Utilization of a Wrist-Mounted Accelerometer to Count Movement Repetitions

Sriram Sanka*, Prashanth G. Reddy*, Amber Alt†, Ann Reinthal‡ and Nigamanth Sridhar*
*Department of Electrical and Computer Engineering, Cleveland State University
†School of Health Sciences, Cleveland State University

Abstract—Stroke is a leading cause of disability. Lasting effects of a stroke may include limited mobility in limbs. In order to restore a reasonable amount of function in the upper extremities, extensive rehabilitation that includes multiple repetitions of practice are necessary. These practice sessions are often boring to the patient. The work we describe in this paper is a part of a larger project using the ENGAGE video gaming protocol to make these therapy sessions more engaging and effective. Instead of repeating a specific exercise, the patient plays a video game using the Nintendo Wii remote or the PlayStation EyeToy. When engaging in such non-standard motion, it becomes more difficult for the clinician to gauge how much of the required practice the patient is actually getting in each session. To help solve this problem, we have designed a simple accelerometer-based sensor node that tracks movement repetitions and helps the clinician track the patient’s progress across sessions. We present results from calibration and statistical validation of this sensor node.

I. INTRODUCTION

In this paper we describe our experience with building a low cost and low power device for tracking patients undergoing rehabilitation after a stroke. A person recovering from stroke often has limited mobility and function in the upper extremities. Such patients often go through intensive neuromuscular rehabilitation to help regain more functional use of the arm and hand.

It is currently difficult to obtain adequate quantities of the necessary upper extremity practice due to the tedious nature of repetitive practice and the need for partial hand use in more engaging functional tasks. In recent years, clinicians have begun using video games as a way of replacing repetitive motion exercises during rehabilitation sessions. Now, the patient has “something to do” instead of a meaningless repetitive motion. The ENGAGE video gaming protocol — “Enhanced Neurorehabilitation: Guided, Activity-based, Gaming Exercise” has been specifically designed to meet the variable motor retraining needs of the heterogeneous stroke population. However, it is difficult to quantify amounts of practice, especially in fast paced games where the arm may move more than on time per second. Visual feedback based in observation is grossly insufficient.

Our work is an effort to bridge this gap. We would like to be able to correctly identify practice repetitions while a patient is engaged in video game play, and track the patient’s progress through a series of rehabilitation sessions. Initially, we tried using off-the-shelf devices such as pedometers, but they did not provide accurate counts. To overcome this problem, we have designed a sensor node that the patient straps on to his/her arm while playing video games. The sensor node keeps an accurate record of the various arm motions and provides data that the clinician can use for analysis. We have validated the sensor node against the traditional methods of motion data collection.

The rest of the paper is organized as follows. In Section II, we provide an overview of techniques used in post-stroke rehabilitation, and present the context of our work. Section III describes the details of the sensor node and experiment design. Section IV presents validation results and some examples of the kinds of data that the clinician sees from our sensor device. We conclude with pointers to future work in Section V.

II. BACKGROUND AND CONTEXT

Stroke is a leading cause of disability [1] leaving many individuals with residual upper extremity dysfunction that limits independence [2]–[4]. Current research suggests that multiple repetitions of practice are required to improve function post stroke in specific functional upper extremity tasks [5]–[8], such as eating with a utensil or tooth brushing. While the magnitude of practice repetitions is not yet fully delineated for various motor skills, it is thought that individuals must complete a minimum of several thousand repetitions in order to relearn a task [5]–[8].

Recent research measuring the amount of practice occurring in a typical outpatient rehabilitation program has shown that individuals post stroke are not getting the necessary intensity of upper extremity repetitive practice [9]. Obtaining this amount of practice is difficult for several reasons. First, the arm is used for a wide variety of different tasks, and practicing one task does not necessarily result in improvement in a different task [7], [9]. Second, repetitive practice of a single task is typically boring for adults [10]–[13]. Third, the learner must actively engage in task practice; it is not adequate to be passively moved through the activity [9], [14]. This is critical since motor learning is best when an activity is meaningful [7]. Finally, it is difficult to monitor the amount of practice repetitions. A simple time measurement, as is common during a therapy session, does not accurately represent the number of repetitions of a task since some tasks involve multiple repetitions per minute, such as using a spoon to eat a bowl of soup. However, others may involve only a single repetition of the task over every minute or two, such as donning a shirt.
There are three primary interventions that have been utilized effectively to mass practice in neuromuscular rehabilitation. In constraint induced therapy, the non-hemiparetic arm is constrained while the hemiparetic arm is forced to complete multiple functional tasks. This intervention is effective for individuals post stroke with enough residual hand function to be able to manage the functional tasks [8]. Robotic interventions use various arm movements, and are effective with individuals with varying levels of arm and hand function post stroke. Monitoring of practice repetitions can be designed into the software. However, a given device can typically provide movement practice for only a limited number of arm motions. In addition, some of the devices are expensive and are frequently unavailable at many clinical sites [15]–[19].

Virtual reality (VR) is the third platform that has been utilized effectively to provide large quantities of engaging and varied repetitive task practice [20], [21]. VR typically provides a three-dimensional computer generated immersion experience; the “player” completes the task similarly to the real world. The VR literature discusses the concept of “presence” [22] as a form of positive, active engagement that occurs during the VR experience. The VR experience is realistic and transfers to a comparable real world activity [21]. In addition, monitoring of practice repetitions can be designed into VR software, and VR can be used with all levels of residual hemiparetic arm and/or hand function. However, these systems are expensive and not typically available in routine clinical practice.

Video gaming systems such as the Wii and the PlayStation II EyeToy are commercially available, inexpensive virtual reality-type systems that can provide both engaging and functional interaction. Video gaming has been utilized as an effective adjunct to traditional neuromuscular rehabilitation (TNR) for individuals with stroke [11]–[13], [23], offering both unilateral and bilateral practice opportunities, and allowing easy modification in order to specifically tailor practice for different individuals with varying degrees of paresis post stroke. In TNR, repetitive practice is typically boring with poor engagement in the task. As such, there is poorer compliance with prescribed exercise programs. In contrast, participants in our pilot gaming studies have found gaming engaging and enjoyable while concurrently obtaining large quantities of repetitive practice.

However, video gaming offers so many differing options that it is often difficult for the busy clinician to utilize optimally. Therefore, the ENGAGE gaming protocol was developed to assist the clinician in providing adequate quantities of meaningful and engaging practice in a realistic clinical environment. It includes a game selection algorithm that provides focused, carefully graded, activity-based, repetitive practice of cognitive-perceptual-motor tasks that is highly individualized and directed in order to specifically address each individual patient’s unique constellation of neurological impairments. The game selection algorithm allows for preparatory work on impairments and task components as part of a meaningful

<table>
<thead>
<tr>
<th>Game</th>
<th>Task Description</th>
<th>Movement Demands</th>
<th>Inter-trial Variability</th>
<th>Analysis Planes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BubblePop (PS2)</td>
<td>Game demands that all blue colored bubbles on the screen be popped</td>
<td>Requires initial forward reach followed by movements in the frontal plane (superior/inferior and lateral); primary movements in x and z axes</td>
<td>High: Direction and distance vary between repetitions</td>
<td>Biplanar: x &amp; z; varied magnitude and plane</td>
</tr>
<tr>
<td>Kung 2 (PS2)</td>
<td>Figures appear in various areas of the screen and must be “punched” out of the way</td>
<td>Triplanar punching movement</td>
<td>High: Direction and distance vary between repetitions</td>
<td>Triplanar but movement in all planes; movement in all planes occurs simultaneously in organized “pack-ets”; varied magnitude and plane</td>
</tr>
<tr>
<td>Mr. Chef (PS2)</td>
<td>Varied cooking activities including putting together orders, grating cheese, salt- ing fries, smashing tomatoes, etc.</td>
<td>Requires initial forward reach followed by movements in the frontal plane (superior/inferior and lateral); primary movements in x and z axes</td>
<td>Very high: Variable direction and distance depending on specific task; within some tasks little variability (such as grating cheese)</td>
<td>Biplanar: x &amp; z; varied magnitude and plane</td>
</tr>
<tr>
<td>Batting (Wii)</td>
<td>Game demands a baseball swing</td>
<td>Semicircular swinging pattern, with primary movement laterally in x plane with small amounts of movement in Y and z axes</td>
<td>Low: Movement pattern highly repeatable from trial to trial</td>
<td>X axis; movement in all planes occurs simultaneously in organized “pack-ets”</td>
</tr>
<tr>
<td>Reaching (TNR)</td>
<td>Reaching to various locations to touch an object on table top</td>
<td>Requires forward reach with varying degrees of superior/inferior and lateral motion depending on target</td>
<td>Moderate: Fairly consistent amount of forward/backward y axis and superior/inferior z axis movement, variable lateral x axis motion</td>
<td>Triplanar movement in all planes; movement in all planes occurs simultaneously in organized “pack-ets”</td>
</tr>
</tbody>
</table>

TABLE I: This table provides a description of the study movement tasks and analyses. PS2: Sony PlayStation II with EyeToy (Play2); Wii: Nintendo Wii (Wii Sports); TNR: reference standard traditional neuromuscular rehabilitation task of reaching.
activity before moving on to practicing the actual task. Another way in which ENGAGE can be distinguished from standard video gaming in that it is guided by the TNR clinician, yet implemented by support personnel, thereby reducing the cost while maintaining the intensity. Finally ENGAGE is important because it targets individuals post stroke with lower level arm function. In summary, ENGAGE addresses many of the problems with currently available intervention strategies to mass repetitive upper extremity practice post stroke.

One problem with commercially available video gaming equipment is that it cannot accurately monitor practice repetitions, which vary greatly between various games, such as the less frequent arm swing in golfing to the almost continuous arm movement in boxing. The purpose of this study was to see if a simple wrist mounted three-dimensional accelerometer could be used to accurately count practice repetitions in the ongoing ENGAGE study using video gaming as a tool to obtain repetitive practice. In addition to providing quantification of practice for the study, the information provided by the accelerometer can be provided to patients in clinical practice to motivate continued practice.

At present, the ENGAGE protocol utilizes two readily available video gaming systems: the Wii, whose controller is accelerometer triggered, and the PlayStation 2 with EyeToy, which is activated by body movement picked up by a camera. Since individuals with stroke present with widely varying degrees of movement dysfunction, having gaming options from the two types of systems provides an adequate range of upper extremity activities to utilize in training. Using this protocol, we have been able to tailor gaming experiences to individuals with very low to high levels of upper extremity motor return (Fugl Meyer upper extremity scores ranging from 11–64). Newer systems such as the Kinect require whole body movement, and do not provide the range of upper extremity activities appropriate for this application. It should be noted, however, that the protocol is restricted to the two gaming systems we have used.

Simple accelerometer devices have been used previously in several different ways to monitor individuals post stroke. These include to monitor activity at home [24], [25], for gait analysis [24], [26], to measure hand steadiness during reaching activities [27], and to calculate arm use in acute stroke [28]. In addition, more complex and expensive devices have been utilized to provide upper extremity activity task discrimination and monitoring [29]. However, there is not currently an application available to inexpensively and accurately measure upper extremity movement repetitions in the clinical environment.

In this study, a group of normal individuals and individuals with stroke were given five gaming and TNR tasks with varied types of movement demands. These tasks were completed wearing the wrist mounted accelerometer while simultaneously recording their activity using three dimensional motion analysis and the accuracy of counting the task repetitions was compared. The purpose of this study was to validate the accuracy of the wrist-mounted accelerometer in counting movement repetitions during upper extremity activities.

### III. Methods

#### A. Subjects

This study was approved by Cleveland State University’s Institutional Review Board for Human Subjects Research. There were five normal participants (3 M, 2 F, mean age 23) and two participants with hemiparesis post chronic stroke (2 and 6 yr post, both M, ages 50 and 53). One individual with stroke had a return of some hand function and an activity tremor while the other individual had minimal hand function (gross grasp) and no tremor.

#### B. Activities

For this study, we used a total of five activities. The first activity is a traditional neuromuscular rehabilitation activity, Reaching, where the subject performs the same limb motion repeatedly. The other four activities are video games that the subjects play on either the Sony PlayStation 2 or the Nintendo Wii platform. Each of the activities is different in that they each require different kinds of limb motion. Table I provides a summary of the activities, and the kinds of movement demands that each of the games places on the subjects.

The Reaching and Batting activities are ones that are fairly consistent across trials. The limb motion demands are highly repeatable from one trial to another. The Reaching activity simply requires reaching to different objects on a table top, while the Batting activity requires a baseball swing while holding the Wii remote. For instance, the plot in Figure 4a shows a healthy subject playing the Batting game. It is quite easy to see the consistent, repeatable, pattern each time the subject takes a swing. In fact, the pattern is quite consistent even for the two subjects who have had a stroke. The BubblePop and Kung 2 activities are not quite as consistent. These activities require the subject to respond to game play actions on the screen, which can include unexpected on-screen stimuli. In Kung 2, the variable target requires a specific triplanar response from the player, while in BubblePop the player has more choice of triplanar movement strategy to pop the variable bubble display. The most complex demands were represented by Mr. Chef, where the player is presented with a wide variety of tasks to complete, each with differing movement demands. These included activities such as putting the correct food selections on a plate, grating cheese, and shaking milkshakes. The five tasks were chosen to provide a variety of scenarios to be used to validate the sensor device and the counting software.

We also experimented with two more tasks: placing pieces in a puzzle, and putting pegs into a peg board. However, these tasks involve more fine motor skills. With just an accelerometer, the data is too noisy to analyze automatically. We will include these tasks in the next round of trials after including additional sensors for fine-tuning.

#### C. Experimental Procedure

After consenting to participate in the study, participants were allowed time to practice the video games so that they knew how to play the games when tested. The Helen Hayes full body reflective marker set was applied and the sensor node
was placed on the posterior surface of the dominant wrist of the normal participants and the hemiparetic wrist of the individuals post stroke just above the distal end of the ulna and radius. The sensor node was secured with an elastic wrap and in this location did not inhibit anyone’s ability to complete the required activities. Participants completed all activities on an adjustable height seat, adjusted with the hips and knees at a $90^\circ$ angle. They then completed each activity/game for three short trials while concurrently recording kinematic motion and accelerometer data. The dominant hand was used for unilateral activities (BubblePop, Kung2, Mr. Chef, and Reaching) except that hemiparetic participants could do the activity with the non-hemiparetic hand assisting the hemiparetic hand when needed, as is the case during the gaming study. Batting was done bilaterally swinging to the right by all participants.

Motion data were tracked and movement repetitions counted. We first visually analyzed the accelerometer response data recorded by the sensor node. Next, we implemented a simple counting program in MatLab that automatically counted repetitions. Due to the variability of movement demands (as summarized in Table I), different counting parameters were set for each activity. In addition, there was variability between individuals in terms of magnitude of acceleration and movement plane. Different people chose differing strategies when playing a given game, and those with stroke had limited movement capabilities. The data that we present here is all captured using these offline counting and classification techniques. We are currently working on implementing the counting and classification algorithms on the sensor node, using techniques described in [30].

To provide an accurate counting of movement repetitions to serve as ground truth, kinematic data were collected using an eight camera, three-dimensional motion analysis system utilizing Cortex motion capture software (Motion Analysis Corp., Santa Rosa CA).

D. Sensor node design

The sensor node we designed is based on the Lakon mote that we designed in earlier work [31]. The Lakon mote supports high-frequency sampling as well as processing of sampled signals on the node. The mote includes two processors, a TI MSP430 low-power microcontroller that is the main controller, and an Atmel microcontroller that is capable of performing digital signal processing operations efficiently. The sensors are placed on a daughter board. In the case of this application, the sensor board uses a 3-axis accelerometer. The mote also includes an SD card for external storage. All raw data samples are recorded on the SD card. Figure 2 shows the sensor node we have used for this project. Figure 2b shows the note in its enclosure attached to a subject’s wrist.

The study described in this paper is focused on testing viability of using a sensor node for clinically valid trials. As such, we wanted to eliminate as many sources of error as possible. We focused on doing as little of the processing as possible on the sensor node itself. The data is transferred to a PC and then analyzed in MatLab. Figures 3—7 show the raw accelerometer readings from the BubblePop, Batting, Mr. Chef, Kung 2, and Reaching activities, respectively. Even a visual inspection of these graphs shows that the accelerometer is sensitive to picking up the mobility patterns quite accurately. It is easy to see the repetitive motions in the graphs, and possible to discern the differences between a healthy person and a subject who is recovering from stroke. The eventual goal is to transfer the analysis to the node itself. The Lakon mote is capable of performing reasonably complex signal analysis.
IV. Validation Results

For each of the activities mentioned, we conducted three trials with each subject. The trials were all counted using the sensor node as well as the motion analysis platform (which serves as ground truth). The number of repetitions as counted by the sensor node is compared with the number of repetitions counted using the motion analysis platform with the Pearson correlation coefficient using SPSS for each of the five activities/games. The correlation came out to be quite close to perfect. The correlation coefficients came out to be 0.98 for the Mr. Chef and Kung 2 activities, 0.99 for the BubblePop activity and 1.0 for the Batting and Reaching activities. Figure 8 shows a plot of repetition counts from the motion analysis platform and the sensor node for the three activities for which the correlation is not perfect.

V. Future Work

The goal of the work described in this paper was to establish the validity of using a low-cost, low-powered sensor device to capture data from clinical rehabilitation sessions of patients recovering from stroke. Based on the data presented here and the correlation with traditional techniques for measuring such progress made by patients, we can establish that our sensor node does indeed provide an effective way of tracking rehabilitation progress post-stroke. Much of the work that we have presented here has clearly been done before. The reason we chose to repeat this work from ground up is so that we can properly validate the sensor device in clinical settings so that the instrument can by reliably used in studies that focus on the efficacy of using video games and other non-traditional techniques for upper-extremity stroke rehabilitation.

The next step in this project is to make this device truly usable by clinicians. The current setup of having to download sensor data into MatLab for analysis is only a proof of concept. We have begun work on on-node counting and classification of the sensor data. Jiang and Hallstrom [30] present a classification scheme that can effectively differentiate between different kinds of physical motion based on accelerometer data. They also present techniques using kd-trees to reduce the amount of data that needs to be used for the analysis such that the amount of compute power and time needed is significantly reduced.
Engaged Learning grant from Cleveland State University.

The other dimension of extension is to improve sensor resolution itself. The current setup only uses a 3-axis accelerometer, which is fine for capturing coarse movements. The next step is to begin measuring fine motor movements as well. We have experimented a little with using electromyography sensors by attaching probes to muscles. We will integrate these sensors as well as a gyroscope to allow for further variety in kinds of fine-motor activities and games.

ACKNOWLEDGMENT

This work was supported in part by a CAREER grant from the National Science Foundation (CNS-0746632) and by an Engaged Learning grant from Cleveland State University.

REFERENCES


