2018 IEEE 15th International Conference on Wearable and Implantable Body Sensor Networks (BSN)
4-7 March 2018
Las Vegas, Nevada, USA

VRInsole: An Unobtrusive and Immersive Mobility Training System for Stroke Rehabilitation

Hawkar Oagaz, Anurag Sable, Min-Hyung Choi, Wenyao Xu, *Member, IEEE,* and Feng Lin, *Member, IEEE*

***Abstract*— Stroke is a leading cause of long-term impairment, causing a fatality if not act upon in time. Home-based post-stroke rehabilitation plays an important role in helping patients to regain normal mobility and functionality at their residence. However, existing home-based rehabilitation approaches fail to effectively motivate patients on frequent engagement with exercise to achieve the intended outcome. In this paper, we develop VRInsole, a synthetical solution combining a Smart Insole footwear sensor and virtual reality (VR), targeting lower extremity mobility training in an immersive environment for stroke rehabilitation. Specifically, the motion information collected from the Smart Insole serve as the input for the VR to perform corresponding exercise animations. To prove the feasibility of VRInsole, an experiment is conducted on the recognition of lower extremity motion direction, which achieves an average accuracy of 93.9%.**

I. Introduction

Stroke is one of the leading causes of long-term ailments, affecting 795,000 people every year in the U.S., out of which 185,000 are recurrent attacks [1]. Deficits following stroke lead to increased rates of fatality or a repeated episode of stroke. Therefore, these individuals require training of movement to optimize their mobile performance with the long-term goal of decreasing fatality rate post stroke and improving balance efficiency.

While many clinical treatments are available for post-stroke rehabilitation, it may not be within every patient's reach. Thus, encouraging patients to practice activities outside of therapy times has been advocated for in rehabilitation. Also, frequently practicing contributes significantly to regain as much motion function as possible. The current rehabilitation practice relies on the static written home program, which is a monotonous repetition and has no encouragement for patients to motivate and refine their motion. The lack of motivation, and assistance in such environments, makes the existing home-based therapy ineffective [2].

In this paper, we proposed *VRInsole*, a home-based, virtual reality (VR) assisted environment that will promote self-management across the lifespan in stroke rehabilitation, with a focus on the lower extremity mobility training. It is a synthetical solution comprising of an unobtrusive Smart Insole footwear device and a head-mounted VR device. Smart Insole can be used in home environments, record foot motion data over extended time, and provide these data for creating VR animation. Many research works have shown the potential effectiveness of VR in rehabilitation therapy[3]. Moreover, VR has demonstrated improvement in walking ability and motor function in general[4, 5]. Therefore, the intention of using VR was to motivate stroke patients to practice more often by providing an immersive near-real environment and feedback on exercise quality. This proposed system is intended to overcome the shortfalls of the current standard of care of written home exercise programs [6] to guide rehabilitation efforts after discharge from clinical therapy services.

II. Related Work

A. VR-based Rehabilitation

Several systems for upper extremity rehabilitation using VR are available in our society. Some utilize off-the-shelf hardware such as Nintendo Wii U VR [7]. In academia, Jack *et al.* [8] used a Cyber-Glove to interact with a VR environment for hand function rehabilitation. Frisoli *et al.* [9] presented an upper-limb force-feedback exoskeleton for robotic-assisted rehabilitation in VR. The exoskeleton measures the user's activity and converts it into VR movement. However, no such system is available for lower extremity mobility rehabilitation.

B. Exergames

Various exergames such as SoccAR [10] use an augmented reality (AR)-based approach for creating fast-paced, motivated games to promote health-related benefits in home and social environments. These systems mainly create a virtual environment to motivate users and provide a suitable scenario wherein the user can perform physical activities. However, these exergames focus more on daily life and sports activities rather than dedicated rehabilitation tasks for stroke patients.

III. System Design

A. System Overview

The overall VRInsole workflow diagram is illustrated in Fig. 1. A patient who is demanded to perform exercises for stroke rehabilitation is supplied with a Smart Insole wearable sensor worn with the shoe. After the user performing exercise routines as prescribed by the VR system, the acceleration, and angular velocity data were generated by the inertial motion unit (IMU) sensor embedded in Smart Insole and were sent to a connected VR system. After that, the VR system can utilize the obtained data to recognize the user's activity and render the activity in a virtual environment.

H. Oagaz, A. Sable, M. Choi, and F. Lin are with the Department of Computer Science and Engineering, University of Colorado Denver, Denver, CO 80204 USA. (e-mail:{hawkar.oagaz, anurag.sable, min.choi, feng.2.lin}@ucdenver.edu).

W. Xu is with the Department of Computer Science and Engineering, State University of New York at Buffalo, Buffalo, NY 14260 USA (e-mail: wenyaoxu@buffalo.edu).

Corresponding author: Feng Lin, phone: 303-315-0161; e-mail: feng.2.lin@ucdenver.edu.

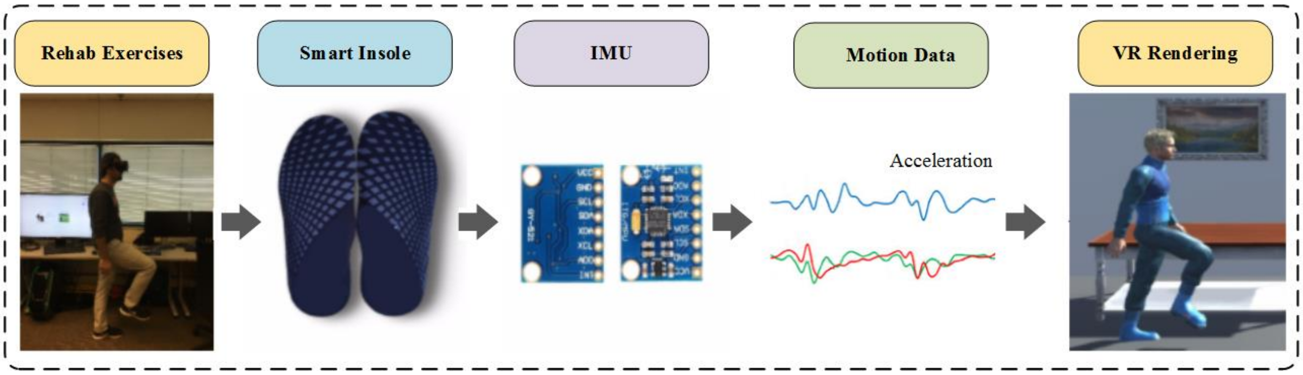

Fig. 1 The diagram of the overall system design. User wears smart insole and VR headset while performing prescribed stroke rehabilitation exercise. The motion data from IMU embedded in the Smart Insole will provide enough information for creating corresponding activities in VR Environment.

B. Rehabilitation Tasks Design

Our proposed mobility training tasks are targeting post-stroke patients who have reasonable mobility, including standing, walking and simple foot movement without assistive devices. The design of these tasks of VRInsole focuses on lower extremity exercises that can be carried out in any indoor or outdoor flat ground environment. The exercise program may be customized and retrofitted to fit the needs of patients in different rehab scenario. This can include simple functional task, aerobic task, and challenging walking [11]. Accordingly, lifting a leg while standing, kicking a soccer ball, and stepping over obstacles are adopted, respectively, to serve for each category task. Functional task like repetitive leg lifting is a proven method for improving the basic mobility as it is a primitive movement in all activities involving lower limbs. Subject lifts one of his/her foot to the desired height, and again sets it down, while taking support from a table or similar object of suitable height. Kicking a ball, serving as an instantiation of aerobic task, can improve the quality of movement by helping with foot orientation and strength in muscle movement. Subject performs kicking motion for one minute, with approximately one-second duration between successive kicks. This activity is also intended to strengthen the cardiovascular system post-stroke [12]. Stepping over obstacles is a kind of challenging walking tasks that are common in daily life requiring proper balance and posture control [10]. Subject performs walking while stepping over similarly sized obstacles.

C. Hardware Design

Smart Insole: Our team has developed an unobtrusive footwear device called Smart Insole [13, 14], as shown in Fig. 1 to capture the motion information. Smart Insole is compact and lightweight by integrating nine-axis IMU, micro control unit (MCU) and Bluetooth modules into the insole. Such compact and small form design of sensing, computing, and communication components of Smart Insole make it comfortable and unobtrusive in use. The IMU sensor, with the model BMX055 from Bosch Sensortec [15], is comprised of a 12-bit accelerometer, a 16-bit gyroscope, and a magnetometer in a single chip. The accelerometer and gyroscope are inertial sensors, which measure the movement information of the subject. The magnetometer is used as the baseline when the inertial sensors (accelerometer and gyroscope) are being calibrated. The IMU sensor communicates with the MCU using an inter-integrated circuit (I2C) bus. Accelerometer, gyroscope, and magnetometer data in X-, Y-, and Z-axes are sampled simultaneously. The MCU and Bluetooth are implemented by a single device CC2541 from Texas Instruments, which is powered by a rechargeable Li-battery placed near the heel of the insole.

D. VR Software Design

Virtual Environment Configuration: A virtual environment (VE) was built with Unity game engine on a conventional PC and Oculus Rift headset for simulating rehabilitation activities for stroke patients. Oculus headset reduces motion sickness and offers a high resolution and audio effects [16]. Unity was chosen for building the virtual environment due to the fast prototype that it offers. Unity3D is a cross-platform game engine, which is one of the top popular game development software. C# was used as our system script.

Character Model: To promote a positive psychological influence on stroke patients, a healthy young character was employed in the VR [17]. Since animations were created based on the sensor data, intuitive sense and previous approaches [18-20] were taken as the base of the creating process. Poses, and full body animations were generated from user activity. We are focusing on blending leg motions or lower body action with natural appearance and balance. Angles of knees and thighs, upper parts, especially arms and hands, are also taken into consideration for the animation to make the character more engaging.

Virtual Environment Surrounding: To make the environment interesting and immersive for patients to perform exercises, a soccer field was established to be the

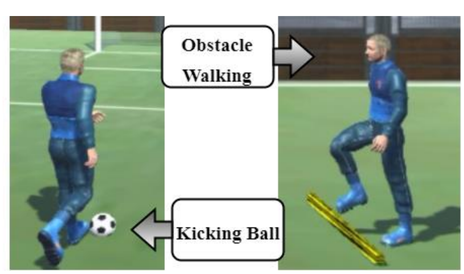

Fig. 2 Two activities rendered in VR corresponding to the lower extremity tasks, 1) kicking ball, 2) Stepping over an obstacle.

arena where kicking a ball and stepping over obstacles were conducted in addition to the indoor leg lifting scenario shown in Fig. 1. For kicking ball activity, the orientation of the kick is sensed from user activity. Lifting a leg and stepping over obstacle movements are similar, though, the stepping over obstacles requires actions on both legs and taking a stride forward while lifting a leg is conducted in a stationary position while maintaining balance during the asymmetric movements. After each activity episode, a visual effect occurs (changing light color, adding/removing an item from the room, change item's materials and showing random videos on TV) to keep the exercise pleasant besides of keeping track of the repetitions. All these activities and visual changes aimed at making the rehabilitation process less tedious and more engaging. Moreover, the environments' view could be toggled between the first person and third person views. This approach will be beneficial that patients could observe themselves in both views while performing activities. Instantiations of three mobility exercises in VR are illustrated in Fig. 1 and Fig. 2.

Stimulative Feedback: VRInsole features stimulative interaction to entertain user and provide necessary feedback on the quality of the rehab exercise for better self-management. The feedback design includes the scoring system and replay system. (1) *Scoring*: The user can get a score for each instance of activity performed based on an evaluation of activity metrics. For example, VR can show a goal on the left of the scene deviating 45° from the front to motivate a user to kick 45° towards left. The closer that real kicking direction gets to the expected direction, the more score is rewarded. This can be used as a motivating factor for the user to perform better. The score can also be tracked for the entire rehabilitation duration for keeping track of overall progress. (2) *Replay*: The VR system can provide two kinds of replay based feedback. First, an instant replay of the activity being performed by the user for instant evaluation and correction, in a third person view, as the VR system primarily runs in a first-person view for the user. Also, these can be monitored by a professional to assess and assist the user from any other location. Second, a series of replays can be stored and replayed over time to keep track of user's progress.

IV. Insole-to-VR Activities Mapping

As a feasibility study, we limited the VR animation scenarios only to the predefined three activities, though additional VR animation can be easily created according to future demands. Acceleration (for all activities) and angular velocity (only for kicking) of Smart Insoles are used for controlling the animations of the model character. Especially, acceleration decides how fast or slow these virtual simulated activities are performed by the character and angular velocity determines the direction of the kicking action.

Since the data were collected using a wearable sensor during motion, typical accelerometer and gyroscope noise is observed. To filter out this noise, a simple finite impulse response (FIR) filter was used. FIR filter is best suited for detecting signals of finite and known deflection. After applying the FIR filter, a clear indication of each activity from the acquired motion data is visible in the graph plots, as illustrated in Fig. 3 taking acceleration data for example.

1) For kicking forward, a significant deflection in the x-axis and respective change in z-axis can be seen.
2) For leg lifting, successive rise and fall in z-axis with a small change in x-axis is observed.
3) For obstacle walking, a constant rise and fall in the z-axis is observed with a corresponding change in the x-axis.

After that, three-dimensional acceleration vector from IMU sensors, shown in Fig. 3, is used in the VE. Magnitude of the acceleration or the acceleration of the dimension that is perpendicular to the ground (in this case z dimension) could be taken as the decision component to actuate the animation in VE. Z-axis acceleration is 9.8 m/s^2 when the foot is on the ground. It generates positive values when the foot has lifted, while when the foot puts down, the acceleration generates negative values. Lagging might happen due to lacking real-time data. However, the lagging time is negligible, and it serves as a real-time system. This virtual system is a game-like environment that could make the patients enjoy the virtual environment with lingering exercises.

V. Evaluation

A. Experimental Setup

To prove the feasibility and effectiveness of VRInsole, we evaluate our system regarding recognizing the kicking direction, so that VR can perform the corresponding kicking in the same direction. The reason for this evaluation is explained in "Stimulative Feedback". Six subjects including three males and three females were recruited in the experiment. The subjects' height range between 160cm and 178cm, and ages range between 22 and 29. The dataset was collected using Smart Insole, with 100 Hz sampling rate, during each activity. All subjects wearing Smart Insole

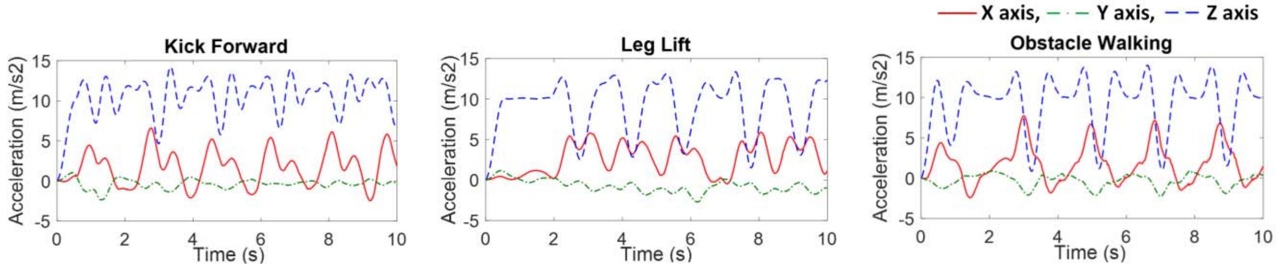

Fig. 3 Acceleration (m/s^2) for all lower extremity mobility training activities, (1) Kick forward (2) Leg lift (3) Obstacle walking.

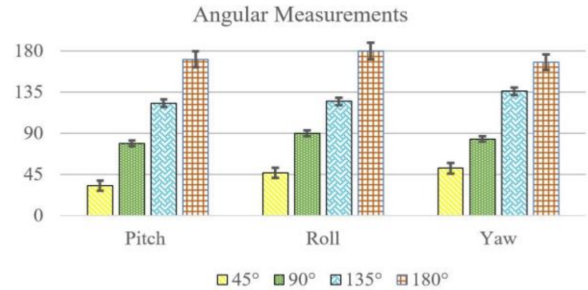

Fig. 4 Angular measurements accuracy comparison for each of the three axes (yaw, pitch and roll).

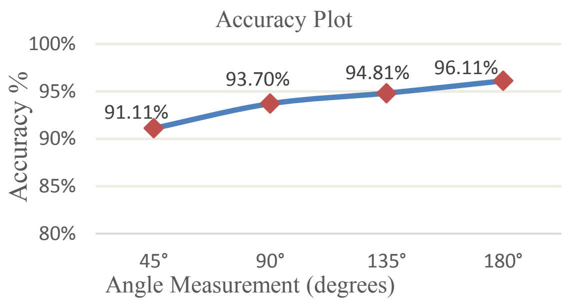

Fig. 5 Accuracy for each angular measurement.

performed an angular movement of foot, measured in real world at 45°, 90°, 135°, and 180°. Each subject performed each task under supervision, for multiple trials.

B. Qualitative Analysis

The gyroscope data collected by Smart Insole was analyzed to derive orientation by using Euler angles and quaternions. For quality assessment, we evaluate the accuracy of angular movement between the real kicking direction and the expected direction in VR environment. As evident in Fig. 4, we observe that the measurement of Pitch is always less than the expected value. Overall, the accuracies are of 92.9% for Yaw, 90.86% for Pitch, and 95.37% for Roll. For different angular measurements, the accuracy observed is 91.11% for 45°, 93.7% for 90°, 94.8% for 135°, and 96.1% for 180° as shown in Fig.5. The average accuracy reaches 93.9%. Note that the error observed decreases with the increase in angle, which is a typical behavior seen from MEMS-type IMUs [21].

VI. Future work

Long-term effectiveness and usability could be thoroughly evaluated with an extensive human subject test (healthy and stroke patients). The system can be further enhanced with application-specific research and improvements, which may include increasing the number of sensors attached on the shank and thigh measuring the flexion angle for more fine-grained motion sensing. In addition, extending the use case to the upper and whole body VR rehabilitation by incorporating sensors on wrist is quite viable. Also, VRInsole can be improved to accommodate more therapeutic activities that include physical movement assessment.

VII. Conclusion

VRInsole was developed to support, monitor, evaluate and provide motivation for home-based stroke rehabilitation. Data acquisition was done using IMU module and Bluetooth module available in Smart Insole. The acquired data was used to convert real-world movement into VR simulation. The preliminary design included three mobility-related exercise routines for lower extremity stroke rehabilitation. Our system achieves the aim to convert stroke rehab exercises into an immersive VR simulation. At present, we are can evaluate the angular measurement quality of the system, further assessment is possible.

References

[1]C. f. D. C. a. Prevention. *Centers for Disease Control and Prevention*. Available: https://www.cdc.gov/stroke/facts.htm

[2]P. S. R. Craig Anderson, *et al.*, "Home or Hospital for Stroke Rehabilitation? Results of a Randomized Controlled Trial," *American Health Association,* vol. 31, no. 5, May 2000 2000.

[3]A. Henderson, *et al.*, "Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery," *Top Stroke Rehabil,* vol. 14, no. 2, pp. 52-61, Mar-Apr 2007.

[4]S. H. Jang *et al.*, "Cortical reorganization and associated functional motor recovery after virtual reality in patients with chronic stroke: an experimenter-blind preliminary study," *Arch Phys Med Rehabil,* vol. 86, no. 11, pp. 2218-23, Nov 2005.

[5]A. Mirelman, P. *et al.*, "Effects of training with a robot-virtual reality system compared with a robot alone on the gait of individuals after stroke," *Stroke,* vol. 40, no. 1, pp. 169-74, Jan 2009.

[6]P. Pamela Duncan, *et al.*, "A Randomized, Controlled Pilot Study of a Home-Based Exercise Program for Individuals With Mild and Moderate Stroke," *American Health Association,* vol. 29, October 1998 1998.

[7]Nintendo. *Nintendo Wii U VR*. Available: https://www.nintendo.com/wiiu/what-is-wiiu

[8]M. David Jack, *et al.*, "Virtual Reality-Enhanced Stroke Rehabilitation," *IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING,* vol. 09, no. 03, September 2001 2001.

[9]A. Frisoli, *et al.*, "A force-feedback exoskeleton for upper-limb rehabilitation in virtual reality," *Applied Bionics and Biomechanics,* vol. 6, no. 2, pp. 115-126, 2009.

[10] J. J. Eng and P. F. Tang, "Gait training strategies to optimize walking ability in people with stroke: a synthesis of the evidence," *Expert Rev Neurother,* vol. 7, no. 10, pp. 1417-36, Oct 2007.

[11] B. French *et al.*, "Repetitive task training for improving functional ability after stroke," *Cochrane Database Syst Rev,* vol. 11, p. CD006073, Nov 14 2016.

[12] S. M. Linder, *et al.*, "Forced Aerobic Exercise Enhances Motor Recovery After Stroke: A Case Report," *Am J Occup Ther,* vol. 69, no. 4, pp. 6904210010p1-8, Jul-Aug 2015.

[13] F. Lin, *et al.*, "Smart Insole: a Wearable Sensor Device for Unobtrusive Gait Monitoring in Daily Life," *IEEE Transactions on Industrial Informatics,* vol. 12, no. 6, pp. 2281-2291, 2016.

[14] F. Lin, *et al.*, "Toward Unobtrusive Patient Handling Activity Recognition for Injury Reduction Among At-Risk Caregivers," *IEEE Journal of biomedical and health informatics,* vol. 21, no. 3, 2017.

[15] B. Sensortec. *Bosch Sensortec BMX 055 Data Sheet*. Available: https://www.bosch-sensortec.com/bst/products/all_products/bmx055

[16] P. R. Desai, *et al.*, "A review paper on oculus rift-a virtual reality headset," *arXiv preprint arXiv:1408.1173,* 2014.

[17] Unity. *Unity Store*. Available: https://store.unity3d.com/

[18] E. DeProft, *et al.*, "Muscle activity in the soccer kick," *Science and football,* 1988.

[19] J. Duysens, *et al.*, "Phase-dependent reversal of reflexly induced movements during human gait," *Experimental brain research,* vol. 90, no. 2, pp. 404-414, 1992.

[20] G. Shan *et al.*, "Soccer: Full- body kinematic characteristics of the maximal instep soccer kick by male soccer players and parameters related to kick quality," *Sports Biomechanics,* vol. 4, no. 1, pp. 59-72, 2005.

[21] A. G. Quinchia, *et al.*, "A comparison between different error modeling of MEMS applied to GPS/INS integrated systems," *Sensors (Basel),* vol. 13, no. 8, pp. 9549-88, Jul 24 2013.