Gamification of Stroke Rehabilitation Exercises Using a Smartphone

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ABSTRACT

Stroke is a disabling disease that requires extensive work of rehabilitation to improve the quality of life of patients. In order to increase the compliance and motivation of the patients, stroke rehabilitation exercises have been developed in a game-like structure using a smartphone. These games were designed to promote and evaluate different movements of the upper limbs and their level of difficulty is adaptable to each patient's impairment level. The feasibility of the use of smartphone built-in inertial sensors to monitor the execution of stroke rehabilitation exercises has been assessed. The accuracy of the angles measured decreased along time and for higher angles, nevertheless the differences between real and measured angles are within acceptable limits. The usability tests in a post-stroke patient case demonstrate the applicability and motivational potential of the developed games. Gamification of stroke rehabilitation exercises using a smartphone is feasible and may be valuable for stroke rehabilitation.

Categories and Subject Descriptors

H.1.2 [**Information Systems**]: Models and Principles—*User/Machine Systems*; J.3 [**Computer Applications**]: Life and Medical Sciences

General Terms

Design, Experimentation, Human Factors e Measurement

Keywords

Stroke rehabilitation, virtual reality, Android, inertial sensors, Bluetooth

1. INTRODUCTION

Stroke is a cardiovascular disease that can affect several faculties such as the ability of moving, seeing, remembering, speaking and reasoning [1]. In order to achieve independence in daily living activities, stroke survivors need extensive rehabilitation work, having to attend long sessions of physiotherapy. The compliance with treatments and therapies is crucial and requires high motivation. The gamification of these exercises and their deployment in ubiquitous and pervasive devices such as smartphones or tablets may enable a more engaging and compelling rehabilitation at home while also improving the cost-efficacy of stroke recovery. The smartphone or tablet screen allows creating virtual-reality scenarios for the rehabilitation games. Additionally, their built-in inertial sensors can be used as wearable sensors, attached to different parts of the body and communicating with the virtual scenario by bluetooth or wifi, to assess the compliance to the movements prescribed. Finally, the smartphone can be used to promptly send the metrics of the patient performance during the rehabilitation exercises to the therapist.

A few smartphone applications have already been developed for stroke rehabilitation. Dr. Droid [2] is an Android application that administers the Wolf Motor Function Test by giving audio and visual instructions to the patient and collecting the accelerometer data of the smartphone in the wrist. The DroidGlove [3] application uses various inertial sensors built-in the smartphone to assess the compliance of the patient to the exercises learned by visualizing a video recorded by the therapist. Using only the smartphone, these applications enable the practice of the exercises anywhere. However none of them allows the visualization of the game in simultaneous with the execution of the tasks.

More sophisticated systems make use of wearable sensors connected by bluetooth to the smartphone, which requires the acquisition of additional equipment. This is the case of SQUID, a smart shirt used to provide feedback to the user by measuring electromyography and heart rate data [4]. UBI-Rehab [5] is a mobile-based rehabilitation system using augmented reality and a wearable accelerometer deployed in a glove (eGlove) to play pick-and-drop games.

In our system, three stroke rehabilitation exercises were implemented in a game-like structure. They are played in a computer screen and the smartphone is attached to the wrist of the user. The first exercise is the supination/pronation of the forearm, the second is the flexion/extension, and the third is the medial/lateral rotation. These exercises are simple to evaluate with a smartphone and the developed games help to assess all degrees of freedom of the forearm.

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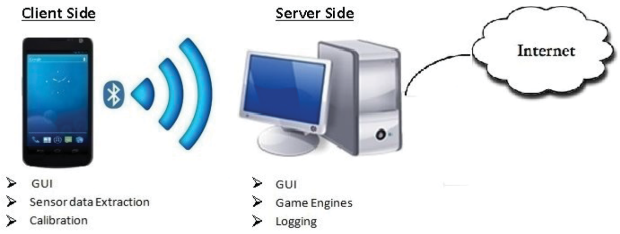


Figure 1: Application architecture.

Figure 2: Smartphone position.

2. MATERIALS AND METHODS

2.1 Setup

The architecture of the system is displayed in Figure 1. The system consists of a bluetooth enabled smartphone (client) and a computer connected to the Internet (server). The smartphone is placed in an armband attached to the upper limb of the user to collect data from the movement prescribed by indications in the screen of the computer, as demonstrated in Figure 2. This server/client architecture enables the use of the computer screen as visual interface of the games. This ensures an intuitive experience and an improved visual feedback that the smartphone alone could not achieve.

The server side of the application is connected to the Internet and can send information to a therapist in a remote location. In this work, an email containing the main angles measured and the score obtained in the games is sent to a therapist.

2.2 Data Processing

A smartphone is equipped with three inertial sensors, a magnetometer, a gyroscope and an accelerometer. The accelerometer measures the acceleration (in m/s^2) of the device, the magnetometer measures the ambient magnetic field around the device (in micro-Tesla (μT)) and the gyroscope measures the angular speed of rotation (in rads/sec) [6].

In order to get the orientation of a smartphone, it is necessary to combine the data of at least two sensors. To do that, the Android API provides a method that measures the device's orientation in the 3-axis plane, in relation to a known initial position. The frame of reference used is called the Earth Reference Frame [6]. In this frame of reference the X axis points East, the Y axis is tangential to the ground and points towards the magnetic North Pole and the Z axis is perpendicular to the ground and points to the sky. The output of rotation over the Z axis is approximately 0° if the smartphone is pointing to the magnetic north and the rotation over the Y and the X axis is approximately 0° if the smartphone is laying perfectly horizontal.

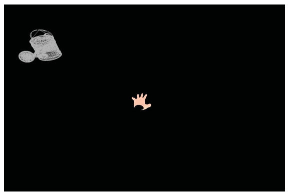


Figure 3: Visual interface of the "Grab and Rotate Game" showing hand and watering can models.

2.3 Developed Games

In general, movements that can be evaluated in angles of rotation are appropriately assessed with a smartphone. Any exercise like extension, flexion, pronation, supination, elevation or depression can be evaluated by a smartphone if it is attached to the segment of the body that is being rehabilitated. Rehabilitation therapies are based on task-oriented repetitive training and, if possible, those tasks should be oriented to activities of daily living. Rhythm and audible or visual feedback are also reported as being beneficial. Rehabilitation sessions should be progressive and fine motor tasks should be included in the process. Therapies that provide high motivational levels are preferred [7].

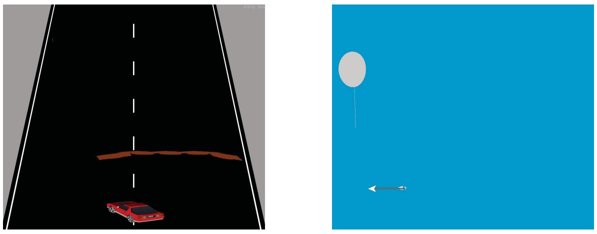
The application contains a calibration phase that ensures that the games are always adapted to the stage of recovery of the patient. That calibration always takes place before the start of the game and evaluates the maximum range of movement of the user (in degrees). All games finish after 1 minute and display the score and the maximum angles of rotation achieved by the player.

2.3.1 Grab and Rotate

This game incorporates medial and lateral rotations, flexion and extension movements and supination and pronation of the forearm. This game is one of the most complete games that can be created specifically to the rehabilitation of the upper limb, since it demands movements in all axis of rotation.

The game begins with a hand model representing the patient's hand at the center of the screen. In it, three different randomly objects appear (a door, a bird's cage and a watering can). Taking into consideration the therapist feedback, the chosen models were real objects that patients can find on their daily routine. To make progress in the game, the patient has to place the hand on top of the object model on the screen and rotate the wrist over itself. The door and the cage must be opened and the water from the watering can must be dumped. The door and the cage disappear with the maximum rotation to the right and the watering can with the maximum rotation to the left. Anytime a model on the screen disappears, another model is rendered.

This prototype assumes that all players are right-handed. Taking that into consideration, this game deliberately demands for more rotations to the right than to the left because patients generally have more difficulties in the supination of the wrist than in the pronation exercise. One point is added to the score of the player for each successful rotation. The hand model and the watering can are displayed in Figure 3.



(a) “Avoid Block” (b) “Balloon Strike”

Figure 4: Visual Interfaces of the Games.

2.3.2 *Avoid Block*

This game focuses on the physiotherapy of the medial and lateral rotations of the forearm/arm. In the “Avoid Block” game the patient has to tilt the phone to the left or to the right to steer a car and avoid roadblocks that appear randomly on the screen. At the moment the game is launched, the rotation over the Z axis of the patient’s arm is considered the center of the screen.

The blocks appear on a higher rate on the left side, to force patients to rotate the forearm more times laterally. That is done because post stroke patients usually show more difficulties in the lateral movement than in the medial rotation. The game is calibrated in a way that every patient, no matter his level of impairment, can have a similar experience while playing the game. That is done by adjusting the car steering sensitivity to be inversely proportional to the patient’s impairment level. The player starts with 0 points, earns 1 point if successfully avoids a roadblock and loses 1 point if he lets the car collide with it. The visual interface of the game is shown in Figure 4a.

2.3.3 *Balloon Strike*

This game’s concern is the flexion and extension of the forearm/arm. As in the “Avoid Block”, this game focuses on just one type of movement. They were created with the goal of extending the inertial sensors rehabilitation concept to patients who can not physically execute a more complete game like the “Grab and Rotate Game”. Even if they are more severely impaired in some other movements, they can still play games that provide a high motivational level.

The “Balloon Strike Game” is a basic 2D game where the player has to move a party balloon up or down, extending or flexing the forearm to catch arrows that appear from the right side of the screen. The game is calibrated to adjust the sensitivity of the balloon movement. The angles evaluated are correspondent to the maximum extension and flexion of the forearm. The visual interface of this game is displayed in Figure 4b.

2.4 Proof-of-concept Tests

The foundations of all games are the inertial sensors. They must measure the angles of movement accurately. To validate the angles measured by the application, one rotation for each axis was performed and a photo of the initial and final positions was taken. In those pictures, the real angle of rotation is measured and compared with the value of rotation that the smartphone displays on the screen. All photos were shot from a fixed spot, with the help of a tripod and all angles were measured in the photos with the software MB-Ruler.

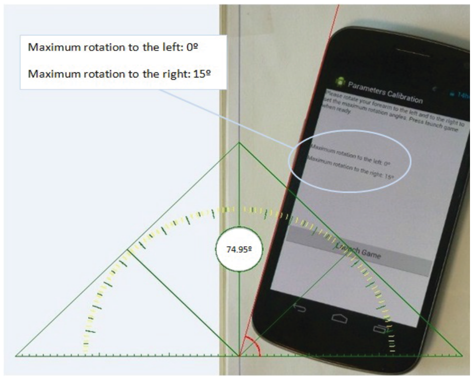


Figure 5: Photo of validation of a rotation measured by the smartphone.

After evaluating how well the smartphone sensors assess one rotation on each axis, an evaluation of how well they perform over time was conducted. To do that, the smartphone was rotated from the same fixed position to three different known angles. These rotations were performed 10 times to each angle and the angles measured by the smartphone were compared to the real angles.

This application was also tested by a patient, who had been discharged from the hospital 2 weeks before. The patient was observed while performing the games and was enquired about his satisfaction and motivation with this kind of rehabilitation approach. The opinion of the patient’s physical therapist about the usefulness and usability of the game was also obtained.

3. RESULTS

To validate the angles assessed in the “Grab and Rotate” and in the “Balloon Strike” games, the smartphone had a natural line of reference for the initial position: the table. To evaluate the rotation over the Z axis, the introduction of an external line of reference was required printed. To do that, a page that contained only a vertical line connecting the top to the bottom of the page was used. The smartphone was placed in contact with that line and it became the reference of the initial position. The smartphone was then rotated to the right and a second photo was shot. The final position of the smartphone can be seen in Figure 5. The smartphone rotated from 90 to 74,95 degrees. That makes it approximately 15 degrees of rotation and that is exactly what was measured by the smartphone.

The results of the tests of accuracy of the angles calculation along time are showed in Figure 6. In the following graphic, the blue line represents the real angles reference and the red line represents the angle of rotation assessed by the application. The trials were made of 10 samples of 30, 60 and 90 degrees rotations and were collected every 20 seconds.

A numeric comparison between the real and the virtual an-

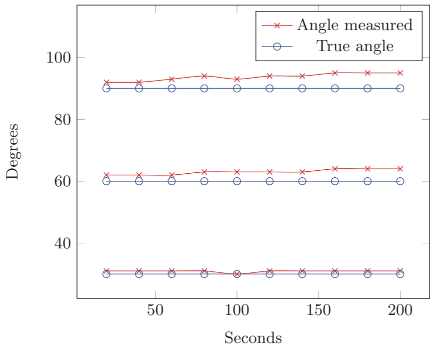


Figure 6: Comparison between angles obtained from sensor fusion and real angles.

Table 1: Mean and Standard Deviation of Measured Angles.

Angle	Mean	Standard Deviation
30 °	31 °	0.3
60 °	63 °	0.8
90 °	94 °	1.2

gles is presented in Table 1. It is noticeable a small decrease in accuracy of the measured angle over time and that variation is accentuated in higher angles. However, these small errors are not really significant in the context of this rehabilitation task, especially when games that have limited continuous game time are considered. Everytime a patient plays a game the sensors are restarted and the drift is eliminated.

The results of the patient trial, showed that he seemed quite satisfied and motivated throughout the process. While playing the games, it became evident that he was struggling a little bit with the difficulty of the games, but not with the usability. In the patient's and his therapist's opinion, the concept has a lot of potential and the application is easy to use and well adapted to the goal. The calibration screens allow a persistent difficulty level adjustment and the implemented games increased the patient's motivation.

4. DISCUSSION AND FUTURE WORK

This work contributed to demonstrate that smartphone inertial sensors can be used to develop stroke rehabilitation games and to monitor the patients performance. The routine of rehabilitation can become tedious, repetitive and demotivational and an application of this kind can increase the patient's motivation. These games may constitute an alternative to more traditional approaches and ensure the continuation of the treatment at home.

This paper presents an original virtual reality application for the upper limbs stroke rehabilitation that relies on a smartphone and on a desktop computer. This application has the advantage of using tools of increasingly widespread access that can be used to monitor the exercise execution and send information to therapists.

This application still needs to be extensively tested with a larger group of patients. For a proper validation of the concept, those results must be compared with the outcome of a similar period of treatment with a more traditional approach. As of this moment, this prototype is able to detect and assess movements from only one segment of the body and works only with Android smartphones. This application should be made available to other mobile operating systems and the graphical interface must be improved and reviewed by designers, to be adapted to the appropriate audience. The feedback the therapist receives can be more detailed and updated in real or almost real-time, providing status of the patient's evolution through a web interface. In the future, different difficulty levels on each game should be studied as a possible alternative to the calibration phase.

This work can be greatly improved with the inclusion of tags of external sensors attached to other regions of patients' bodies. These tags are smaller than smartphones and would make the evaluation of more movements possible. A version of the same application that uses external sensors instead of the smartphone and an Android tablet instead of the desktop/laptop computer is currently under development. The communication in this new version is based on Bluetooth Low Energy.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] L. Brewer, F. Horgan, A. Hickey, et al. Stroke rehabilitation: recent advances and future therapies. *QJM: An International Journal of Medicine*, 106(1):11–25, September 2012.

[2] Andrew Goodney, Jinho Jung, Scott Needham, and Sameera Poduri. Dr. droid: Assisting stroke rehabilitation using mobile phones. In Martin Gris and Guang Yang, editors, *Mobile Computing, Applications, and Services*, number 76 in LNICST, pages 231–242. Springer Berlin Heidelberg, January 2012.

[3] D. Maggiorini, Palazzi, and Claudio E. Droidglove: An android-based application for wrist rehabilitation. *Ultra Modern Telecommunications & Workshops, 2009*, pages 1–7, October 2009.

[4] Younggeun Choi. Squid: Sensorized shirt with smartphone interface for exercise monitoring and home rehabilitation. *2013 IEEE International Conference on Rehabilitation Robotics*, pages 1–6, June 2013.

[5] Younggeun Choi. Ubi-rehab: An android-based portable augmented reality stroke rehabilitation system using the eglove for multiple participants. *International Conference on Virtual Rehabilitation*, pages 1–2, June 2011.

[6] Shahid Ayub, Alireza Bahraminisaab, and Bahram Honary. A sensor fusion method for smart phone orientation estimation. In *Proceedings of the 13th Annual Post Graduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting, Liverpool*, 2012.

[7] L Oujamaa, I Relave, J Froger, et al. Rehabilitation of arm function after stroke. literature review. *Annals of physical and rehabilitation medicine*, 52(3):269–93, April 2009.