-sensor data processing and fusion as well as for real-time feedback generation. To enable the extraction of high level information, sensor sampling is performed at high frequency which generates a large amount of data. The high rate data exchanged at real-time between the components of the system have an impact on the communication protocol design. In brief, although challenges faced by legacy WSN for healthcare supervision are in many ways similar to rehabilitation supervision, there are intrinsic differences between the two which create new challenges or make traditional challenges harder to tackle as we show in the next section.

4. Challenges of WSN for rehabilitation

WSN can bring a wave of breakthroughs in rehabilitation supervision. Nevertheless, several scientific and technical challenges have to be tackled before fully enjoying the power of this technology. In this section, we present the design considerations and challenges that must be tackled in the design of new WSN for rehabilitation.

4.1. Design considerations

Applications of WSN are numerous and from one application to another, the design considerations may be different. In order to provide a better understanding of the current research challenges in WSN for rehabilitation, we have considered the requirements and the characteristics of rehabilitation supervision and then we have derived either new challenges specific to this application or traditional challenges that become harder to tackle because of unique needs of rehabilitation. At the top level of Fig. 6, we present the requirements of rehabilitation supervision from the application perspective. At the next level, we enumerate the characteristics from system perspective. These characteristics are consequences of one or several design requirements. At the third level, we show the challenges resulting from combining one or several characteristics and requirements:

- *Wearability*: WSN for rehabilitation must be carried by the patient during exercising. Consequently, sensor nodes must have an attachment to ensure a steady fixation even during rude movements. Taking into account the proximity of the nodes on the body, interferences should be considered at network layers to provide reliable communications.
- *Comfort*: Since the patient carries several sensor nodes for long periods and during physical activities, the comfort become an important design consideration to provide the highest degree of convenience. This requires the development of unobtrusive devices and small form factor batteries.
- *Durability*: Sensor nodes should have a maximum lifetime without battery charging which may be burdensome especially for elderly or impaired patients.
- *Accuracy*: Likewise WSN for healthcare, the system must show high accuracy in data collection and data processing in order to extract correct medical information. For the same reason, sensors should be sampled at high frequencies to correctly get the phenomenon being monitored.
- *Safety*: Considering the criticality of the application, the proposed solution should be safe for the patient, namely, it should be context aware to consider the patient environment and physiological state. Also, it should be without any adverse or harmful effect on the patient.
- *Interactivity*: To replace the traditional clinical rehabilitation, WSN based solutions must be interactive to guide the patient during his therapy. Particularly, the sensor network must provide real-time feedback such as indicating correct or incorrect movements to allow the patient to adjust his movements immediately.

4.2. Challenges

The combination of the application requirements and the system characteristics creates the following challenges:

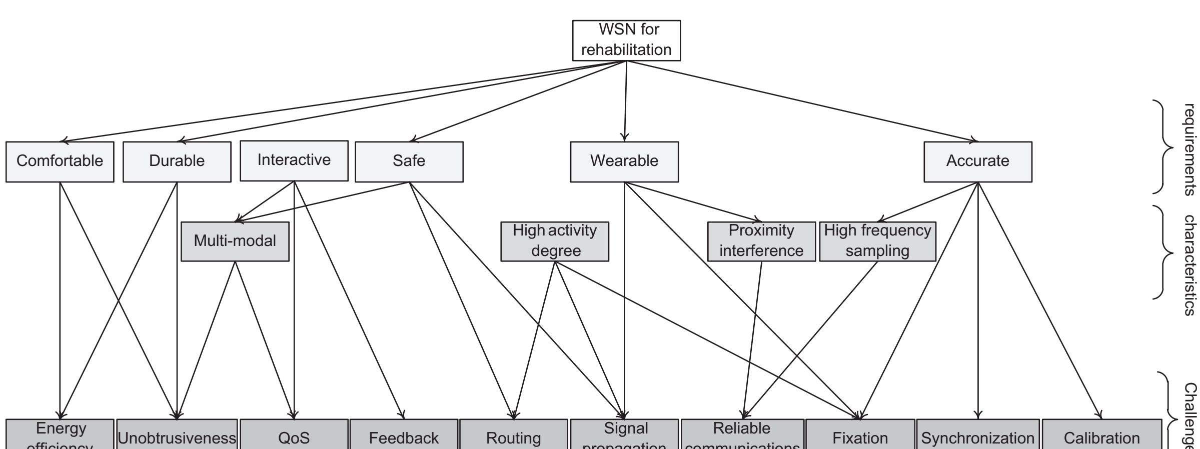

Fig. 6. Requirements and challenges of WSN in rehabilitation supervision.

4.2.1. *Unobtrusiveness*

In rehabilitation supervision, the patient carries several sensors attached on his body during rehabilitation sessions. Since he performs physical exercises for long periods, unobtrusiveness becomes one of the basic needs and requirements for the acceptance of this technology. Nodes must be lightweight and small enough to provide the highest degree of comfort and convenience (Anliker et al., 2004). As previously discussed, multi-modal supervision enables safe rehabilitation monitoring of high-risk patients. However, integrating different types of sensors into one device makes it a challenge to build small multi-modal sensor nodes. Furthermore, the battery size constitutes the biggest miniaturization bottleneck since it is the largest contributor to the sensor size and weight. Indeed, developing smaller batteries with fair energy resources is a hard challenge since the battery capacity is directly related to its size (Otto et al., 2006).

4.2.2. *Fixation*

One potential direction to improve the accuracy of collected data during rehabilitation is the development of new node attachment techniques. If a sensor node does not have a good contact with skin, it may drift from its initial position and influence the quality of data. This issue is a challenge because of the high-degree activity of the patient. Indeed, several papers have reported that skin mounted accelerometers may overestimate amplitudes and low-pass filter the acceleration signal (Lafortune, 1991; Light et al., 1980). Harms et al. (2008) indicated critical aspects that should be considered in posture and garment selection when developing comfortable garments for rehabilitation. Finally, we should mention that the proposed attachment technique should be easy to handle even for people with significant loss of functions (Zhou and Hu, 2008).

4.2.3. *Energy efficiency*

Energy efficiency is a significant challenge in rehabilitation supervision because of the specific characteristics of the application. Indeed, the high rate sampling of sensors and the transmission of the high amount of generated data consume much of energy. To achieve low power consumption, sensor nodes often use low duty cycling by going off most of the time. Unfortunately, duty cycling cannot be used in rehabilitation supervision because motion sensors must be continuously sampled. Nodes battery charging is burdensome for elderly and disabled rehabilitation patients. In order to prolong the sensor node life time and reduce charging overhead, the battery volume must be considerable. However, this goes against the unobtrusiveness requirement. Consequently, development of novel power supplies is paramount. It is widely recognized that wireless communication is the most power consuming process in wireless sensor networks. Energy aware MAC protocols (Marinkovic et al., 2009) must be developed to control the dominant sources of energy waste: idle listening, overhearing and collision (Ullah et al., 2010). At the same time, rehabilitation applications need highly reliable communications and high data rates, resulting in contradictory objectives at network design. Trade-off must be found to conciliate performance and network lifetime which is a hard challenge.

4.2.4. *Body impact on signal propagation*

In rehabilitation supervision, sensor nodes are worn by the patient and the effect of human body on the wireless transmission must be understood. The signal propagation through the body is affected by the diffraction around the body and the reflection from the body (Chen et al., 2011). These phenomena affects the communication performance especially if sensors are placed on different side of the body (Taparugssanagorn et al., 2008) which is often the case in rehabilitation. Consequently, we need accurate and realistic propagation models in order to optimize or to develop new communication device and protocols. Developing propagation models is a key challenge because of the complexity of body structure (skin, bone, liquid) and especially because of the high degree of activity during rehabilitation exercises. Indeed, Di Franco et al. (2010) showed that even small involuntary movements along with respiration can cause significant signal fading. Beside the effect of human body on the wireless transmission, the adverse biological effect of radio transmissions on human body must be investigated too.

4.2.5. *Reliability*

In rehabilitation supervision, several sensor nodes must be used to measure the different signals characterizing the movement of the monitored limb. For instance, three nodes at least are required to monitor the movement of an arm (fixed on the hand, on the segment between the shoulder and the elbow and on the segment between the elbow and the wrist). Also, monitored signals, such as acceleration and velocity, are continuous and the amount of collected data needs to be large enough to correctly get the phenomenon being monitored. Proximity issues regarding the placement of several nodes on the body and the continuous streaming of high volumes of data lead to heavy collisions and extra energy consumption. Developing a MAC protocol which provides reliable data transfer is a key challenge for rehabilitation supervision. The proposed protocol must achieve maximum throughput in spite of severe interference and relatively low bandwidth available in WSN.

4.2.6. *Quality of service*

Considering the limited buffer size and the high sampling rate, the communication protocol should support online communications to send data before being dropped out due to buffer overflow (Hadjidj et al., 2011a). Moreover, the communication protocol should support *real-time communications* with guaranteed delays to deliver real-time feedback to the patient during rehabilitation sessions. As the health of patients is involved, the system must guarantee the delivery of alerts, such as falls of elderly during exercising, within strict delay constraints. For this purpose, emergency *data prioritization mechanisms* should be developed. WSN for rehabilitation supervision often combine several sensors which we summarized in Table 2. This table clearly shows that generated traffic have different characteristics (data rate, sampling frequency, packet size). Due to specific characteristics of each traffic type, the communication protocols should implement *service differentiation* to differentiate between packets and to process them accordingly.

Table 2
Sensors commonly employed in rehabilitation.

Sensor	Data rate	Bandwidth	Sampling	Data
Acc	High	35 kbps	0–500 Hz	12 bits
Gyro	High	35 kbps	0–500 Hz	12 bits
ECG (12 leads)	High	288 kbps	100–1000 Hz	12 bits
ECG (6 leads)	High	71 kbps	100–500 Hz	12 bits
EEG (12 leads)	High	43 kbps	0–150 Hz	12 bits
EMG	Very high	320 kbps	0–10,000 Hz	16 bits
Temperature	Very low	120 bps	0–1 Hz	8 bits
Image sensor	Very high	1 Mbps	–	–
Video sensor	Very high	100 kbps	–	–

4.2.7. Routing

Star topology with one-hop communications has been assumed to be the best network topology for body area networks considering the traffic pattern and the short distance between nodes. However, with unique characteristics of rehabilitation and the impact of human body on wireless transmissions, one can justifiably ask if really one-hop communications are better than multi-hop communications in terms of reliability and energy efficiency. To hop or not to hop data in WSN for rehabilitation is a non-trivial question that must be considered. The work presented in Zasowski et al. (2003) was the first attempt to point the benefits of using multi-hop communications in wireless body area networks (WBAN). Later, Natarajan et al. experimentally investigated the impact of network topology on the average number of retransmissions, network lifetime (Natarajan et al., 2009) and packet delivery ratio (Natarajan et al., 2007). They concluded that the multi-hop strategy is more reliable especially in outdoor settings. This can be explained by the fact that wireless communication through the human body is impossible even at high power transmission.

4.2.8. Calibration

Inertial sensors (accelerometer and gyroscope) are the most used sensors in rehabilitation supervision. Unfortunately, these sensors suffer from errors in motion estimation because of measurement noise and fluctuation of offsets. This problem is known as the ‘‘drift problem’’ (Kavanagh and Menz, 2008) and should be solved by calibration techniques. Sensor calibration is an adjustment applied to the sensor output so it matches the real value of the monitored signal. This adjustment is made by applying an offset to the measured value in order to eliminate a constant component called ‘‘fixed error’’ as well as a variable component called ‘‘random error’’ which may vary over time and environment (e.g. electrical noise, thermal drift). Building calibration techniques that take into consideration the fluctuation of the random error when the sensor environment changes (e.g. ambient temperature) is a challenge that must be tackled.

4.2.9. Synchronization

In WSN for rehabilitation, data generated at different sensor nodes is highly correlated. Indeed, several nodes are usually fixed on the same limb at different segments to monitor its movements. The sensed signals must be matched following their sampling instant to enable the reconstruction of the correct original movement. Sensor nodes do not share a common clock and need a synchronization mechanism to time stamp their data with the same reference. Consequently, accurate data time stamping and tight synchronization are critical problems that need to be addressed.

4.2.10. Feedback

Providing useful and motivating feedback to patients is both a key factor in the motor recovery process and a real challenge to address. Indeed, indicating incorrect movements and immediately correcting them have been shown to optimize motor recovery (Sveistrup, 2004). In addition, feedback have been described as more interesting and enjoyable, thereby encouraging the patient to spend more time in therapy (Bryanton et al., 2006). The main challenge in providing feedback is to convert raw sensor data into relevant clinical information. This requires the development of efficient *signal processing algorithms* and novel *kinematic/kinetic models*. For instance, the conversion of angular velocity and accelerations into displacement and positions (particularly specifying the reference point) is an active research area. *Multi-sensor data fusion* is also a problem since several sensors are needed for clinical data extraction. Overall, these algorithms must be *real-time* and guarantee response within strict time constraints to preserve the interactivity and reinforce the benefits of therapy. Finally, there is a clear need for *adequate feedback presentation*. For example, the feedback should be multi-modal (image, sound, movement, touch) to be useful for patients with different impaired functions such as visual or hearing problems. Virtual reality and interactive gaming are emerging as a new presentation approaches for the patient movements and progress.

5. Review of wireless sensor networks architectures for rehabilitation

In this section, we review conducted projects on WSN for rehabilitation in order to highlight addressed challenges and proposed solutions. We classify research works, with respect to the design objectives, into four main classes: sensor node design, communication protocols design, signal processing design and frameworks design.

5.1. Sensor node design

To achieve comfortable and non-invasive continuous rehabilitation supervision, sensor nodes should satisfy the following requirements: *minimal weight*, *miniature form factor*, *wearability and unobtrusiveness*. However, these requirements represent a challenging task for sensor node design since the batteries capacity is directly related to its size. Accordingly, sensor nodes should implement low power consumption hardware to enable long life time with small batteries. In addition, wireless medical sensor design should promote flexibility and easy integration of other sensors/actuators.

In Saito et al. (2009), authors designed a small sensor unit with gyroscope and accelerometer sensors to build a simplified, low cost and wearable sensor network for gait evaluation. In this study, authors focussed on measuring ankle and knee joint angle during gait rehabilitation. In order to reduce error accumulation inherent to inertial sensors and unknown initial joint angles, they applied a stationary Kalman filter to the difference between inclination measured by the accelerometer and the gyroscope. Although the form factor of the developed sensors is small, they are interconnected by wires which may limit the patient's activity and level of comfort and thus negatively influence the measured results.

In Lim et al. (2010) have developed a wireless sensor network which is used in upper arm rehabilitation for stroke patients. Their work focussed on the design of a wearable, compact and low cost sensing module able to measure the arm movement with accuracy. The wearable sensor module consists of an Optical Linear Encoder (OLE), an accelerometer sensor, a 16 bits microcontroller and a CC2420 radio-transceiver. The wearability of the sensor module is done with a plaster that adheres to the human skin as illustrated in Fig. 7.

Actis (activity sensor) described in Milenkovic et al. (2006) and Jovanov et al. (2005) consists of a standard Telos mote and a custom Intelligent Signal Processing Module (ISPM) board. The authors extended the Telos mote capabilities by adding two perpendicular dual axis accelerometers and a bio-amplifier for Electrocardiograph (ECG) sensor. This sensor is integrated into a multi-tier telemedicine architecture for computer-assisted physical rehabilitation application.

The iNode presented in Ying et al. (2009) is a miniaturized sensor node with a Force Sensitive Sensor (FSS) and a Respiratory Inactive Plethysmography (RIP) sensors. iNode measures the locomotive and respiratory signals and analyzes the coordination

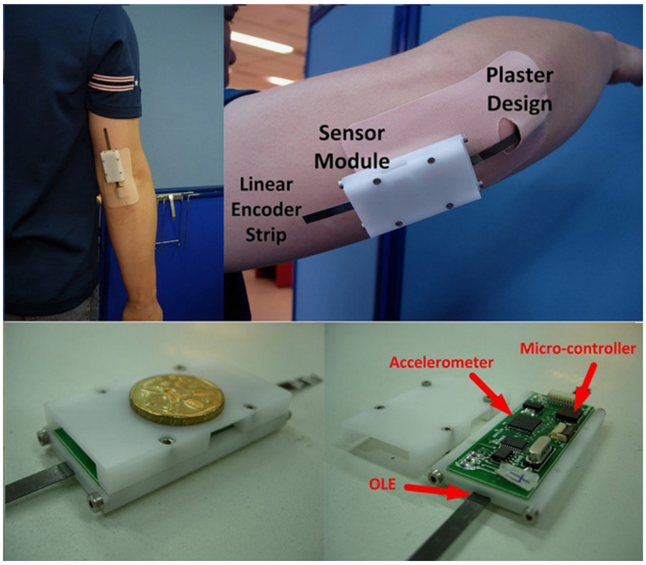

Fig. 7. Plaster design of sensor module (Lim et al., 2010).

between them in order to facilitate the rehabilitation for Parkinson patients. It implements an on-board 2-phases steps detection algorithm and a respiratory phase detection method, which have been optimized for the MSP430 processor hardware.

5.2. Communication protocol design

WSN for rehabilitation have two specific characteristics which impact the network performance and cannot be ignored. First, the placement of several adjacent sensor nodes on the body causes serious interferences problems. Second, sensor nodes need to continuously stream high volumes of data at a determined rate over long periods in order to extract clinically relevant information. Consequently, reliable communication protocols able to handle large amount of data, in spite of severe interference and relatively low bandwidth, are needed.

Some existing works address the challenges of designing a communication protocol for wireless sensor networks used in rehabilitation supervision. In Schloesser et al. (2008), authors developed a communication protocol based on the 802.15.4 standard to network the iNode sensors. However, it does not support a mesh topology and has a communication range limited to 10 m. In Hamel et al. (2008), authors developed a complete telerehabilitation system that combines information from a wearable sensor network and a video conferencing system. The sensor network consists of MicaZ modules with different sensor sets (respiratory belt, instrumented shoes, pulse oximeter and accelerometer). The objective of this work was to study the impact of the number of sensor nodes used and the sampling rate on the reliability of the radio transmission. Authors showed that high sensor sampling frequency dramatically reduces the reliability of the communication protocol but did not propose a solution for this issue.

HipGuard (Soini et al., 2008) is a wireless sensor network for patient recovery from hip surgery. It is a set of wireless modules with accelerometer, magnetic and capacitive insole sensors to measure hip/leg position and rotation as well as the force between the foot and the shoe. Authors used ANT (http://www.thisisant.com/) networking technology to collect data from sensor modules to the base station. However, this technology presents significant drawbacks such as limited communication range and fixed packet size.

In Silva et al. (2011), authors presented an inertial/magnetic wireless sensor network for motion capture which allows monitoring of several patients at the same time. This system has a modular and portable architecture and implements a modified version of the LPRT MAC protocol (Afonso et al., 2006) for data transport. Unfortunately, this protocol showed limited performance because it is implemented on the top of another protocol.

We have proposed in a previous work (Hadjidj et al., 2011a) an hybrid CSMA-CA/TDMA protocol for WSN for high-fidelity rehabilitation supervision. Our protocol defines two traffic classes which are HRP (High Rate Periodic) traffic sent with TDMA and LRA (Low Rate Aperiodic) traffic sent with CSMA-CA. Although our protocol achieves high performance by combining different medium access techniques, it defines only two traffic classes.

5.3. Signal processing algorithms

The development of efficient signal processing algorithms able to handle a high amount of sensor data is of great importance. These algorithms must treat data and provide a real-time useful feedback. This is one of the hardest challenges in wireless sensor networks for rehabilitation. Single sensor data is often not sufficient to extract clinically-relevant information. In these cases, more signals have to be combined to produce meaningful information that evolve into medical knowledge.

In Liu et al. (2007), authors proposed a wearable sensor system that measures reaction force in order to detect the eight different gait phases during rehabilitation illustrated in Fig. 8. This solution is based on a motion analysis system and a gait phase detection algorithm. To deal with sensor errors and calibration, authors implemented an intelligent calibration process that fuses accelerometer and gyroscope signals.

Zhou et al. (2006) designed an arm movement tracking system for rehabilitation of stroke patients and a kinematical model that integrates human arm movements. The system is based on a wearable wired sensor network and a weighted least squares filtering method in order to capture arm movements in 3-D space at real-time. The former measures the acceleration of the arm with accelerometer sensors and the latter eliminates the errors whose Euclidean distance is larger than a threshold. Both works described in Liu et al. (2007) and Zhou et al. (2006) use wired sensor networks which may limit the patient's activity and reduce user's level of comfort.

Choquette et al. (2008) investigated the feasibility and accuracy of wireless sensor networks in measuring the active time in rehabilitation (ie: the time during which the patient is active

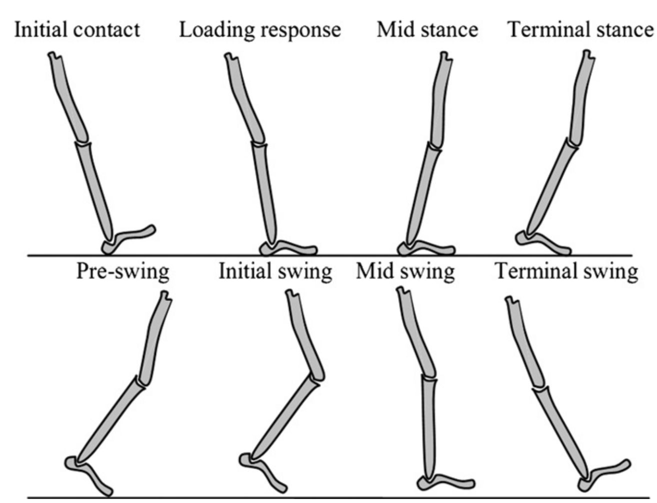

Fig. 8. Gait phase of normal walking (Liu et al., 2007).

physically). They used three Micaz modules with 3D accelerometer sensors that sample and record data at 50 Hz. Collected signals from different modules and axes are combined, low-pass filtered, rectified and high-pass filtered. Finally, the active time is estimated by extracting temporal density of the treated acceleration signals.

The Bio-WWS system described in Brunelli et al. (2006) tracks patient's movement and provides real-time feedback to correct posture and balance. It includes three modules with accelerometer sensors, a PDA acting as a gateway and a lightweight headphone for audio feedback generation. Bio-WWS collects gravitational and dynamic planar accelerations from sensors and computes the sway of the user's center of mass. In addition, it implements an algorithm to convert accelerations into a dynamic sound that guides the user to remain inside a target region. The dynamics of the generated sound (direction, volume, frequency) depends on the user's acceleration and the distance between him and a target region which is very useful for the rehabilitation.

Olivares et al. (2011) developed a WSN to monitor human movement in tele-rehabilitation applications with real-time 3D animation of the movement being performed by the patient. The system is based on wireless sensor nodes called Wagyromag (Wireless Accelerometer GYROscope and MAGnetometer) as well as a calibration and a signal processing algorithms to extract human kinematics from collected data. The Wagyromag sensor measured tilt angles instead of acceleration, angular velocity and magnetic field values. Authors used an accelerometer-aided calibration for the gyroscope calibration and an ellipsoid-fitting calibration for the magnetometer. In order to measure the inclination of body parts with high accuracy, authors developed a sensor fusion and an adaptive filtering approach. This approach used different variation of the Last Mean Square (LMS) and Recursive Least Square (RLS) filters.

In Zhou et al. (2008), authors proposed a sensor network to monitor the upper limb motion for a home based rehabilitation system. The motion tracking system consists of two sensor nodes (with accelerometer, gyroscope and magnetometer sensors) placed near the wrist and elbow to compute the wrist and elbow joints. In addition, authors developed a Langrangian based optimization technique which integrates data measured by the two sensor nodes to estimate the position of the shoulder joint. The novelty of this work is obtaining the position of three joints (wrist, elbow and shoulder) using only two sensors.

5.4. Framework and architectures design

Much effort has been done in designing easily deployable wireless sensor networks for rehabilitation monitoring. These solutions are based on frameworks that support *dynamic network construction and configuration*, *services discovery*, *resources discovery and sensor node management at runtime*. A combination of different technologies like video sensing, gaming and virtual reality have also been investigated in order to enhance the context awareness and attractiveness of existing solutions.

Mercury (Lorincz et al., 2009) is a wearable wireless sensor network platform for motion analysis of patients who suffer from neuromotor disorders. It is based on a flexible programming interface allowing clinicians to implement different policies following the application requirements. This interface enable real-time configuration of sensor sampling rate, storage mode, feature extraction and data transmission mode. Mercury achieves a network lifetime of a couple of days by collecting high-level features from sensor nodes.

In Kifayat et al. (2010) presented a framework that combines wireless sensor network technology and gaming to assist rehabilitation of patients with physical disabilities. The system is based on a framework which supports dynamic nodes, sensors and service discovery. The wireless sensor network is attached to the patient's body to measure its acceleration. While the patient plays the game, acceleration data is collected in real-time by the wireless sensor network and sent to a control service allowing the patient to control its virtual representation (avatar showed in Fig. 9) by physically moving his body. At the end of the game, the framework generates different reports and graphs for doctor and patient.

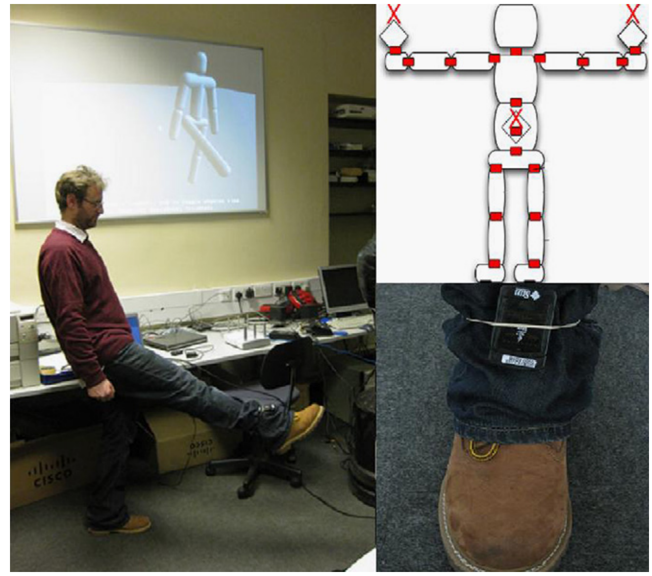

Fig. 9. Gaming for rehabilitation (Kifayat et al., 2010).

RehabSPOT proposed in Zhang and Sawchuk (2009) is a highly customizable wireless sensor network platform for rehabilitation built on the top of SunSPOT sensors. The system is based on a software architecture which enables sensors management at runtime (addition/removal of sensors, adjusting sampling rate). In addition, RehabSPOT architecture implements dynamic network construction, devices and sensors discovery and fault tolerance features. Although the usability of RehabSPOT, it requires a long (a fifteen minutes) and a complex setup procedure.

Otto et al. (2006) proposed a hardware and software WSN architecture for health monitoring. They developed a prototype made up of two activity sensors ActiS (Jovanov et al., 2005), an ECG/tilt sensor (eActis) and a PDA base station. Each sensor node samples sensor signals, analyzes data and transmit application event messages. The software architecture provides several application services such as time synchronization, power management, configuration and commands transmission.

Hamon (Health signs and Activity MONitoring) (Alhamid et al., 2011) is a real-time monitoring framework which can be used in several physical rehabilitation such as cardia rehabilitation and Parkinson's Disease rehabilitation. The main objective of this framework is to provide an open and flexible software for the development of applications which collect, analyze and present data collected by a WSN. Hamon can monitor the number of sensor nodes making it easy to collect data from any newly added sensor node. In addition, the framework can implement any processing algorithm for data interpretation.

5.5. Discussion

There has been a host of research works on WSN for rehabilitation supervision which we reviewed in this section. We classified these works into four categories following their design objective. The first category addressed challenges faced at the hardware level. The objective of this class of works was to build unobtrusive, miniaturized and multi-modal sensor nodes fitted to rehabilitation supervision. To achieve their objective, most of researchers designed and implemented new hardware platforms integrating intelligent sensor boards along with different kind of sensors (see Table 3). Data collected by this sensors was locally processed before being wirelessly sent to the base station. Unfortunately, these works did not consider energy saving neither the fixation of sensor nodes in their design.

The second category of works investigates the transport of collected data. They proposed communication protocols to wirelessly gathering samples generated by sensors and collecting them at a central gateway. These protocols are often based on a TDMA or an hybrid CSMA/TDMA access technic in order to provide reliable data collection under high data transmission rate (see Table 4). However, other QoS mechanisms such as real-time communication, prioritization and service differentiation has not been proposed. In addition, energy efficiency is a major challenge and a paramount design consideration that has not been considered.

The third category targets the extraction of clinical relevant information from the collected data (see Table 5). This information should evolve into medical knowledge which is useful and viable for doctors. These works proposed efficient signal processing algorithms combining several optimized techniques such as features extraction, fusion and clustering. Most of these works used filtering technics (high-pass filters, low-pass filters, Kalman filters) to clean out the collected data from noise and errors. However, adequate calibration technics, to reduce the undesired components and errors caused by different kind of offsets, should be developed and used. In addition, some proposed algorithms must be optimized to support real-time data processing.

The last category deals with the development of flexible, easy to use and efficient architectures for rehabilitation supervision. Namely, they proposed frameworks which support deployment, configuration and management of nodes in real-time. Combinations with other technologies, such as games and virtual reality, have been proposed and successfully implemented. Table 6 shows different features implemented by works falling in this category.

It is clear from the number of surveyed works that WSN for rehabilitation is a broad and a complex research area. Several research communities are involved in this field proposing complementary innovative solutions. However, these research communities worked solitary, each one separately on her own, to tackle challenges introduced by this new technology. Consequently, there is no complete framework today with a whole design that considers node design, data transmission and data processing for rehabilitation supervision. We believe that bridging researchers with different scientific backgrounds could have a significant impact on the development of such solution and could improve the way rehabilitation is provided today.

6. Open issues and potential research directions

In this section, we describe the main open issues and suggest directions for future researches and works.

6.1. Advanced hardware design

Considerable amount of research has been conducted on the design of unobtrusive and miniaturized sensor nodes. However, a lot of open issues still exist. The level of comfort necessary for widespread adoption of WSN in rehabilitation supervision

Table 3
Comparison of sensor node design projects.

Ref.	New platform	Integrated sensors	Fixation	Wireless	Energy	Onboard processing
Saito et al. (2009)	✓	-Uniaxial gyroscope -3 axis accelerometer	×	×	×	-Error and offset reduction -Lower limb joint angle measurement
Lim et al. (2010)	✓	-OLE	✓	✓	×	-Upper limb joint angle measurement
Milenkovic et al. (2006)	×	-2 axis accelerometer -ECG	×	✓	✓	-Acceleration filtering -User activity estimation
Ying et al. (2009)	✓	-FSS -RIP	×	✓	×	-2 phases step detection optimized for the MSP430

Table 4
Comparison of communication protocols.

Ref.	Access technique	Energy saving	Service differentiation	Traffic prioritization	Topology
Hamel et al. (2008)	CSMA	×	×	×	Star
Soini et al. (2008)	TDMA	✓	×	×	Star
Silva et al. (2011)	TDMA	✓	×	×	Star
Hadjidj et al. (2011a)	CSMA/TDMA	✓	✓	×	Star

Table 5
Comparison of signal processing projects.

Ref.	Objective	Real time	Calibration	Error reduction	Filtering	Fusion
Liu et al. (2007)	-Detection of 8 gait phases	×	✓	✓	✓	✓
Zhou et al. (2006)	-3D arm movement tracking	✓	×	✓	✓	×
Choquette et al. (2008)	-Measurement of active time of rehabilitation	×	×	✓	✓	×
Brunelli et al. (2006)	-Estimation of sway of the user's center of mass and generation of Audio feedback to correct balance	✓	×	×	×	×
Olivares et al. (2011)	-Extraction of human kinematics	✓	✓	✓	✓	✓
Zhou et al. (2008)	-Monitoring upper limb motion	×	✓	✓	✓	✓

Table 6
Comparison of rehabilitation frameworks.

Ref.	Node discovery	Sensor discovery	Dynamic configuration	Other features
Lorincz et al. (2009)	×	×	-Sampling rate -Storage mode -Transmission mode	-Features extraction -Energy management
Kifayat et al. (2010)	✓	✓	-Not supported	-Gaming
Zhang and Sawchuk (2009)	×	×	-Sampling rate	-Fault tolerance -Secure communications
Otto et al. (2006)	✓	×	–Supported but not detailed	-Time synchronization -Energy management -Visual node identification -Realtime alerts and feedback
Alhamid et al. (2011)	✓	×	-Not supported	-Alerts and real-time feedback -Support any processing algorithm

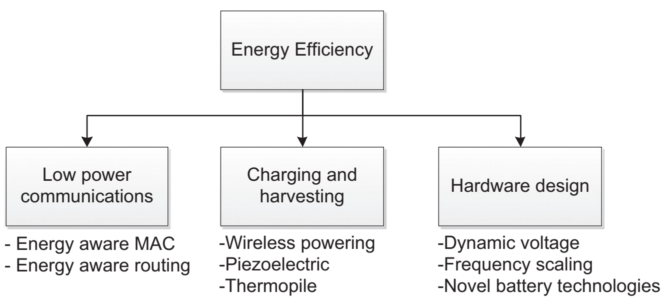

Fig. 10. Energy efficiency solution for WSN in rehabilitation.

requires more miniaturization of batteries, circuits, sensors and radio transceivers. Wire connections should be completely removed because they may limit the user activity and significantly interfere with his normal behavior. For instance, developing electrodes with separate radio transceiver to wirelessly connect to an EMG board remains a challenge (Chen et al., 2011). Smart textiles (Park and Jayaraman, 2010) is an open research area with promising potential due to good contact between the sensors and the skin (Pantelopoulos and Bourbakis, 2010) leading to steady fixation and reliable motion estimation.

6.2. Energy saving

The unobtrusiveness requirement obviously limits the size of the batteries that will power the node and hence reduce the network lifetime. Consequently, we believe that a combination of power-optimal hardware design, energy harvesting techniques and low power communications is the optimal solution for achieving prolonged continuous monitoring (Fig. 10).

Activity-aware energy models are an interesting research direction in order to minimize the power consumption. In these models, the node dynamically manages its sensors sampling, data processing and data transmission following the patient activity level (Sun et al., 2011). For instance, a context-aware episodic sampling technique, such as developed in Au et al. (2009), can be used to reduce the sampling frequency when the patient takes a rest between two rehabilitation exercises. Also, an on-demand performance processor with dynamic voltage and frequency scaling (Raskovic and Giessel, 2009) can be used to provide high performance when required and low power consumption otherwise. Developing such on-demand performance processors remains an open research challenge.

Energy harvesting is another option to tackle the energy efficiency challenge, but the amount of power available from such techniques is relatively small. In rehabilitation applications, solar cells cannot be used since sensors are often worn under the patient clothes (Tadayon et al.). However, power scavenging methods through motion (Piezoelectric Olivares et al., 2010) or body heat (thermopile Hoang et al., 2009) have a good potential. These techniques turn the patient ambient energy (motion or thermal gradients generated during exercises) into an electrical form in order to supply power to nodes. However, further research has to be conducted in order to tackle the poor density and poor miniaturization possibilities of these techniques. More extensive discussions on these techniques can be found in Mitcheson (2010) and Romero et al. (2009).

Development of novel power supplies is paramount to tackle battery recharging issues. Recently, researchers from the University of Illinois developed a novel battery that can be 90% charged in 2 min (Zhang et al., 2011). Another hot research topic that must be investigated is wireless powering methods such as light, capacitivo or ultra sonic techniques (Zhang et al., 2009, 2010). Researchers from MIT (Kurs et al., 2007) succeeded in wirelessly powering sensor nodes over several meters using magnetic resonance. We believe that these kind of technologies can easily alleviate the battery charging issue with elderly or disabled rehabilitation patients.

6.3. Calibration

Calibration techniques are paramount for the accuracy of measured data especially in dynamic conditions due to patient activity. Design of hardware and software calibration techniques is still an open research area. Particularly, efficient calibration techniques are still needed for sensors other than accelerometers (Alemdar and Ersoy, 2010). Self calibration, as proposed by Gietzelt et al. (2008), should be investigated to enable a sensor node to automatically compute the offset and adjust his calibration algorithm.

6.4. Development and evaluation of improved propagation channel models

Characterization of On-Body channel is a hard and open research challenge due to the complexity of human tissues and body structure. Several propagation patterns has been proposed recently (Alves et al., 2011; Taparugssanagorn et al., 2008; Eid and Wallace, 2011). However, none of them take into account patient movements which is well known to have a significant impact on communication performance (Di Franco et al., 2010). New models that consider patient activity during rehabilitation are needed. Also, thorough works should be conducted to evaluate existing models at lower layer (antennas performance) as well as at higher layers (energy consumption, network performance, QoS) since their impact on the network performance have not been studied yet (Chen et al., 2011).

6.5. Development of new communication technologies

Wireless transmission suffer from fading because of the body structure and the patient movements during rehabilitation. Hence, we believe that novel communication technologies can improve the network performances. Intra Body Communication technologies (IBC), which use the human body as a communication channel, can be a breakthrough solution for this problem. Galvanic coupling (Wegmueller et al., 2010) uses two coupler electrodes inducing current into the human tissue and two detector electrodes sensing the potential difference. The signal is transformed into modulated electrical signal which is applied differentially over the two coupler electrodes and generates an electro-magnetic field in the body. The signal is received by the two coupler electrodes and the original signal is extracted. Researchers from NTT (Nippon Telegraph and Telephone) brought a major breakthrough using Electro-Optic (EO) crystal for IBC and reached a speed of 10 MB/s half duplex communication through 150 cm (Sasaki et al., 2009). Bone conduction techniques, such as OsteoConduct (Zhong et al., 2007), is another IBC based on mechanically excited bone conduction inside the human musculoskeletal system. Since these new technologies are still in their infancy, a strong need exists for further research and investigation. Particularly, their impact on human health necessitates further investigation for social acceptance.

6.6. Bio-effect of radio transmission

Human exposure to electromagnetic fields generated by sensor nodes during rehabilitation should be kept minimal to avoid advert effect. Some works have investigated the adverse biological effect of radio transmissions on human body in wireless sensor networks (Ren and Max, 2006) but research in this field is still incomplete. IEEE issued a standard which contains recommendations to protect people against harmful effect of electromagnetic fields (Revision of IEEE Std, 2006). This standard defines a threshold which must be respected to guarantee safety of patient in continuous, long-term exposure to electromagnetic fields. According to this, the output transmission of sensor nodes should be kept minimal to cope with health concerns (Ren and Meng, 2006). Low power transmission through small antenna causes high transmission errors. Consequently, antennas need to be controlled by an intelligent coupling circuit to provide both necessary signal strength and safety level which is a complex technical challenge.

6.7. Quality of service

The MAC layer is a vital element for the communication protocols as well as for the whole system design (performance, lifetime). However, only few works on rehabilitation supervision have considered the design of an appropriate communication protocol. Protocols with service differentiation, real-time communications and energy conservation should be proposed like in Saxena et al. (2008) and Otal et al. (2009). Schedule-based protocols perform well in terms of reliability and energy consumption under high contention conditions of rehabilitation supervision. However, the main drawback of these protocols is that they require tight synchronization. Li and Tan (2007) proposed an ingenious synchronization mechanism exploiting human heartbeat rhythm information. By following the rhythm, the network can achieve time synchronization without having to send any message.

6.8. Routing

The development of appropriate routing algorithms is of great importance. Indeed, all existing WSN for rehabilitation adopted a star topology with one-hop communications between each node and the gateway. However, there are evidence that multi-hop communications can be better than one hop communications in several cases (Natarajan et al., 2009, 2007). Thus, multi-hop communications should be used in rehabilitation applications and their performance should be investigated. Specific context aware routing protocols able to tune the network topology following the environment are needed. Furthermore, more appropriate routing protocols such as temperature aware routing (ALTR Bag and Bassiouni, 2006), cluster based routing (AnyBody Watteyne et al., 2007) or cross layer routing (CICADA Latre et al., 2007) can be used.

6.9. Software architecture

While a lot of researches have been carried out in the design of signal processing algorithms, only few studies have been done regarding data presentation, progress monitoring and performance feedback. Existing WSN require data transformation algorithms in order to present data in high level format. Indeed, a challenge arises from the gap between the low level sensor output and the high level user requirements of therapists (Roantree et al., 2012). Feedback in real-time has not been achieved in all works. In clinical settings, therapist guides the patient to correctly perform useful exercises for his rehabilitation. However, therapist instructions cannot be properly acquired in existing solutions. We believe that virtual reality is a potential solution that can guide the patient to perform the correct exercises without therapist intervention. However, the management and interaction with virtual environments raises new open problems discussed in Ibanez and Delgado-Mata (2011). Interactive video gaming have emerged as new treatment approaches and can brings several improvements to existing solutions. A comprehensive survey on this topic is available in Rego et al. (2010). Finally, Incorporating social dimension such as competitiveness or collaboration should be considered in future works.

7. Conclusion

Rehabilitation is a long process undertaken by a patient to return to his initial motor capabilities after a stroke, an accident or a surgery. To achieve optimal rehabilitation outcomes, the patient should be monitored and corrected during exercising. However, continuous monitoring of patients creates management and economic issues that wireless sensor networks can tackle. Indeed, wireless sensor networks for rehabilitation supervision is an emerging interdisciplinary research area that can dramatically improve the way rehabilitation is provided today.

In this paper, we have presented the different applications of wireless sensor networks in rehabilitation as well as their benefits. From the requirements of these applications and the characteristics of WSN, we have identified challenges that should be tackled before fully enjoying the potential of this technology. We have reviewed existing projects conducted by all research communities involved in this field and we have studied their advantages and weakness. Furthermore, we have studied issues that are still open and have proposed possible solutions and directions for future works.

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