A Customizable Framework of Body Area Sensor Network for Rehabilitation

Mi Zhang, and Alexander A. Sawchuk
Department of Electrical Engineering
University of Southern California
Los Angeles, CA 90089, USA
{mizhang@usc.edu, sawchuk@sipi.usc.edu}

***Abstract*—Body area sensor networks are becoming more and more popular for pervasive medical monitoring. Conventional wearable sensor systems lack flexibility for dynamic network construction and the capability of rapid configuration to facilitate personalized healthcare. In this paper, we propose RehabSPOT, a highly customizable networked wearable sensor system for medical monitoring and physical rehabilitation. The system is based on a novel software architecture. It supports various sensors and contains on-board general computing capabilities to enable dynamic body area network construction, sensor management, and adaptive data collection and display. The customization of the system is extremely fast even by non-engineering staff. We evaluate our system by deploying RehabSPOT for a rehabilitation program. Promising feedback illustrates that RehabSPOT has a significant benefit on physical therapists' daily work.**

I. Introduction

In the US, more than 700,000 people annually suffer a stroke, an event that is a leading cause of long-term disability [3]. This disability can manifest itself as difficulty in performing activities of daily living such as dressing, eating meals, bathing, or work related tasks. Fortunately, during the early post-stroke period, the impaired limb is not completely paralyzed but has limited movement capability. Studies show that the loss of function can be improved with rehabilitation therapy through some type of task-oriented motor training [12]. However, motor-training tasks used in conventional therapy are carried out by physical therapists based on their many years' experience. This methodology is limited in their capability to systematically control stimulus presentation and precisely capture motor performance for diagnose and evaluation in real time [17]. As a result, the status and the progress the patient achieves during the rehabilitation program can not be reliably monitored and precisely evaluated. Meanwhile, from the perspective of physical therapists, it is also very difficult for them to evaluate the efficiency of their designed motor-training tasks.

The emergence of wearable systems based on body area sensor networks (BASN) attempts to fill in this gap. These systems transmit physiological and motion data via either wired cables or wireless technology to a centralized location where the data can be monitored and processed by trained medical personnel. Numerous assets are provided beyond what is currently available with traditional methods by using these systems. They (1) address the weakness of traditional patient data collection, such as imprecision (qualitative observation) and undersampling (infrequent assessment) [9] [13]; (2) offer real-time sensing, signal processing, and feedback in an interactive way; and (3) enable telehealth applications to shorten hospital stay for patients under treatment.

In order to fully exploit these benefits, three important criteria must be followed when designing a wearable sensor system for rehabilitation. First, the BASN nodes must be non-invasive to make patients feel comfortable when equipped with the wearable system. In addition, the system must not limit the movement of the patients. Otherwise, the fidelity of the collected data can not be guaranteed. Second, as the focus of healthcare shifts from being "hospital-centered" to "patient-centered", wearable systems must evolve to facilitate highly personalized care. In the other hand, as with any technology, economic concerns must be taken into consideration. To balance these two aspects, BASN nodes should be designed with a high degree of configurability. Therefore, the cost of customized healcare over a large range of applications can be amortized. Furthermore, considering that the users of wearable systems are patients and medical personnel, who are people normally with limited engineering background, the system must be designed for ease of use and quickly configured. Finally, if wearable systems are to control or help assess life-critical physiological events, they must be reliable. This paper describes a BASN system design to achieve these goals.

In this paper, we describe the design, implementation, and experimental evaluation of RehabSPOT, a highly customizable wireless networked body sensor platform for rehabilitation. RehabSPOT is built on top of Sun SPOT technology [2] from Sun Microsystems. The platform consists of a number of free-range BASN nodes attached to various parts of human body, and a basestation connected to a PC. Each free-range BASN node is integrated with a standard interface making it easy to attach many external sensors. RehabSPOT fully utilizes wireless technology to provide patients with maximum freedom of movement. To enforce a high degree of system configurability and reliability, both the free-range BASN nodes and basestation are powered by a novel software architecture.

RehabSPOT's software architecture includes these features:

- A sensor management module enabling sensor addition/removal and adjustable sampling rate for each sensor during runtime;

- An exception handler inside each free-range BASN node for sensor failure detection;
- A device discovery manager installed in both free-range BASN nodes and basestation for dynamic network construction during runtime;
- Leveraging the on-board flash memory for multi-hop routing and local data storage in case free-range BASN nodes temporarily lose connections with the basestation;
- Adaptive data collection and display according to the number of BASN nodes and the types of active sensors.

Our prototype system has been installed in a local clinical center [1] in Southern California for testing and evaluation. Initial feedback from the patients under rehabilitation treatment and professional physical therapists were positive. Therefore, we believe that our RehabSPOT system can play a significant role in motor rehabilitation and greatly facilitate physical therapists' daily work.

The rest of this paper is organized as follows. Section II discusses work related to wearable networked sensor system designs. Section III explains the architecture and implementation of our RehabSPOT platform. Results from real-life experiments with RehabSPOT are described in Section IV. Finally, we summarize our work in Section V.

II. Related Work

Numerous wearable sensor systems have been proposed for physical rehabilitation [13] [10], health monitoring [4] [14] [11] [15] [5], and kinetics studies [7] [8]. In this section, we review the existing literature on wearable sensor system designs from the perspective of system architecture, and in particular, the capability of system configuration.

The LiveNet project in [13] presents a wearable mobile platform for long-term health monitoring. The system uses a central sensor hub to wire heterogeneous sensors located on various parts of the patient body. The data is then streamed to a PDA for display from the hub via a cable. However, a wire interface is intrusive in the sense that it limits users' movement so that the fidelity of the collected data is ruined.

Emil et al. in [10] present a multi-tier telemedicine system used for ambulatory monitoring. The system leverages wireless technologies to acquire data from on-body sensors. It is also capable of connecting to high-level infrastructure, such as mobile network and internet, to transfer data to remote servers. Although the authors explain the benefits brought by this system architecture, they do not discuss the implementation detail and how their system is meant to be used.

The MEDIC system proposed in [15] shares a similar multi-tier architecture as [10]. The authors design a centralized software architecture installed in a PDA. The software not only permits end users to enable/disable particular on-body sensors, but also supports system configuration and sensor management by receiving commands sent from medical professionals at remote sites. Although the system can be customized to provide personalized healthcare, its configurability is quite limited. The software only supports static configuration in that sensor devices can only be paired with the personal server before runtime. As a result, the body-area sensor network can not be re-constructed if necessary during runtime.

In [5], the authors propose a platform for health monitoring applications with the goal of reducing system customization time. The system consists of a personal server (a Pocket PC) and a multitude of Mednodes. A Mednode is a standalone embedded system equipped with a processing unit, a sensor board, and supports wireless communication. Customization at Mednode is realized by downloading different software onto Mednodes depending on patients' gender, age, medical condition, and other variables. Furthermore, the software can be downloaded onto Mednodes over-the-air and even after the system has been deployed and initialized.

Our RehabSPOT platform resembles [5] in spirit, in terms of both using a standalone device equipped with computing power and wireless interface to form a networked sensor system. However, RehabSPOT differs from the existing literature and compliments it in the following aspects: (1) RehabSPOT's software architecture follows the message-passing distributed computing paradigm by leveraging the computation power embedded inside the free-range BASN nodes; (2) We propose a lightweight protocol for device discovery at both free-range nodes and basestation to support dynamic body-area sensor network construction; and (3) Instead of downloading different programs onto different sensor nodes, RehabSPOT runs a uniform program on all free-range BASN nodes although they may perform different functions during runtime.

III. System Architecture

Figure 1 illustrates the three-tier architecture of our RehabSPOT platform. The first tier consists of all the free-range nodes that are organized as a standalone mesh network. Equipped with a unique address, each free-range node can communicate with any other node within the range. A base station connected to PC along with free-range nodes in its neighborhood compose the second tier. This tier forms a star network where the basestation acts as the master node. Data gathered and processed by the free-range nodes is transmitted to the basestation wirelessly. The basestation then streams the data to the program running on the PC for real-time display and online processing. Meanwhile, physical therapists can configure the system via a graphic user interface (GUI) provided as a part of the program. The communication among free-range nodes and basestation is based on IEEE 802.15.4 technology. We choose IEEE 802.15.4 instead of other low-power RF technologies such as Bluetooth because Bluetooth devices require a static pairing process that is not dedicated to flexible networking scenarios as in our case. In addition, a Bluetooth device can support up to eight active devices in a network while IEEE 802.15.4 offers support for a network with a capacity of over 65,000 devices [16]. This capacity limitation can not be ignored especially in the cases where a large amount of sensors are employed (e.g. fine-grained motion tracking). Our system relies on the established internet infrastructure as its third tier. In this tier, data stored inside the PC can be transmitted to a remote server for further processing.

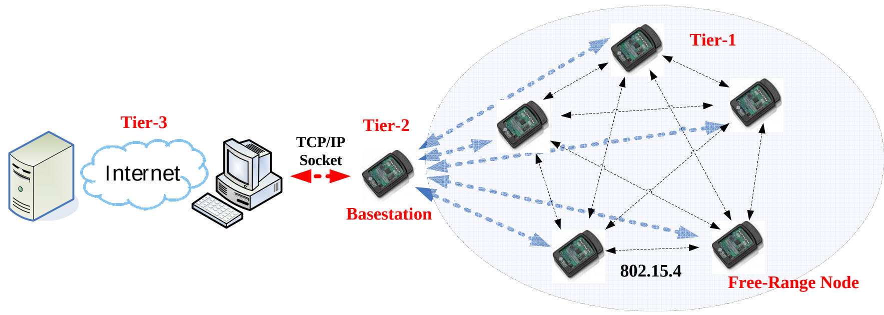

Fig. 1. Overview of RehabSPOT architecture

A. Hardware

Our RehabSPOT system hardware is based on Sun SPOT technology from Sun Microsystems. The system is composed of Sun SPOT free-range nodes, Sun SPOT basestation, and a multitude of sensors that we deploy in rehabilitation programs. Further details of these three major components are provided in this subsection. The Sun SPOT free-range node and basestation are shown in Figure 2.

1) Sensors: In health monitoring systems, sensors play key roles in sensing vital physiological signals as well as monitoring physical behaviors of users. For physical rehabilitation in particular, various types of kinetic sensors are employed in our RehabSPOT system for continual movement measurements to identify and quantify a patient's physical dysfunctions. Table I summarizes the kinetic sensors we have used and applications where these sensors can be utilized.

2) Sun SPOT Free-Range Node: The SunSPOT free-range node is a standalone small device designed for low-power RF applications. Like general embedded systems, it is software programmable that can be customized for various applications. The device consists of a 180MHz ARM microprocessor, an on-board radio for wireless communication, a sensor board, and battery [2]. The powerful 32-bit microprocessor and an 4M on-board flash memory make real-time processing and local data storage possible. The radio works at 2.4GHz and is IEEE 802.15.4 compliant. The sensor board not only includes a range of built-in sensors, such as a 2g/6g 3-axis accelerometer, but also provides a standard interface to outfit external sensors, such as the ones listed in Table I. Furthermore, we have implemented a signal conditioning accessory board to facilitate interfacing external sensors with our free-range Sun SPOT nodes in some scenarios. The board itself and a Sun SPOT free-range node coupled with the board are shown in Figure 3.

3) Sun SPOT Basestation: Compared to the Sun SPOT free-range node, the Sun SPOT basestation does not have the sensor board and battery. It is a device wired to a development machine (a PC) and allows users to write programs that can run on the PC and use the basestation's radio to communicate with any remote Sun SPOT free-range node.

B. Software Architecture

The system software is based on client-server architecture. The server program is installed and running on the PC while the client program is installed in the free-range SunSPOT nodes. Both the client and server programs are written in Java language. The communication between client and server programs follows the message-passing distributed computing paradigm. Each message contains a source address, a message type code, and data payload. The size of payload varies among different message types. The detailed message format is illustrated in Figure 4. The communication security is enforced by utilizing a highly efficient pure Java cryptographic library which supports key exchange and digital signatures based on Elliptic Curve Cryptography (ECC). In addition, it is worthwhile to note that the design philosophy that our RehabSPOT platform follows is to build a reliable and highly customizable system for personal use. This philosophy is enforced in both our server and client programs. The following

Fig. 2. Sun SPOT Free-Range node (Left) and Sun SPOT Basestation (Right)

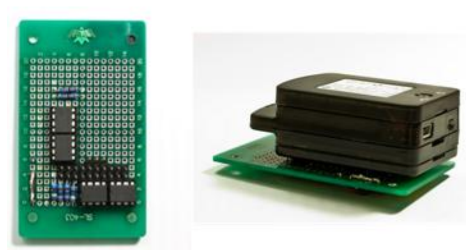

Fig. 3. The signal conditioning accessory board with voltage amplifiers and voltage divider circuitry. (Left) The free-range Sun SPOT integrated with the signal conditioning accessory board. (Right)

Sensor	Applications
Accelerometers	Gait analysis, Activity recognition, Upper extremity dysfunction identification
Gyroscopes	Gait Analysis, Upper extremity dysfunction identification
Bend	Single-finger dysfunction identification
Pressure	Gait analysis, Finger / Foot pressure measurement
IR Ranger	Upper extremity dysfunction identification
Stretch	Multi-finger dysfunction identification

TABLE I
VARIOUS KINETIC SENSORS USED IN PHYSICAL REHABILITATION TRAINING TASKS

subsections describe the design and implementation details of these two parts.

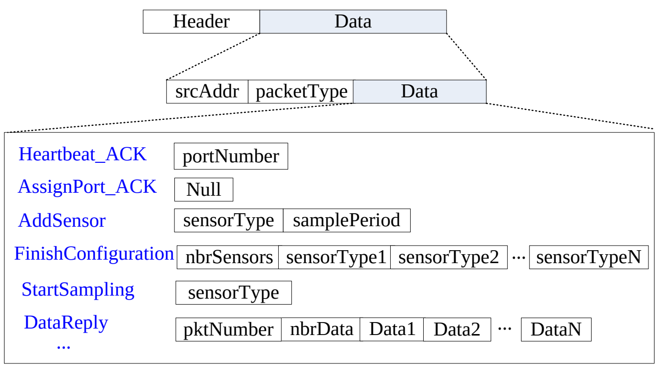

Fig. 4. RehabSPOT Message Formats

1) Client Program: Figure 5 presents the software architecture of the client program. It consists of four main components, the device discovery manager, command listener, sensor controller, and data aggregator. The device discovery manager is responsible for establishing and maintaining wireless connections with basestation and other free-range nodes in the neighborhood. Considering that the microprocessor embedded in the free-range node has a relatively constrained capability, a lightweight device discovery protocol with a small memory footprint is designed and implemented. To initiate the connection, a *Heartbeat* message is broadcast via a well-known radio port. Between two consecutive broadcasts, the free-range node goes to deep sleep mode to save power. If there are any other nodes nearby, a *Heartbeat_ACK* acknowledgment message with the sender's unique MAC address will be received. This information is stored and maintained in a local routing table. If the connection with the basestation is temporarily lost, the device discovery manager will opportunistically route the data to one of the available nodes. In the worst case, if there is no free-range node alive, it pushes the data into the flash memory and goes back to the initial state to broadcast *Heartbeat* message with a much longer period until the basestation is recovered.

The command listener running as a background thread listens to commands sent from the basestation. It then dispatches the corresponding commands to either the sensor controller or data aggregator respectively. The sensor controller is a software layer abstracting out the common aspects of connectivity into a generic controller. As a result, any sensor powered by either 3VDC or 5VDC can be connected onto the free-range node externally. Based on the received configuration messsages (*Add_Sensor*,*Remove_Sensor*), the sensor controller turns on/off any connected sensor and manipulates some of the operating parameters, such as sampling rate. Furthermore, by leveraging the powerful 32-bit on-board microprocessor, a FIR low-pass filter is implemented to prevent oscillations from unwanted impulse data. In addition, this low-pass digital filter helps detect sensor failure if the output data from the filter falls beyond the threshold several times in a row. In such cases, an exception handle is activated to turn off the broken sensor.

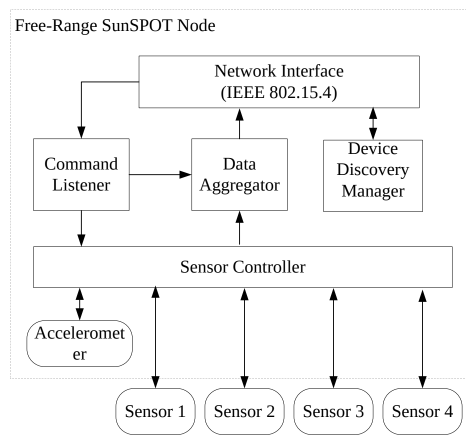

Fig. 5. RehabSPOT client architecture

When configuration is complete, a format file recording the types and sampling rates of chosen sensors is generated and passed to the data aggregator. The data aggregator then composes the *Data_Reply* messages based on it and pushes the messages into a queue where the messages are sent out in order. In addition, it should be noted that during our experiments, we found that the overhead to send a message could be significant (2-4 ms depending on message size). As a result, this radio overhead becomes the bottleneck for real-time performance even though the sensors' sampling rates are high enough. To amortize this overhead, multiple samples are bundled together into a single message. Another benefit of doing this is it reduces radio usage so as to reduce the radio power consumption, making the system more energy-efficient.

2) Server Program: The software architecture of server program is shown in Figure 6. Similar to the counterpart

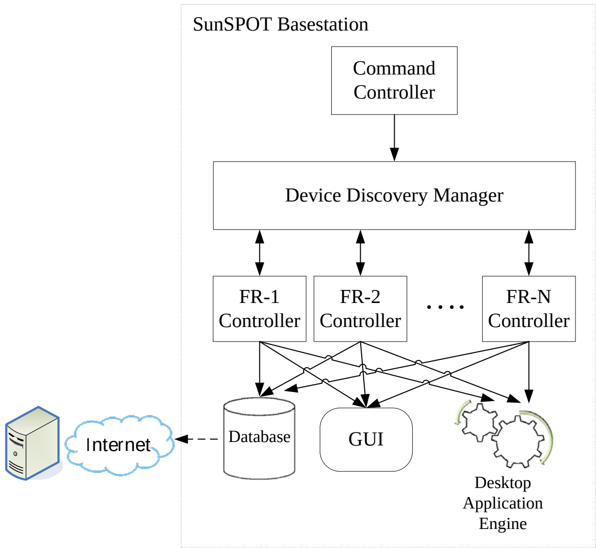

Fig. 6. RehabSPOT server architecture

in free-range node, the device discovery manager in the basestation plays a significant role in constructing body area sensor network during runtime. Whenever the device discovery manager detects a new free-range node that wants to join the network, it dynamically assigns a unique port number for that free-range node to establish a point-to-point communication channel. A bitmap is used to keep track of what port numbers are still available. In the cases when some free-range node quits the network, the occupied port number is released for reuse. This connection maintenance work is performed in the background and is totally transparent to users. Compared to many static configuration methodologies, such as TDMA-based polling, which has been adopted in many health monitoring systems [6] [7] [15], our dynamic network construction methodology is much more flexible and fault-tolerant.

Once the free-range node accepts the port number offered by basestation, a free-range (FR) controller is created as a new-spawn thread to maintain the connection between basestation and the specific free-range node. The FR controller sends the commands issued from the command controller and receives data from the free-range node. When data streams in, the FR controller first parses it according to the format file generated and sent from the free-range node. It then forwards the parsed data to both the GUI and the back-end database. The GUI itself is implemented as a multi-thread program too. Each thread is responsible for displaying the streaming data from one single sensor onto an independent sub-window. The number of sub-windows is equal to the total number of sensors employed in the body area sensor network. Furthermore, the scale of sensed data value is calibrated adaptively for different types of sensors during runtime.

Furthermore, our system is extensible in that the streaming sensor data can be exported to any other desktop programs. This is realized by establishing a TCP/IP socket between two programs. Benefiting from the language-independence offered by TCP/IP interface, the desktop programs can be written in multiple programming language choices. As an example, we have connected a machine learning engine with our RehabSPOT system and relayed the streaming data into the engine for real-time activity recognition.

IV. Application and Result

RehabSPOT system is a feasibility experiment using the Sun SPOT development platform. To illustrate the use and configurability of the system, we deploy it in a physical rehabilitation program for upper extremity dysfunction identification.

The process begins when the physical therapist first picks up the necessary sensors for a particular rehabilitation session and plugs them onto the Sun SPOT free-range nodes. In this case, we use two free-range nodes, and equip each with one gyroscope. The therapist attaches one node onto the patient's left upper arm and the other on his left wrist and then powers them on. A Sun SPOT basestation is connected to the therapist's laptop. It listens on the broadcast channel and receives connection setup request messages from the free-range nodes. After connections are established, the GUI displays the list of available free-range nodes in its Sun SPOT list panel as illustrated in Figure 7. The therapist can configure each Sun SPOT free-range node one by one by selecting any number of sensors from a sensor pool and setting the sampling rate for each sensor (In this case, we select the built-in tri-axis accelerometer and the external gyroscope, and set all the sensors' sampling rates at 100Hz). In addition, the therapist can mark each free-range node with a easily remembered label. For example, the free-range node attached to the patient's left wrist can be labeled as *LeftWristNode*. The configuration

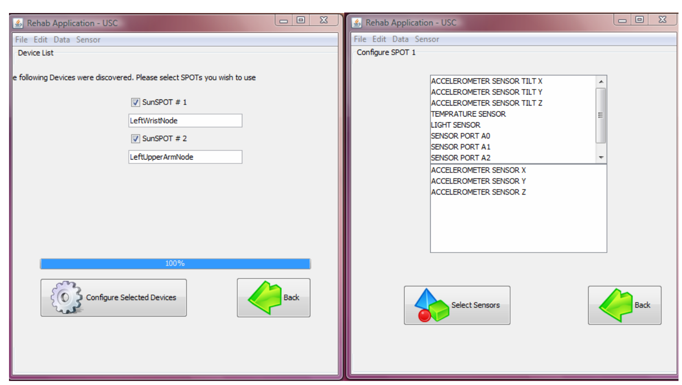

Fig. 7. The device discovery manager at basestaion detects two available fre-range nodes in its neighborhood. The therapist selects both of them, labels the first node as *LeftWristNode* and the second one as *LeftUpperArmNode*, and is ready to configure these two nodes. (Left) Therapist selects sensors to be configured for the first free-range node from a sensor pool. (Right)

message is then passed to the basestation where it is forwarded to the corresponding free-range node. The sensor controller on the free-range node interprets the message, checks the availability of the chosen sensors, and passes the format file (unwrapped from the message payload) to the data aggregator. The data aggregator starts aggregating sampled data after the therapist clicks on the *Start* icon. The data is then transmitted to the basestation, which in turn relays the data to the Java GUI for display. The therapist can pause sampling by clicking on the *Pause* icon. Figure 8 shows a snapshot of the data captured from the two free-range nodes where the patient was slowly moving his left arm up and down. When the session is complete, the therapist clicks on the *Stop* icon to turn off all the sensors and close the connections with all the free-range nodes. The back-end database allows the therapist to build up a profile for each patient and stores the sensor data gathered in each rehabilitation session. Furthermore, the sensor configuration file that records the number of nodes used in the session, types of sensors plugged onto each node, and sample periods setting for each sensor can also be saved for future access. As a result, a complete healthcare information system is set up.

Fig. 8. A snapshot of the data captured from the two free-range nodes where the patient was slowly moving his left arm up and down

Based on our experiment, the sensor plug-in and placement of free-range nodes takes five to ten minutes depending on the number of nodes needed. The sensor network connection setup and sensor configuration process takes approximately five minutes. Those steps in total take no more than fifteen minutes, which represents the maximal amount of required user intervention. The fully charged battery can support about six hours of operation, which is sufficient for a standard rehabilitation training program. Although the usability of RehabSPOT, and wearable computers in general, is very difficult to quantify, the initial feedback from both physical therapists and patients is promising. This indicates that the RehabSPOT platform holds a great potential to benefit physical therapists' work.

V. Conclusion and Future Work

This paper presented RehabSPOT, a reliable and highly customizable medical monitoring platform for physical rehabilitation. We described the platform with a special focus on its novel software architecture. We also explained how this architecture supported dynamic construction of body area sensor network and rapid system configuration to satisfy an individual's requirements. Finally, we evaluated the system by deploying RehabSPOT for a rehabilitation program, and showed how physical therapists benefited from this platform.

Currently, most BASN systems are designed for individual use. However, for physical rehabilitation, it is extremely difficult to maintain a patient's engagement when presenting him alone with a repetitive series of training challenges. Future research based on RehabSPOT has involved extending the system to enable inter-BASN communication and multi-user applications. It is foreseeable that by getting many patients involved and interacting with each other in one rehabilitation program, their motivation will be greatly enhanced, and the efficiency of the training program is increased.

Acknowledgment

The authors would like to thank Dr. Sheryl Flynn, the clinical director of research at Precision Rehabilitation clinical center, for her inspiring discussion and for serving as one of the domain experts. The authors would also like to thank Dr. Shih-Ching Yeh, Dr. Belinda Lange, and Mr Chien-Yen Chang from VRPsych laboratory at the University of Southern California's Institute for Creative Technologies for their technical supports and guidance.

References

[1] Precision Rehabilitation. http://www.precisionrehabilitation.com.
[2] Sun SPOT platform. http://www.sunspotworld.com.
[3] Heart disease and stroke update. *American Heart Association*, 2006.
[4] R. A., S. Rhee, A. HH., S. P., and H. RC. Mobile monitoring with wearable photoplethysmographic biosensors. *IEEE Engineering in Medicine and Biology Magazine*, 2003.
[5] R. Andre, A. Encarnacao, A. Zahoory, F. Dabiri, H. Noshadi, and M. Sarrafzadeh. Wireless sensor networks for health monitoring. *International Conference on Mobile and Ubiquitous Systems*, 2005.
[6] M. Annavaram, N. Medvidovic, and et. al. Multimodal sensing for pediatric obesity applications. *UrbanSense*, 2008.
[7] S. Bamberg, B. A.Y., S. D.M., K. D.E., and P. J.A. Gait analysis using a shoe-integrated wireless sensor system. *IEEE Transactions on Information Technology in Biomedicine*, 2008.
[8] E. Berkson, R. Aylward, J. Zachazewski, J. Paradiso, and T. Gill. Imu arrays: The biomechanics of baseball pitching. *Orthopaedic Journal at Harvard Medical School*, 2006.
[9] M. A. Hanson, H. C. Powell, and et. al. Body Area Sensor Networks: Challenges and Opportunities. *Computer*, 42(1):58–65, 2009.
[10] E. Jovanov, A. Milenkovic, and et. al. A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, March 2005.
[11] A. D. Jurik, J. F. Bolus, A. C. Weaver, B. H. Calhoun, and T. N. Blalock. Mobile health monitoring through biotelemetry. *BodyNets*, April 2009.
[12] M. McLaughlin, A. Rizzo, and et. al. Haptics-enhanced virtual environments for stroke rehabilitation. *IPSI*, 2005.
[13] M. Sung, C. Marci, and A. Pentland. Wearable Feedback Systems for Rehabilitation. *Journal of NeuroEngineering and Rehabilitation*, 2005.
[14] A. Van Halteren, D. Konstantas, and et. al. Mobihealth: Ambulant patient monitoring over next generation public wireless networks. *Studies in health technology and informatics*, 106:107–122, 2004.
[15] W. Wu, A. Bui, M. Batalin, L. Au, J. Binney, and W. Kaiser. Medic: Medical embedded device for individualized care. *Artificial Intelligence in Medicine*, 42:137–152, 2008.
[16] G. Z. Yang. *Body Sensor Networks*. Springer, London, 2006.
[17] S. Yeh and A. Rizzo. An integrated system: Virtual reality, haptics and modern sensing technique (vhs) for post-stroke rehabilitation. *ACM symposium on Virtual reality software and technology*, 2005.