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WIRELESS VIBROTACTILE FEEDBACK SYSTEM FOR POSTURAL RESPONSE IMPROVEMENT

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Abstract - *This paper presents an evaluation of a real-time wireless body sensor network for the improvement of postural balance response. The system senses body sway using accelerometers and provides vibrotactile feedback to multiple points on the inner forearm, allowing the subject to obtain a clear indication of imbalanced movements within their center of gravity and respective surroundings. The wireless body sensor network is ergonomic, allowing the subject to feel comfortable and experience unconfined movements during its use. The system transmits real-time data to a local host computer, where the data is recorded and displayed graphically. This recorded data monitors the subject's progress and allows any sudden falling movements to be overseen by care-givers. Pilot data measuring postural responses to perturbations with and without the system are conducted. Results obtained suggest that this system can improve postural responses, where it is demonstrated that such an intelligent and user-friendly system can be applied to rehabilitate the loss of balance in hospital and home-care patients.*

Keywords – postural balance, vibrotactile feedback, wearable biomedical devices, wireless body sensor network

I. INTRODUCTION

Falling has become a serious concern in individuals with balance disorders and in elderly subjects. Vestibular impairments can cause dizziness, blurred vision, decreased orientation to one's surroundings, and an inability to stand and walk. A recent study conducted has shown that over 40% of the reasons for admitting elderly family members into a nursing-home were due to falling [1]. As the baby-boom generation continues to increase in age, projections indicate that fall-related problems such as hip fractures will quadruple over the next 40 years, where the US currently exhibits 100,000 hip fractures per year [2]. Given this fact, there is clear indication of a need for apparatus' or methods which can enhance postural stability and avoid injuries due to vestibular impairments.

The inner ear and central nervous system (CNS) provide information of self-motion to maintain visual stability and orientation while moving or standing. The inner ear consists of 3D sensing capabilities to detect angular motion and linear acceleration with respect to gravity. The 8th nerve is responsible for carrying hearing and balance information from the inner ear to the brain [3]. However given any deterioration of this sensory pathway, the balance information is then distorted or lost, resulting in the individual's loss of balance. Vestibular impairments can be caused by strokes, brain injuries, infections, and age [4]. Therefore, due to the wide variety of causes, postural instability can arise from numerous medical conditions.

The control of posture and other cognitive processing tasks are executed concurrently within the brain, having to share the same resources. Falls in general occur when secondary tasks impede a postural task from being executed, where there exists a lack of cognitive processing resources to maintain balance [5]. The use of a tactile feedback unit to improve postural stability can be employed in an effective manner to override such cognitive impedances, and stimulate the senses to act on balance instabilities. It has been proven that learning to execute motor tasks is most natural and effective through tactile feedback [6]. These types of tactile responses are typically used in rehabilitation to give feedback on movements and performance. As a result, the subject develops a conceptual mental model to reference when performing a task, which is greatly improved upon through repetition and motivation. Strategies which are typically used to return the body back to equilibrium include stepping and reaching. Therefore as one loses balance, a primary movement is to extend the arm and hand outwards to prevent falling. It has been shown that the forearm is especially sensitive to bioelectrical impulses [7]. These impulses could then in turn trigger an immediate postural response to prevent falling and possible tilting movements.

Researchers have spent a great deal of their efforts in creating wireless body sensor networks (WBSN) for biomedical applications. A WBSN is a portable device which incorporates master and slave devices to create a means of wireless signal data acquisition while dissipating low power. The slave devices are responsible for retrieving information and recording signals, whereas the master manages the overall functionality of the devices within the network. Masters are referred to as the central control unit, where slave sensors are known as sensing nodes within medical applications. Such slave applications in a WBSN include nerve stimulation [8].

This work employs a WBSN to assist individuals in postural control by using a vibrotactile feedback approach. This approach can be used to compensate for sensory deficits and/or overriding cognitive interference experienced by the subject through the stimulation of several acupressure points to the forearms. By providing feedback to the forearms, the user can instinctively reach out in the direction of a perturbation to avoid falling. It will be demonstrated that the wireless vibrotactile feedback system (WVFS) employed in this work is able to dissipate low power, while providing sensory input to the user and supplying caregivers with real-time data of patient movements.

II. PREVIOUS WORK

There have been many techniques and systems created to correct balance disorders. In general, vestibular impaired subjects will often undergo therapy treatments to achieve equilibrium and correct related symptoms. Special types of treadmills with foot plates have also been used to gradually restore a sense of balance. In addition to rehabilitation, the treadmills also provide patients with a means of exercise. Yano et al have implemented the Gaitmaster to be used subsequent to achieving healthy and stable walking patterns [9]. The system uses footpads which follow the prerecorded motion of healthy walking, climbing, and descending motions of stairs to help move the user's feet in a balanced fashion. Despite the widespread use of treadmills to rehabilitate the loss of balance, these devices do not give the user a representation of real-

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world situations, nor provide them with a sufficient margin of safety [10]. Hence, new rehabilitation techniques have been researched and developed to overcome these balance deficits.

Wu et al have developed a torso-based tactile feedback system for patients with balance disorders [11]. The system consists of a vest which detects user balance levels and provides feedback for balance correction. A 2D accelerometer is mounted to each of the shoulders, where pneumatic balloon base actuators inflate portions of the vest to provide sensory feedback when a loss of balance is encountered. Although the device demonstrates rehabilitation possibilities to the vestibular impaired, the system is also bulky, consisting of many exposed wires and RS232 ports to connect numerous components, while essentially restricting the subject's movements.

Wall and Weinberg have developed a vibrotactile array belt to control sway and body tilt [3]. The belt consisting of 3 rows of 16 tactors are placed around the waist to measure the gyroscope and accelerometer readings. Each row is activated based on the forward or backward tilting level experienced by the subject. The device also consists of two large battery packs placed on the sides of the user's thighs, where the processor, vibration display, tilt sensors, and central unit are all connected through a CAN bus. Although the belt does provide tactile feedback to the user, there is a lack of clear indication to the direction of the tilt movement as a row of tactors are used. Furthermore, the battery packs placed on the sides can be heavy and bulky, resulting in confined and subtle subject movements.

Contrary to previous systems, our system is a lightweight, low power device which transmits data wirelessly in real-time. Vibrotactile responses are provided to the user, depending on the direction (i.e. right, left, backwards, forwards) and degree of tilt, and movements are graphically displayed in real-time. The rest of this paper is organized as follows: Section 3 gives an overview of the WVFS presented in this work. Section 4 describes the architectural implementation of the system, with specifics on its functionality, communication between components, and power considerations during design. Section 5 presents our experimental results, where Section 6 provides concluding remarks based on our findings.

III. WIRELESS VESTIBULAR REHABILITATION SYSTEM OVERVIEW

The WVFS consists of the following three modules:

- → Tactile Module Interfaces
- → Main Module Interface
- → Host Computer Interface

The general WVFS communication flow is presented in Figure 1. Each module provides a different contribution to the system network functionality. In general, the Main Module is responsible for sensing body tilt and communicating concurrently with the two Tactile Modules. The module is placed on a pack located on the subject's back, fastened securely around the shoulders and placed between the lower shoulder blade area. The Main Module is also responsible for transmitting data to the host computer. The host receives data and plots the information on a Graphical User Interface (GUI) for the respective caregivers to monitor. The Tactile Modules provide vibrotactile feedback given the direction and degree of tilt which is being undergone by the user. These modules are implemented as gloves which extend from the mid-palm to the mid-forearm area. Therefore, the WVFS allows the subject to conduct their daily routines without being subject to stationary, restricted movements due to bulky components and wiring.

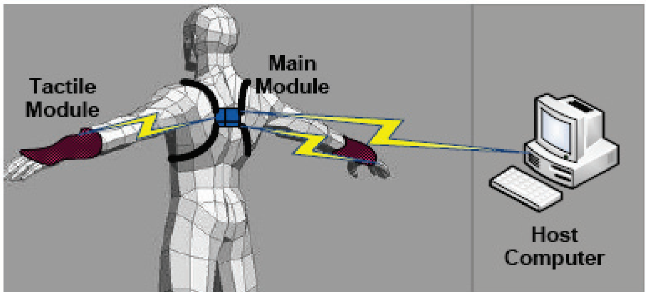

Figure 1: WVFS Module Communication Flow

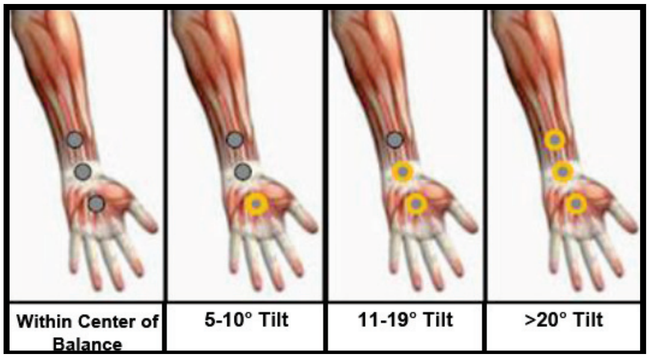

Figure 2: Vibrating Disk Activation for each Respective Degree of Tilt

IV. SYSTEM ARCHITECTURE IMPLEMENTATION

A. Tactile Module Interfaces

The WVFS consists of two Tactile Module gloves, each located around the subject's palms and forearms as discussed previously. The two Tactile Modules consist of a microcontroller, three vibrating disks, a power supply, and a wireless transmitter and receiver. The prototype used in this particular implementation makes use of the 8-bit, 20 MHz low power Arduino Lilypad microcontroller with a power supply of 5V and 100mA. The Lilypad is 0.8mm thick and washable if needed, making the gloves both practical and easy to wear. For transmitting and receiving purposes, the ZigBee 802.15.4 protocol was used to setup the communication network between the modules. The overall network is capable of communicating at a 250kbps RF data rate, operating at 2.4GHz speed and providing real-time data to the system. The vibrating disk motors operate at 3V, 80mA, and vibrate at 12000 rpm. Therefore, when a disk is activated, it vibrates at 200 Hz, a vibrational frequency to which humans are subject to sensitivity [12].

The microcontroller on the Tactile Module is responsible for interpreting the data received from the Main Module, and determining the corresponding vibrating disk(s) to be turned on. Tactile feedback to the user depends on the degree of tilt that the subject is currently undergoing. Three vibrating disks are integrated in the modules and are placed within the glove to provide tactile responses to the user's upper-mid palm, lower wrist, and mid inner forearm area respectively. If the subject is within their center of balance, vibrations will not be experienced. However, given that the subject is experiencing a 5°-10° tilt to the left, right, frontward or backward, the subject is no longer within their center of balance and one vibrating disk will provide tactile feedback to the user's inner forearm on the corresponding side (left or right). Given that the user undergoes a 11°-19° tilt, or greater than 20° tilt, two or three vibrating disks will provide tactile feedback respectively. The user will therefore gain a sense of their balance offset given the number of disks and corresponding side to which the vibrotactile feedback is being experienced at the given moment. If the subject is to tilt frontwards or backwards, both forearms will vibrate according to the degree of tilt mentioned previously. The diagram of the vibrating disks and respective degree of tilt for tactile feedback is given in Figure 2.

B. Main Module Interface

The Main Module is the central unit of the WBSN. It is responsible for processing the data required for both the Tactile Modules and the Host Computer Interface for real-time monitoring capabilities. In order to provide real-time data to both the subject and monitoring system, the Main Module consists of two microcontrollers, an accelerometer, a power supply, and two XBee units to establish the ZigBee 802.15.4 network between the Tactile Module devices (local-range network) and host computer (extended-range network) simultaneously. The two networks are differentiated using a unique Wireless Personal Area Network Identification (WPAN ID). The implementation of this particular prototype makes use of an ATMEGA168 8-bit low power RISC microcontroller, exhibiting a 20MHz clock speed with 1KB of RAM. The ADXL335 tri-axis accelerometer is used to provide ±3g axis data, using an analog interface operating at 2V (V_{ref}).

The accelerometer is placed at the center of the module. The module is on a flat surface, placed comfortably on the subject's back between the lower shoulder blade area. The accelerometer is placed within this upper body region to account for the linear and angular acceleration measurements of the upper torso, much like the biological functions that a healthy vestibular system experiences. It is clear however that the curvature of the back is different depending on the individual. Thus, a special pillow which conforms to the subject's back and Main module was developed to maintain a reference angle for correct accelerometer readings.

The microcontrollers within the Main Module read the x, y and z axis values continuously from the accelerometer, where each microcontroller interprets the same information in a unique way. One microcontroller will broadcast the accelerometer readings through the local-range network to the Tactile Modules, where the second microcontroller transmits the axis data to the host computer through the extended-range network for the monitoring system. The local-range network microcontroller interprets the readings from the accelerometer before transmitting the data values to the Tactile Modules, where the raw data from the accelerometer produces analog values which must be converted into degrees. The ADXL335 ±3g axis accelerometer analog values used in this prototype were converted into degrees by employing the following expression:

$$Degree_{x|y|z} \cong \cos^{-1}\left[\frac{(RawData_{x|y|z} * V_{ref}/2^{n-1})/V_{sens}}{Angle_{ref}}\right] \quad (1)$$

Here:

- → $RawData_{x|y|z}$ signifies the analog data obtained from the accelerometer (g).
- → $x|y|z$ symbolizes the axis under evaluation (x or y or z).
- → V_{ref} is the reference voltage as specified previously as 2V.
- → n is the number of bits provided by the accelerometer (in this case 10, i.e. $2^9 = 512$).
- → V_{sens} is the sensitivity voltage (approximately 0.36 V)
- → $Angle_{ref}$ is the reference angle (°) as initially set up at the startup. Assuming the cushion and apparatus has been well placed, this approximates to $\approx (500*2V/512)/0.36V/g\ \forall$ axes.
- → $Degree_{x|y|z}$ represents the corresponding converted degree angle of tilt obtained in degrees (°) to provide data for the tactile feedback.

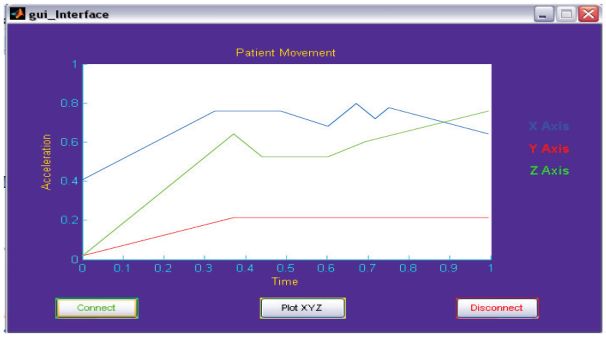

Figure 3: Host Computer GUI

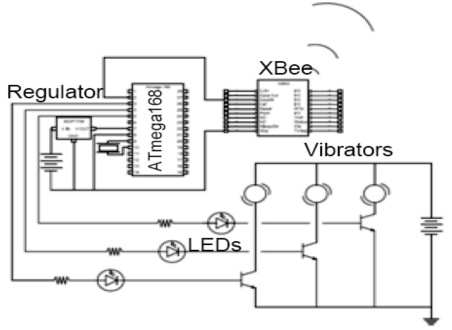

Figure 4: Layout of Tactile Module

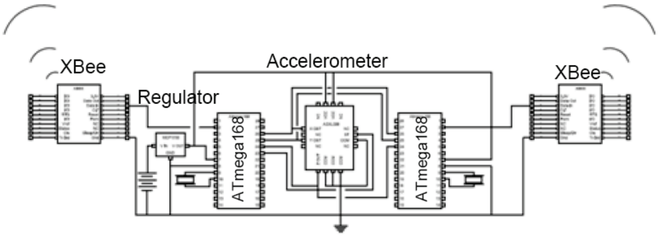

Figure 5: Layout of Main Module

C. Host Computer Interface

The user interface on the Host Computer is a monitoring system for both caregivers and recording purposes. The caregiver is able to experience a graphical interpretation of the movements being made in real-time. The GUI is able to connect to the COM port of the Host Computer, establishing a connection to the WPAN and obtaining data packets from the Main Module.

The GUI used in this prototype is implemented using MATLAB®. All 3 axes are plotted in the GUI on a scale of acceleration versus time. The user is allowed to connect or disconnect from the monitoring system at any time. The data is also stored on the computer for later retrieval if needed. A sample screenshot of the GUI is displayed in Figure 3.

D. Power and Current Design Implementation

The implementation of the Tactile and Main module initially presented certain power considerations. The first consideration was the wireless network connectivity between all modules. The constant fluctuation of current between modules resulted in a large amount of noise within the system, in turn providing false readings to the rest of the system. The second obstacle was experienced during the activation of the vibrators which created false triggering reactions from the microcontroller.

In alleviating the first and second obstacle, a series of voltage regulators accompanied with battery supplies and a switching circuit were used. Through investigation, it was determined that the power supply consisting of a AAA battery as specified by the Lilypad only provided the system with enough current to function

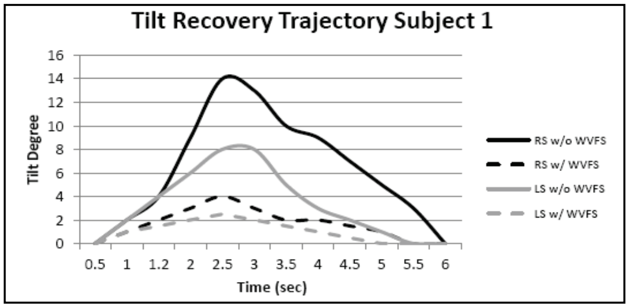

Figure 6: Subject 1 Anterior Posterior Recovery

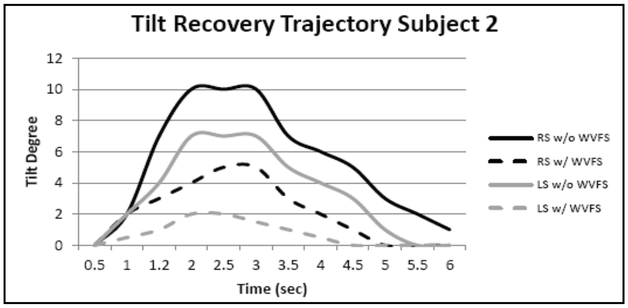

Figure 7: Subject 2 Anterior Posterior Recovery

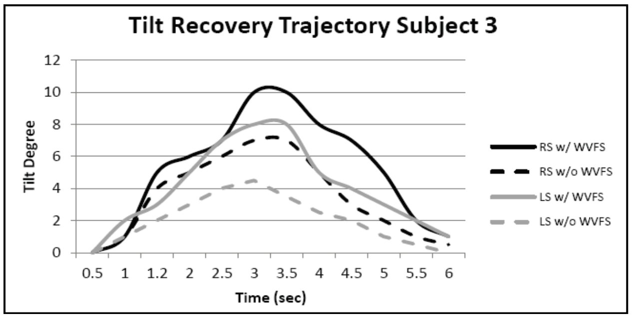

Figure 8: Subject 3 Anterior Posterior Recovery

properly. A switching circuit was designed to avoid loading when actuating the vibrators and prevent false triggering of the microcontrollers. In terms of battery operation, the Main module required four AA batteries, whereas the Tactile modules used one AAA and two AA in order to compensate for the factors mentioned above. The resulting architectures for the Tactile and Main modules are presented in Figures 4 and 5 respectively.

V. EXPERIMENTAL SETUP AND RESULTS

The effects of vibrotactile feedback on postural stability and body tilt were evaluated using three test subjects (ages 40 – 70). The subjects were studied under multidirectional anterior posterior perturbations with (w/) and without (w/o) the use of the WVFS apparatus. The perturbations were applied to the waist and upper torso with a smooth or jerking acceleration depending on the trial run. In order to minimize anticipatory reactions, the subjects were asked to stand with their eyes closed.

Figure 6, 7, and 8 display the tilt degree and respective response times for the three subjects, where the ordinate scaling varies within the respective figures. Perturbations start at the 0.5 second mark, where the right (RS) and left side (LS) tilt motion with or without the use of the WVFS are shown. The RS and LS data within the figures signify the Tactile modules which were actuated during the time of the multidirectional perturbations. The x axis indicates the time which the user needed in order to regain balance. The data was plotted based on the mean of the three trials conducted per subject, each trial conducted every seven days. During this time, the subjects were additionally exposed to the WVFS approximately two times within a week. Through experimental observations and results, the WVFS was able to aid in the recovery of tilt movements in both the left and right side by an average of 55.9%, and slightly reduce response time by an average of 0.51 seconds.

All subjects agreed that the vibrotactile feedback provided by the apparatus assisted in indicating their tilting movements, in addition to reaching out towards the vibration direction to prevent from falling. They also concurred that the WVFS did not confine their bodies during testing and other various movements when under use.

VI. CONCLUSION

In summary, the WVFS was able to reduce tilt experienced by the subjects, while also decreasing the respective response time. The device demonstrated an ergonomic compactness which in turn allowed subjects to experience unconfined movements, while simultaneously aiding in postural control. Specifically, the device was able to reduce the angle of tilt and response time in the perturbation tests by an average of 55.9% and 0.51 seconds respectively. The WVFS has therefore given a clear indication that a rehabilitative technology for vestibular impairments is well within reach of hospital and homecare patients.

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