Wireless Sensor Networks for Telerehabilitation of Parkinson's Disease Using Rhythmic Auditory Stimulation

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Abstract. Parkinson's Disease (PD) is a neurodegenerative disease affecting mainly the elderly. Patients affected by PD may experience slowness of movements, loss of automatic movements, and impaired posture and balance.

Physical therapy is highly recommended to improve their walking where therapists instruct patients to perform big and loud exercises. Rhythmic Auditory Stimulation (RAS) is a method used in therapy where external stimuli are used to facilitate movement initiation and continuation.

Aside from face-to-face therapy sessions, home rehabilitation programs are used by PD patients with mobility issues and who live in remote areas. Telerehabilitation is a growing practice amid the COVID-19 pandemic.

This work describes the design and implementation of a wireless sensor network to remotely and objectively monitor the rehabilitation progress of patients at their own homes. The system, designed in consultation with a physical therapist, includes insole sensors which measure step parameters, a base station as a phone application which facilitates RAS training sessions and communication interface between the therapist and patients, and an online server storing all training results for viewing. Step data from the system's real-time analysis were validated against post-processed and reconstructed signals from the raw sensor data gathered across different beats. The system has an accuracy of at least 80% and 72% for the total steps and correct steps respectively.

Keywords: Parkinson's disease · Wireless sensor network · Rhythmic auditory stimulation

1 Introduction

Parkinson's Disease (PD) is a neurodegenerative disorder which targets the nerve cells in the area of the brain for controlling movement. It mostly affects the

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elderly population. Symptoms can start to manifest for people ages 60 and above, and have a mean age diagnosis of 70.5 years [1]. In the United States alone, 60,000 people are diagnosed per year and at the present, about 10 million people in the world have this condition [2].

People affected by this disease may experience a variety of symptoms. In the early phases, noticeable changes in basic functional movements like the swinging motion of the arms while walking or the person's speech patterns can be observed. As time progresses, more gradual symptoms like tremors in the limbs, usually at the hand and fingers; slowness of movements (also known as bradykinesia); stiffness in different muscle groups; speech changes; loss of automatic movements like blinking; and impaired posture and balance can be observed [1]. The manner of walking of people with PD is described as having small and narrow steps (gait festination), slow movements, freezing of gait, and loss of balance [3].

Physical rehabilitation is a highly recommended step in order to improve and increase mobility, strength, balance and most importantly, independence of these patients [4]. In physical therapy of patients with this disease, therapists structure rehabilitation programs aimed to target and improve the patients' movements, most importantly, their manner of walking. They train patients to be able to walk safely, walk with independence, and walk on leveled and non-leveled surfaces.

Several studies have shown the role of auditory cues in improving a person's motor and predictive processes. Rhythm auditory stimulation (RAS) uses external temporal or spatial stimuli to facilitate movement initiation and continuation [5,6]. Therapists use RAS as a pacemaker in order to improve the coordination and walking of patients with PD or with similar conditions.

Aside from face-to-face sessions between patients and therapists, home rehabilitation programs are also being used. Recent advancement in technology gave way to different telerehabilitation systems. Telerehabilitation involves the use of electronic devices in order to remotely monitor and rehabilitate different kinds of patients [7]. It is practical to use especially for patients with mobility impairments such as limb amputations and patients living in remote and far places which make their access to rehabilitation clinics limited. Furthermore, amidst the Coronavirus Disease (COVID-19) pandemic where limiting time spent outside and social distancing are enforced, telerehabilitation can prove to have a lot of potential.

2 Related Work

2.1 Telerehabilitation

Telerehabilitation is a growing technology which aims to deliver evaluation, consultation, and therapy to patients remotely through information and communication technology as opposed to face-to-face delivery of rehabilitation in clinics. Even before the pandemic, the uptake of telerehabilitation from 2012 has increased, compelled by a more accessible mode of rehabilitation in rural areas [8]. Moreover, health precautions made from the COVID-19 pandemic pushed

for telerehabilitation systems which are found effective for patients with musculoskeletal conditions, targeting the improvement of motor functions [9].

Despite the growing trend, telerehabilitation methods are prone to error due to its subjective nature and can, therefore, yield unreliable results. Other challenges of telerehabilitation include: lack of knowledge and skills in mobile health, lack of policies, laws and support for this method, and internet connectivity problems [7]. Given these challenges, there is a need to implement a system which can give objective evaluation to assess progress, and to prioritize ease of use and convenience for both patient and therapist.

2.2 Rhythmic Auditory Stimulation

Studies have shown the effectiveness of Rhythmic Auditory Stimulation (RAS), a method of using rhythm and music in improving the motor functions of patients with Parkinson's Disease and other related conditions [10]. It shows that motor learning is preserved after training with RAS for PD patients [5]. However, a more recent study during the COVID-19 pandemic shows that there is a lower uptake of RAS for telerehabilitation. Considerations in patient's conditions in the remote set-up, including safety, access to a caregiver and technological challenges influenced this result [11]. While RAS is an effective method for rehabilitation, efforts must be made to address patient's conditions in patient-therapist interpersonal connection, technological, safety, and health aspects.

2.3 System Design for Telerehabilitation

Walking assessment in telerehabilitation is an emerging application of wireless sensor networks (WSN). For the purposes of home programs classified under telerehabilitation, WSN is used to monitor human motion and activities to supervise rehabilitation. Hadjidj et al. discusses applications for WSN in continuous rehabilitation monitoring which cannot be done with current management and economic issues. Design considerations for WSN were divided into its 4 components: sensor node, communication protocols, signal processing, and framework [12].

Given the remote applications of the system, the system's ease of set-up and use, sensor functionality, and communication aspects were focused similar to the following studies [6,13,14] to cater to the elderly population.

3 System Design

The system is a supplement for the rehabilitation programs of people diagnosed with PD. It can be used during days where the patient and the therapist won't meet or even after the whole rehabilitation period to keep the patients engaged in physical therapy. It monitors the patient's progress throughout the rehabilitation period and gives objective assessment for their performance in the home setting.

The system has three major parts: the sensor node, the base station node, and the server. The sensor node is responsible for gathering and computing data for every training session. It connects wirelessly to the base station node (phone) and sends the computed data through Bluetooth connection. The Android phone application facilitates rhythmic auditory stimulation training and serves as an interface for both the patient and therapist to communicate and visualize training results. Through a Wireless Fidelity (WiFi) connection, it sends data to the server where data is stored and accessed by both users (Fig. 1).

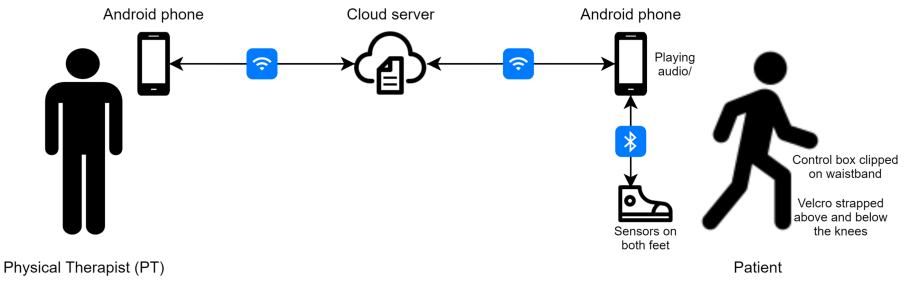

Fig. 1. Full system set-up

3.1 Sensor Node

The sensor node is composed of the insole sensors and the microcontroller. The insole sensors can be placed on slides and they are wired directly to the microcontroller. On the other hand, the microcontroller, the power supply and the insole sensor circuit are housed in a casing that are clipped to the waistband of the clothing of users. Velcros are used to strap the wires on each leg of the user to keep them in place when trainings are executed.

Insole Sensor. The insole sensor approach was adopted from the researches [15–17]. The insole sensor model, ZNX-01, is made out of eight force sensitive resistors placed in different areas of the foot. The body itself is laminated on a plastic material shaped as an insole which prevents air bubbles and unwanted contamination from dirt, affecting the readings of the sensors. Its tail, composed of the pins, is separated from the insole body so that it prevents bending during walking and thus, prolongs the usability of the device.

Both feet had one insole sensor each. The insoles can be placed on different footwears but it is highly recommended to use footwears with open backs to exclude the sensor tail from the bending stress during walking. This is essential since the sensors can produce unnecessary readings when stress is applied on the tails. The insole sensors were able to identify steps when weight is applied on the toe area.

Arduino Nano. Arduino Nano was used in this project because of its small size. The microcontroller was responsible for performing necessary calculations for the step parameters which are cadence (steps per minute), total steps, and correct steps.

3.2 Bluetooth Module and Communication

Bluetooth was used for short-range data transmission, from the sensor node to the phone. Bluetooth was the chosen network technology since it ensures interoperability and compatibility with other devices to fit end user's gadgets, transmission of data, and communication with other services such as the Internet so that information can be relayed to therapists remotely [18]. To provide the communication between the microcontroller and the phone, a Bluetooth module (HC-06) was used to transmit the training data once training is completed.

3.3 Base Station Node

Since patients perform training sessions remotely, android phones, an easily accessible item, serve as the base station of the system. From the sensor nodes, it receives the computed data which are presented in the Android application. Furthermore, it serves as the gateway to the cloud server where all past training session data are stored and accessed anytime.

The application facilitates the RAS training of the patient by playing the mp3 files of generated metronome sounds which the patients follow per training session. It provides options for the beat pace which are 49, 55, and 60 beats per minute [20]. Training durations of 10, 15, and 20 min were also implemented in the application. Both the beat pace and training duration will be based on the instruction of the therapist.

On the physical therapist's side, they have access to data of all their patients for the ease of progress monitoring and provide feedback afterwards. They can also schedule training sessions, view the schedules and give feedback for each of their patients.

Used in many health applications [21,22], Android Studio is chosen as the IDE for developing the Android-based application because it is a free and open source platform with many online libraries and resources. Furthermore, Samsung Galaxy S7 and Samsung Galaxy A7 were the Android phones used to run the application due to their similarities and availability.

3.4 Server

Database and Authentication. To connect the therapist and patient remotely, a cloud server is made with the use of Firebase. All computed training data from the phone is uploaded and stored on the database for online access. A user database was set-up to manage user profiles and login. From the gateway, the server obtains this data. Both the online database and authentication heavily rely on the internet since the server is online.

4 Testing

Testing was done on each of the system's components: sensor node, Bluetooth communication, base station node, and server, and the integrated system functionality, focusing on the sensor node's accuracy on counting correct and total steps.

4.1 Sensor Node

The behavior of the insole circuit was tested for no load and when load is applied. Different known weights with 1 kg increments were placed on cell C to identify their effect on the data reading displayed in the serial monitor of the Arduino IDE. 2 kg was used as the trigger point of the system. A step was only counted if this minimum weight was applied into the sensor and registered into the microcontroller. Moreover, filtering was done to implement the minimum step duration for the total step counter in the code. A step must be held for a specified amount of time in order for it to be counted (Table 1).

Table 1. RAS training step parameter

Step parameters	Conditions
Total steps	Minimum stepping duration achieved
	Minimum trigger point reached
Total correct steps	Minimum stepping duration achieved
	Minimum trigger point reached
	Where $T_{beat-start} \leq t_{step} \leq T_{beat-end}$

The minimum step durations for total steps and correct steps are shown below (Table 2):

Table 2. Minimum step duration filters

BPM	Total step duration	Correct step duration
49	475 ms $\leq t_{step}$	175 ms $< t_{step}$
55	450 ms $\leq t_{step}$	175 ms $< t_{step}$
60	425 ms $\leq t_{step}$	175 ms $< t_{step}$

Data computations were made in the microcontroller while the results were initially displayed on the Arduino serial monitor on a computer for easier debugging. After the sensor node prototype was completed, it was tested on the phone for connectivity and data transfer testing.

4.2 Base Station Node

Bluetooth Protocol. For the purpose of checking the functionality of the Bluetooth connection, received computed training data from the sensor node were printed on the application. At the same time, received instructions from interfacing with the application were printed on the serial monitor of the Arduino IDE. This was to ensure that the application is able to control the functions of the microcontroller especially when starting the data polling for training sessions.

Android Application. The Android application was tested separately for the patient and the therapist sides. Given the functions for patients and therapists, user interface testing and database testing were conducted to test the frontend and the backend functions of the application.

User Interface Testing includes validating buttons, dropdowns, page navigation, and the overall look and feel of the application. It must be readable and interactions with buttons and clickable elements must function properly. Database Testing on the other hand, includes validating the fields of the database, and queries.

The application's capability to facilitate RAS training sessions was also tested by simulating training sessions. User-friendliness and convenience were also ensured to address the users' remote situation.

4.3 Server Node

To test the server, the Android phone application sent dummy data based on the fields set-up on the database. The database includes the user information, training schedule, step parameters such as the total step count, correct step count, and the cadence. The dummy data must be reflected on the mobile application after uploading.

4.4 Integrated Testing

To simulate the use of the system in a remote set-up, it was divided into 2 parts: the patient and the physical therapist side. Both parts were integrated into one system with the common point of integration being the Android phone application and Bluetooth module. With this, the interactions by the users with the phone application were fully tested.

The full system was subjected to tests varying in bpm and duration to ensure every component was working. The accuracy for the computed step parameters were tested by simulating multiple complete training sessions and validating against baseline results from the reconstructed and post-processed plots of the sampled data using a python script.

The application functionalities for different user roles were also checked. Lastly, the system's capability to handle multiple users were simulated to ensure that data sent in the database corresponds to each user properly.

5 Results and Discussion

5.1 Sensor Node Tests

Considering that the majority of users are in the elderly population, it was ensured that the system is comfortable to wear and easy to use. From the rubber shoe insoles, to the wire, velcros and control box placements, the physical therapist confirmed at online consultations its ease of wearing the device and use in walking, so that the patient would not trip from the wires.

Highly sensitive FSRs utilized filters implemented on the microcontroller to identify and count steps based on the specified conditions. Moreover, since conditions for total steps and correct steps are not dependent on each other, any direct calculations between the two parameters such as a wrong step parameter, defined as the difference between the total step and correct step, were not possible.

5.2 Base Station Node Test

The application's User Interface was validated by interacting with each of the buttons of the application on Android Studio's emulator, then installed on Samsung Galaxy A7. Moreover, since the application has a function to start training sessions, its Bluetooth communication with the sensor node was also tested.

Bluetooth Communication. A Bluetooth serial application was used to initially test sending and receiving of data of 1s and 0s from the microcontroller to the phone. The data sent would contain the start command, BPM, and duration. These values for bpm are: 49, 55 and 60 while the values for the duration are: 10, 15, 20.

Similar to the function of the Bluetooth serial application, sending and receiving of data was added into the application in development to test the sending and receiving of commands. The serial monitor of the Arduino was monitored alongside the terminal for the phone application. With the Bluetooth communication coded into the application, data was sent in json format, processed and uploaded into the database.

Time Synchronization. For earlier testing of synchronization between audio sending data, it was observed that there was a noticeable delay between the time the audio starts playing and the time the start command is received by the Arduino. Since synchronization of both devices is important in the function of the system, round trip times were measured. The round trip time was assumed to be uniform for the Bluetooth communication. One-way trip time or half the round-trip time of 536 ms was the delay coded onto the application to ensure data has reached the Arduino before playing the audio.

5.3 Server Tests

To test reading data from Google's Cloud Firestore platform, test data were manually inputted and verified on the Firebase console in order to be read by the application [13].

5.4 No Load Test

The first test for accuracy done was the no load test. The system was run for three 10 min tests where no load was applied on the insole sensors. This was done to check if the system detects stray signals and unwanted values and counts them as steps.

An average accuracy of 100% was obtained for the three tests performed which shows that the system was able to filter out noise properly for cases where no load was applied on the sensors.

5.5 Correct Step Test

To characterize the performance of the system during training sessions, three 10 min tests were conducted for the 49, 55, and 60 bpm options. The researcher walked through a walkway with minimal obstruction and the beats played through the phone application were followed as much as possible. The 10 min duration option was chosen since it was long enough to produce sufficient data points needed for the results.

After each training session, the sampled data from the microcontroller were saved in a CSV file which was processed by analyzing the graphs of the signals from the CSV file automated using a Python script with a recreated filtering and step counting algorithm based from the microcontroller code. The baseline data was set to be the ideal performance of the system since it utilizes the raw and actual readings from the sensors without the effects of the real time filtering and step counting algorithm from the microcontroller (Fig. 2).

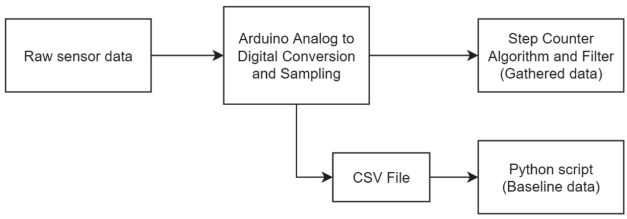

Fig. 2. Gathered and baseline values

The errors from each test came from the difference between the gathered and the baseline values. These differences came from the delays caused by the off synchronization between the microcontroller and the phone application due

Table 3. Gathered and baseline results for 49 BPM, 10 min

Test	Parameter	Gathered	Baseline	Difference
1	Total steps	352	382	30
	Correct steps	212	321	109
	Cadence	35.2	–	–
2	Total steps	496	436	60
	Correct steps	258	243	15
	Cadence	49.6	–	–
3	Total steps	573	432	141
	Correct steps	332	227	105
	Cadence	57.3	–	–

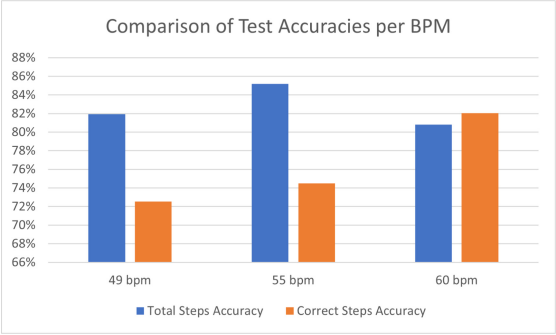

Fig. 3. Comparison of test accuracies per BPM

to the beat generation in the microcontroller. The microcontroller has its own process of beat generation independent from the phone application. The beats in the microcontroller were run sequentially within a single loop. The delays caused the off synchronization between the microcontroller and the phone, which affects the performance of the system especially for longer training durations. Synchronization is critical since the microcontroller and phone application work independently in terms of generating the beats. Thus, beats heard by the patient can differ significantly from the generated beat by the Arduino (Table 3 and Fig. 3).

5.6 System Functionality

Multiple user accounts were made to verify the functionality of the system in receiving and transmitting data properly. 3 patient accounts along with 1 therapist account were created to test the start training, view results, and calendar functions for the patient, and to view and access all the training results of every patient and calendar functions for the therapist.

6 Conclusion

A wireless sensor network was designed and implemented to aid Parkinson's Disease patients and therapists to objectively assess and monitor rehabilitation progress during telerehabilitation. The system was composed of a sensor node, a base station node, and cloud server. Considering the age demographic of users, ease of use and comfortability were considered in the design.

The sensor node was able to gather data and compute for the step parameters which were the cadence, total step count, and correct step count. It was found that delays, which became more evident on longer training durations, were present in the system and affected its accuracy and overall performance.

The base station node in the form of a phone application was able to communicate with the sensor node using Bluetooth at every start and end of a training session. To facilitate rhythmic auditory stimulation training, auditory cues with 49, 55 and 60 bpm frequencies were played through the phone. The application displayed the results of every training session as well as serve as an interface for both the patients and therapists.

The server was used as an online authentication and database where data such as user information, training schedules, results and feedback gathered every session are uploaded and requested for viewing for both patients and therapists.

An accuracy of at least 80% and 70% for the total step and correct step parameters respectively were measured for a 10 min training session. These are favorable results given that the system is still in its first stages of prototype development.

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