Smartphone-Based Assistant for Walking Rehabilitation of Patients with Parkinson's Disease

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ABSTRACT

Parkinson's disease (PD) is a progressive degenerative disorder. In addition to controlling the condition through medication, rehabilitation is required to maintain physical function, muscular strength, and coordination. Walking is necessary in performing activities of daily living, and it involves moving the feet in straight line and turning the body to change direction. However, patients with PD experience difficulty walking in straight line and turning because of rigidity or freezing. Furthermore, they are at an increased risk of falling. Physical therapists assess the quality of walking rehabilitation and provide verbal feedback to correct their patients' movements. However, in most cases, patients practice walking and undergo rehabilitation independently; consequently, they cannot evaluate their rehabilitation outcomes, which decreases their intent to continue practicing. This study utilized the internal inertial systems in smartphones (e.g., accelerometers and navigation) to assist patients with independently evaluating their rehabilitation quality. The inertial systems were also used to count the number of steps and record the time that patients spent on walking in a straight line and executing turning movements. Finally, the researchers provided feedback to the patients regarding their movement quality.

KEYWORDS

Parkinson's Disease, Rehabilitation, Smart phone, Gait, Accelerometer.

1 INTRODUCTION

Parkinson's disease (PD) is a neurological disorder typically presenting in adults aged 60 years and older [1]. With the trend of population aging, the number of elderly adults is increasing annually, thereby increasing the incidence of PD. The number of patients with PD in Taiwan was approximately 100,000 in year, and the number of diagnosed cases has been increasing annually [2]. PD is mainly caused by apoptosis in dopaminergic neurons in the midbrain substantia nigra complex. The resulting decrease in dopamine causes uncoordinated body movement [3, 4]. Postural changes are necessary in performing activities of daily living. Transitioning from walking in a straight line to turning the body is a common body function. Standing and walking tests are frequently used as rehabilitation tools for evaluating the effectiveness of patient rehabilitation [5]. As the disease progresses, patients with PD experience changes in gait and posture, particularly when turning the body to change direction. Patients with PD experience difficulty turning while walking [6] and they generally need to take more steps than healthy adults do [7]. Previous studies have used inertial component sensors to assess the movement performance of patients with PD by attaching the sensors to the legs or head [8, 9] and using additional signal receivers or smartphones to acquire data for analysis. During the measurement process, participants must wear multiple sensors, which inevitably affects their movements. By contrast, current smartphones are typically equipped with inertial system chips and can facilitate detecting the body movement characteristics of patients with PD. Therefore, this study used a smartphone to detect physical movement and assess the corresponding parameters during standing and walking tests. When patients with PD performed walking and turning rehabilitation exercises at home, they could independently assess the effectiveness of their rehabilitation from home and document the entire rehabilitation process by using the system developed in this study. Hospital physicians and therapists were able to remotely observe the patients' physical activity status as necessary via a Web server. The system enabled therapists to follow-up the patients' rehabilitation progress and effectiveness. Figure depicts the system concept.

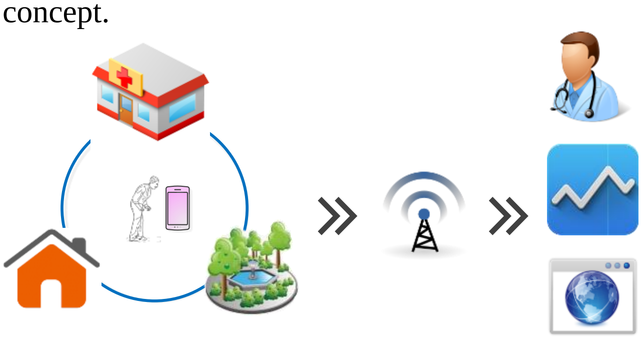

Figure 1. Conceptual diagram of the system.

2 METHOD

This section describes the methods employed in this study to test human body movements, rehabilitation processes, and the developed application software.

2.1 Inertial Measurement Unit

Most smartphones are fitted with accelerometer chips that can determine the acceleration value in 3-dimensional space. Figure 2 shows the triaxial distribution of a smartphone. The *x*-, *y*-, and *z*-axes represent the directions along the height, width, and front–rear sides of the smartphone, respectively.

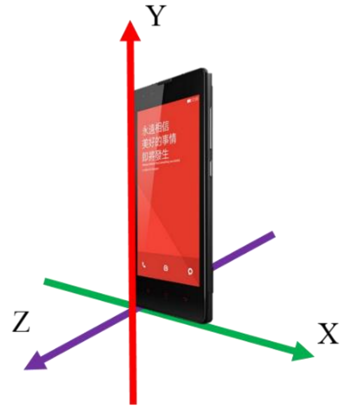

Figure 2. Triaxial distribution of a smartphone.

During the pilot study phase, the acceleration of the smartphone had to be normalized to eliminate the effect of the Earth's gravity (i.e., 9.8 m/s^2) on the experiment and improve the precision of acceleration values. During the normalization process, the smartphone sampling frequency was set at 100 Hz. The mean value of the smartphone triaxial acceleration over 5 s was calculated by using Eq. (1):

$$aveX = \frac{\sum_{i=1}^{n} x_i}{n} \quad (1)$$

where *aveX*, *aveY*, and *aveZ* represent the *x*-, *y*-, and *z*-axes, respectively; and *n* = 500.

While walking forward, the body also moves upward during the swing phase of the gait cycle. This upward acceleration is particularly notable. Thus, the proposed system considers the acceleration generated along 3 dimensions of space and calculates the signal vector magnitude (SVM) in the space based on the triaxial acceleration, as shown in Eq. (2):

$$\mathrm{SVM} = \sqrt{(AccX - aveX)^2 + (AccY - aveY)^2 + (AccZ - aveZ)^2} \quad (2)$$

where *AccX*, *AccY*, and *AccZ* denote the acceleration along *x*-, *y*-, and *z*-axes measured by the sensor, respectively.

2.2 Clinical Requirement

Independent walking rehabilitation processes involve practicing walking in a straight line and turning while walking. For example, the Timed Up and Go test is a rehabilitation measure that enables rehabilitation and assessment [10, 11]. Through interviews with physical therapists and neurologists, the clinical requirements of patients with PD were identified. The proposed system assessed the total time spent and total number of steps taken when walking and turning, the time spent and the number of steps taken when turning. The smartphone was attached to the lower back of the participant, which is the center of mass. The implemented test was a walking and turning test (Fig. 3). The participants walked around 2 objects spaced 6 m apart. The process involved walking in a straight line and performing a U-turn, covering a total distance of 12 m. The patients walking speed was inferred based on this distance and the time they spent walking. Shorter times indicated higher performance regarding walking function, and fewer steps implied a longer gait. Because, patients with PD commonly experience difficulty turning, observing the walking time and number of steps can indicate their turning function. The data of the 4 parameters (i.e., total steps, total time, turning time, and number of steps taken when turning) can assist neurologists or physical therapists with evaluating the disease development and determining the appropriate course of action for rehabilitation [12].

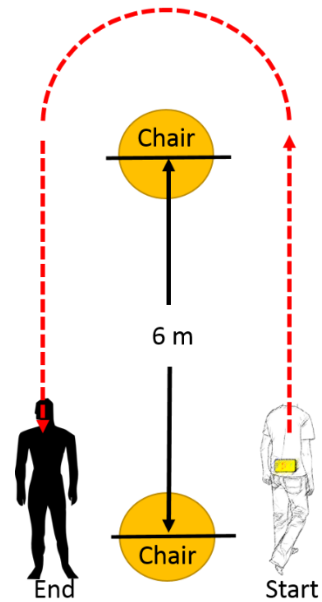

Figure 3. Walking and turning test.

2.3 System Design

Figure 4 shows that the architecture of the proposed system comprises 6 primary components: a sensor, prompts, display, physical buttons, measure, and database.

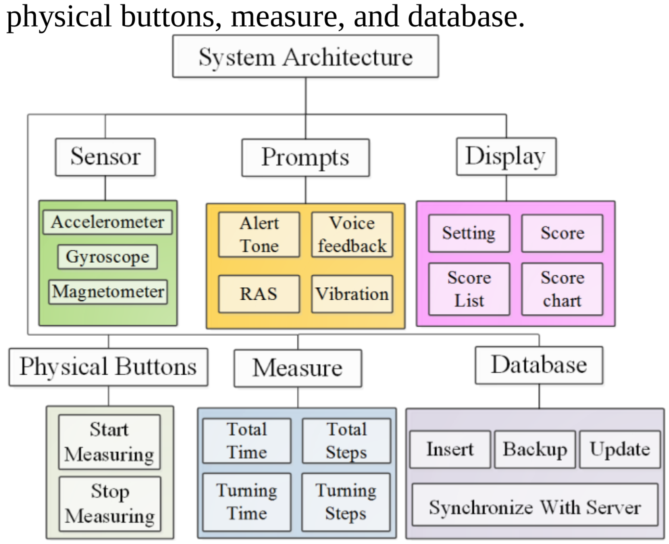

Figure 4. System architecture.

The proposed system utilizes the built-in inertial modules (i.e., accelerometer, gyroscope, and magnetometer) of a smartphone. Through the inertial module chips, the acceleration and angle of the participants can be determined. The volume buttons on the smartphone were used to start and stop the system, specifically because using the touchscreen interface could easily result in the wrong button being pressed or other difficulties with operating the system. During the test process, alert tones were set and text-to-speech technology was employed to convert digital text into speech, providing the participant with rhythmic auditory stimulation (RAS) that assists them with walking and striding. To detect the participant's movements, the algorithm in the program was used to determine the 4 parameters (i.e., total time, total steps, turning time, and turning steps) of the patient. These parameters were then displayed and stored in the database, which was constructed using Android SQLite. This database application enabled data insertion, updating, backup, and remote synchronization. The measurement results were displayed on the screen, and lookup functions enabled users to view the relevant data charts.

Figure 5 is a process flow diagram depicting the system operation. In this study, measurements were first conducted in a hospital to obtain baseline values for subsequent data comparison. Upon first usage, the participants were requested to enter their basic personal information. Instructions were displayed on the screen to assist the participants with fitting the smartphone. The system automatically detected the orientation of the smartphone and alerted participants if adjustment was required. Pressing the volume-up button activated the system in a null state. During the walking and turning rehabilitation exercises, the system provided RAS to assist the participants with completing the exercises. Upon completing the exercises, the participants pressed the volume-down button to stop the measurements. Subsequently, the results were displayed on the screen, as well as a comparison with the baseline values to indicate whether the participant's performance had improved. Finally, the data were stored in the database.

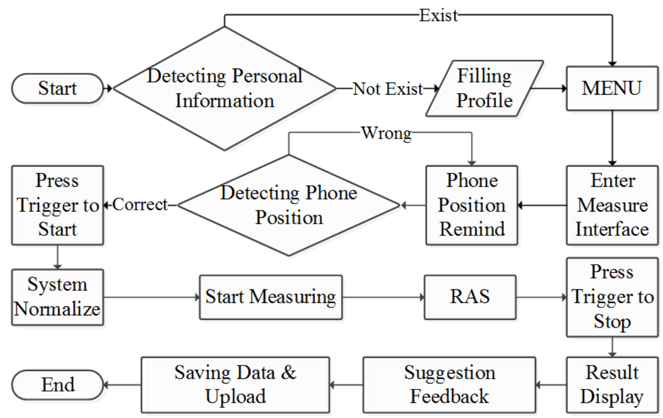

Figure 5. System process flow diagram.

3 RESULTS

Smartphone accelerometers are affected by gravity. Consequently, when the smartphone was fitted to the lower back of the participants, the 3 acceleration axes would normally be unable to determine an ideal position, that is, with the *x*-axis vertical to the ground; hence, the normalization method was incorporated to prevent gravity from affecting the experimental results. Successful normalization of the triaxial accelerometer enabled the acceleration readings to be obtained accurately, regardless of the alignment of the smartphone when fitted, and the SVM was subsequently calculated. The effectiveness of the normalization process is indicated in the graph in Fig. 6. In the figure, the signals are not normalized for the first 10 s of the process, where the acceleration is 9.8 m/s^2. After 10 s, applying the normalization process clearly reduced the SVM value to zero, indicating that the effect of gravity was successfully eliminated.

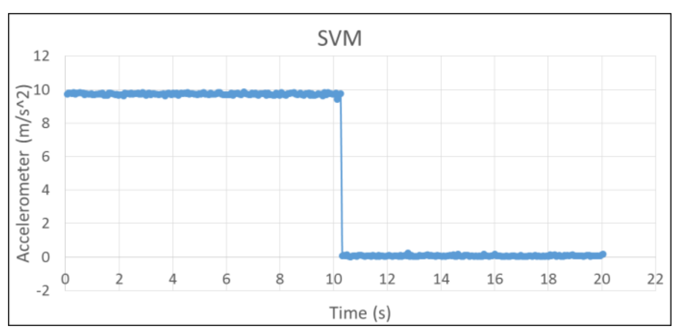

Figure 6. SVM results before and after normalization.

A sensor data logger developed in this study effectively measured the acceleration. After the measurements were recorded, the system calculated the participant's SVM. A pilot test was conducted with a laboratory staff member acting as the participant. The proposed system was fitted, and the participant walked in a straight line after initiating the system. Subsequently, the program computed the results, determining that the participant had walked 5 steps within 15 s (Fig. 7).

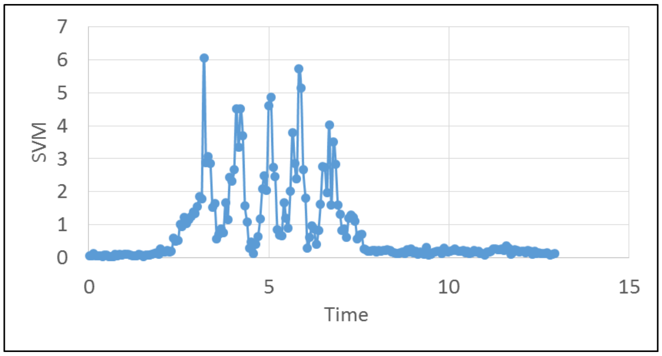

Figure 7. SVM data.

The sensor data logger also recorded the angle of the participant while turning. The described rehabilitation process involved performing a U-turn at 6 m. Theoretically, the participant would turn 180° upon completing the process. However, the pilot study results indicated an approximately 30° change while walking in a straight line, and 210° change after walking around the object (Fig. 8). The proposed system can determine the participant's change in angle, turning status, and turning time. After performing the measurements, the proposed system calculated the total time, total number of steps, turning time, and turning steps from the walking and turning rehabilitation exercises.

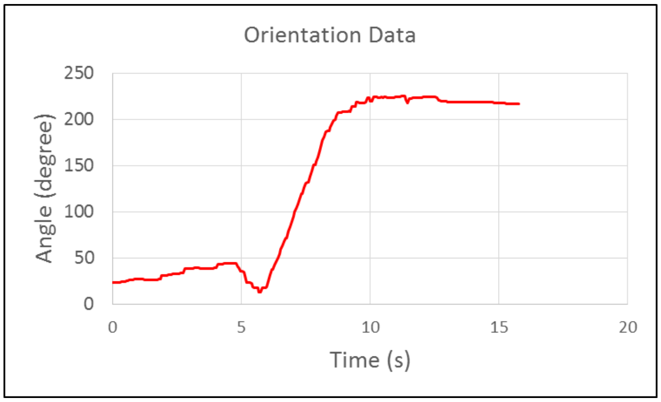

Figure 8. Orientation data.

Figure 9 shows the basic design of the measurements displayed on the interface. The figure indicates how the results would be displayed on the screen after completing rehabilitation exercises, informing the user of the total number steps, total time, turning steps, and turning time. In addition, simple messages can be displayed on the screen (or delivered using voice feedback) to provide advice to the user. The user was notified with the difference between the current and previous measurement results. After completing rehabilitation exercises, the user can press the "try again" button to restart the process.

Figure 9. System design.

4 DISCUSSION

For the pilot study, a sensor data logger was designed to verify the feasibility of the proposed system. Measured data were successfully stored in the smartphone. By analyzing the data, the system recorded the number of steps and calculated the walking time. The test process was initially affected by gravity. By using the proposed algorithm, the acceleration measurements were normalized to eliminate the effects of gravity. Furthermore, using a human-machine interface enables a convenient design for users to operate the system. In future studies, a system usability scale will be developed to obtain feedback from health care professionals and patients through face-to-face or telephone interviews to verify the usability and appropriateness of the system.

Current devices that are suitable for patients with PD include visual cueing devices, which could be used to project a red laser dot onto the ground in front of patients PD to guide them [13]. A previous study installed one or more sensors on a patient with PD to measure their acceleration or change of angle, and the measurements were recorded using a smartphone [14]. However, using these devices would require multiple sensors to be fitted to the patients. In this study, accelerometers and orientation functions built into smartphones were used to measure the acceleration and angle change of participants performing walking exercises—additional sensors were not required, thus providing a system that is convenient to use. In future studies, a back-end Internet-based platform will be developed to enable the measured data to be synchronized with a server immediately after the patient completes the exercises, thereby enabling physicians and therapists to monitor the rehabilitation status of patients remotely. Therefore, patients may perform rehabilitation exercises from home and determine their rehabilitation status independently. By reviewing their data history, the patients can track their rehabilitation progress, and physicians or therapists can periodically monitor the rehabilitation progress of the patients and if necessary, appropriately adjust the patient's medication or rehabilitation plans.

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