The VRehab System: A Low-Cost Mobile Virtual Reality System for Post-Stroke Upper Limb Rehabilitation for Medically Underserved Populations

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***Abstract*—Stroke disparities are widespread in both developed and underdeveloped countries, with a disproportionate burden placed on individuals who live in rural areas, those of lower socioeconomic status, and those with inadequate or absent medical insurance. Underserved individuals are often unable to access post-stroke rehabilitation services due to their high out-of-pocket costs, difficulty with transportation, and/or the lack of stroke rehabilitation providers in their geographical area. After a stroke, patients exhibit upper limb problems, such as hemiparesis, hemiplegia, loss of sensation, pain and spasticity, and ataxia. Although it is recommended that patients undergo physical rehabilitation for limb impairments, patients with moderate to severe impairments do respond well to conventional physical therapy programs, are less likely to regain upper limb function, and consume substantial hospital and clinic resources, compared to stroke patients with mild to moderate upper limb impairments. These issues have motivated researchers to develop Virtual Reality (VR) applications that have the potential to combat the distinctive challenges that medically underserved stroke patients' face. In this project, we introduce the VRehab system: a low-cost, portable, flexible, and interactive VR system for stroke rehabilitation. VR system user expectations were examined via online survey, while walkthrough and semi-structured interviews were conducted to evaluate the usability of the VRehab system. Overall, the results of the online survey (n = 73) indicated that individuals thought that a VR system should be priced between $100-300, take no more than 10 minutes to set up, and contain sports content. Usability testing revealed that while the system was quick and easy to setup, and featured engaging game content, further refinement was required in order to enhance the usability and acceptability of the platform for users. Future directions for research are discussed including clinical trials in which the effectiveness of the VRehab system to improve upper limb motor function in medically underserved stroke patients is examined.**

Keywords—stroke rehabilitation, virtual reality, mobile application

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I. Motivation

Stroke is the second leading cause of mortality and the third leading cause of serious long-term disability worldwide [2]. Post-stroke upper limb impairments (e.g., paralysis, muscle weakness (paresis), spasticity, difficulties controlling movement, and pain) affect up to 80% of stroke survivors [3]. These impairments are accompanied by lower health-related quality of life [4] and well-being [5], high levels of anxiety [6], and a loss of independence [7]. In most cases, once the stroke patient is medically stable, upper limb impairments are addressed by comprehensive rehabilitative programs that help the patient regain physical strength and mobility [8]. Conventionally, this is achieved by having the patient engage in high-intensity, repetitive, task-specific training in a specialized rehabilitation facility.

Stroke rehabilitation is a lengthy process that requires hard work, perseverance, and patience on the part of the patient. This is especially true for the approximately 33% of stroke patients with moderate to severe upper limb impairments who often exhibit no or very limited voluntary upper limb movement [9] and are unable to complete task-oriented activities (e.g., drinking from a cup, grasping and placing objects). For an adult patient accustomed to having full control of their body, rehabilitation routines that consist of basic movements (e.g., repeatedly making a fist) quickly become tedious in their simplicity and frustrate more than they motivate. Thus, it is not surprising that patients with severe upper limb impairments do not respond well to conventional therapeutic interventions, are less likely to regain function of the arm and hand, and consume the majority of medical and social resources [10, 11].

A. Disproportionate Effect of Stroke

Stroke has a disproportionate effect on underserved populations, such as individuals of lower socioeconomic status, rural areas, and the medically underinsured. For example, it is now well known that people of low socioeconomic status (SES) suffer from a significantly elevated risk of stroke incidence and mortality as compared to higher SES groups [12]. The SES-based trend of inequality extends into the stroke recovery phase as well. In a study conducted with a sample of

11,050 patients admitted to a hospital with stroke or transient ischemic attack, those in the higher SES were more likely to be referred to stroke secondary prevention clinics compared with those in the lower SES, and that having a higher income resulted in an increased number of physician visits within the first three months of discharge [11]. Moreover, it has also been reported that income is associated with recovery six months post-stroke, with individuals from the the high income group exhibiting greater motor and functional recovery as compared with the moderate and low income groups [13].

In addition to differences in treatment by the healthcare system, underserved individuals have troubles accessing post-stroke rehabilitation services due to their high out-of-pocket costs, difficulty with transportation, and/or the lack of stroke rehabilitation providers in their geographical area [14, 15]. Thus, devising strategies to address the disparity in recovery experienced by stroke patients from underserved populations has become an important goal for health policy in local communities and globally.

II. Background

Motivated by the numerous issues related to post-stroke rehabilitation, a number of researchers have focused their efforts on developing Virtual Reality (VR) applications because of their ability to combat the distinctive challenges that patients face during stroke recovery [16]. VR applications can offer a more engaging experience for stroke patients, often taking the form of a game that guides the user through one or more therapeutic exercises [16]. This game format provides an enriched environment that results in better performance of functional tasks as compared to training in basic environments [17]. In addition, recent technological advances have made it possible to program fully immersive virtual environments, which enable the patient to perform functional upper limb activities of daily living (e.g., cutting food with a sharp knife) in a safe and ecologically valid environment. A recent Cochrane review has indicated that there are a wide range of VR system designs and implementations that have been developed or are commercially available [16]. That said, the majority of VR systems suffer from one or more limiting factors that render them generally inaccessible to the average stroke patient, such as limited variety of contexts and difficulty levels, overdependence on static environments, high costs, and limited "presence".

A. *Limited Context and Difficulty*

Post-stroke upper limb physical impairments are heterogeneous in nature, which makes creating a VR application that can be used by a broad range of patients a formidable task. One possible solution to this issue is to create VR content that includes a comprehensive range of functional upper limb activities, with each activity consisting of different difficulty levels. This is feasible when the visual content of the application involves a game environment (e.g., table tennis) rather than real life scenarios (e.g., placing an item on a shelf). The game format establishes a common theme, maintaining a sense of continuity across multiple levels that incorporate increasingly difficult exercises. While present VR rehabilitation systems based on table tennis currently exist, they do not include an extensive, built-in hierarchical system that can target as many levels of physical ability as possible. For example, Anderson et al [17] outline how the movements required to play the table tennis game available for the Xbox Kinect mimics a traditional table tennis game (i.e., extend the arm away from the body in a swinging motion) [17]. However, performance for this game requires control of only movement timing and targeted reaching, thus participants with distal upper limb impairments, discoordination, spasticity, and limited power would be able to use the system.

B. *Dependence on a Static, Supportive Environment*

In general, rehabilitation-based VR systems require two separate sets of hardware devices. The first corresponds to the generation of the VR environment itself, which can occur through the use of a head-mounted device, projection system, or flat screen monitor [16]. In general, head-mounted devices are preferred as they more closely achieve the sensation of a truly immersive environment. Unfortunately, however, these headsets usually rely on high-powered PCs as an intermediary to the second category of devices, as they alone do not possess adequate processing power [16]. The second type of devices record, evaluate, and provide feedback regarding patient performance. These devices range from generic video game consoles (e.g., Wii) [17] to sophisticated motion capture camera systems (e.g., Vicon, OptiTrack). In most currently recognized systems, at least one hardware component (and thus the entire system) is tethered to a single location and can be exceptionally difficult to install and customize to a specific user's needs. Thus, the majority of VR rehabilitation systems are confined to a hospital or clinic and are only accessible to the patient during appointments [16]. In addition, to use the system correctly stroke patients must rely on the guidance and oversight of trained staff. These issues influence the uptake and continued use of a VR system for post-stroke upper limb rehabilitation, as a tool that is not readily available or easy to use is unlikely to have a legitimate impact on the patient's overall recovery.

C. *Financial Costs*

While there are several commercially available VR options, the overall acquisition cost poses a substantial obstacle to stroke patients in medically underserved areas. For example, commercially available motion capture systems range between $14,000USD (IREX VR rehabilitation system, Gesturetek Health, Canada) [18] and $19,000USD (VR Prime 13 system, OptiTrack, USA) [19]. The price tag associated with commercially available VR systems has lead researchers and enthusiasts to construct VR systems using commercially available hardware components. While custom-built VR solutions reduce the costs substantially, they still require purchasing a PC-compatible VR headset (~$300), a high-power PC capable of running the VR program (~$1000), and a motion input device to record and evaluate the user's movements (~$100-$500USD). Thus, even when selecting hardware in the most economical manner possible, the custom-built system will still cost approximately $1500-$2000USD. The hardware acquisition costs for a commercially available and custom-built VR solution may be affordable for a hospital or clinic, as they can recuperate these costs by billing the patient and/or their insurance. However, these systems are still quite expensive for clinics in medically underserved areas, and low SES stroke patients with financial restrictions (due to medical bills and reduced employment) [20]. For many, the advantages of owning a VR system does not outweigh the acquisition costs, and as such, engineering teams must consider how much users would be willing to pay for a system before developing a VR system for stroke patients in medically underserved areas.

D. Presence

In the field of VR, the term "presence" refers to the phenomenon of enabling people to interact with and feel connected to a world outside their physical bodies via technology – the subjective sensation of being truly present in the virtual environment [21]. The goal of any VR application is to maximize presence and simulate an environment that feels as real as possible. In order to do so, the virtual environment should stimulate as many of the physical senses as possible in a cohesive manner. In general, visual and auditory feedback are extensively used by VR applications. In contrast, haptic and olfactory feedback remain far less commonly available [22], despite the evidence that haptic feedback leads to better user performance for tasks completed within a virtual environment [23]. Results from a recent single case study in which a PHANToM haptic device (3D Systems, USA) and Crystal Eyes CE-2 (Stereographics, USA) was integrated into the VR system, showed improved upper limb motor control and the ability to perform daily activities in a patient with left side hemiparesis and weak lateral grasp who could not perform many activities of daily living with the affected arm [24]. This project seeks to capitalize on the beneficial aspects of haptic feedback by using it to reinforce existing visual cues that indicate whether the user is successfully completing their exercises.

III. Project Goal

The goal of this project was to develop a low-cost, portable, flexible, and interactive VR system (hereafter referred to as the VRehab system) and evaluate its usability for medically underserved stroke patients who exhibit upper limb motor dysfunction.

IV. The VRehab System

A. System Architecture

In order to create an application that responds to the user based on the completion of a physical movement, an intuitive motion control interface (MCI) was developed and incorporated into the VRehab system. The MCI collects electromyographic (EMG) and motion data from the user using a commercially available input device (Myo armband, thalmic Labs, Canada). The Myo armband features a set of eight surface EMG sensors that record the electrical activity of skeletal muscle tissue (200Hz sampling rate) from the forearm muscles, and motion data from a 9-axis inertial measurement unit (IMU, 50Hz sampling rate) to the linear and angular motion of the upper limb. The MCI processes and analyzes EMG and IMU data to recognize the movement performed by the user. This information is then sent to the VRehab application to control the VR rehabilitation game. In addition, the VRehab application can send control signal to the MCI to induce haptic feedback that is experienced by the user as a vibration in the armband. A short vibration indicates a successful repetition, a long vibration indicates that the user must try again.

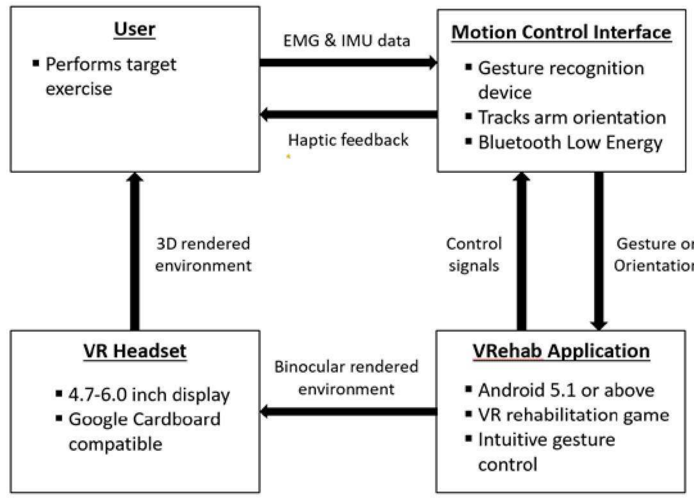

Fig. 1. VRehab System Architecture

As depicted in Fig. 1, the VRehab system consists of four independent components: the user, the MCI, the VRehab application, and the VR headset. The user is responsible for executing a particular therapeutic exercise, and the EMG and IMU data generated by the user's upper limb movement passes to the MCI which operates on the data and sends its prediction to the VRehab application. VRehab, running on a mobile device, responds to the data it receives by manipulating the virtual environment and inducing specific types of haptic feedback based on the successful or unsuccessful completion of the target exercise. The virtual environment is rendered in binocular mode on the mobile device, which in turn is experienced as a 3D environment by the user via the VR headset.

B. Hardware Platforms

The MCI required by the VRehab system was implemented via the Thalmic Labs Myo armband (Fig. 2), which can be worn on either forearm. The Myo armband is available commercially for less than $200 and is accompanied by proprietary software that allows developers to create applications that respond to five hand gestures. Commercially available and custom-built applications (including VRehab) communicate with the Myo armband by means of Bluetooth Low Energy (BLE) and can send control signals to induce a vibration in the armband or change its settings. Although the VRehab system currently relies on the software provided by Thalmic Labs, software development kits are available to create unique Myo-compatible software tailored to a specific application. This allows developers to expand the usability of the Myo armband, as an application can be developed to detect more than just the standard set of gestures [25].

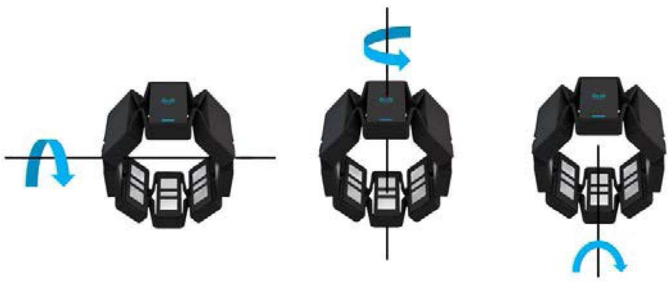

Fig. 2. The x (left), y (middle), and z axes (right) of the Myo armband (Thalamic Labs, USA).

The VRehab system will work with any google Cardboard compatible VR headset (e.g., Merge VR, Mattel View-Master), however for the current implementation we utilize an ETVR 3D VR headset (11.6 ounces, 83-85° field of view; ETVR, China) because of its accessibility and affordability (~$35 on Amazon.com) and its ability to accommodate iOS and Android smartphones with screen sizes between 4.7 and 6.2 inches. Prior lab tests utilized the Motorola Moto G5 Plus smartphone featuring the Qualcomm Snapdragon 625 processor, 64GB memory, and the Android 7.0 operating system for testing and evaluation.

C. Software Development

VRehab is compatible with any smartphone that runs Android 5.1 or above. The VR component of the application was developed using Unity 3D (Unity Technologies, USA) and the Google Cardboard software development kit (Google LLC, USA). VRehab includes two proprietary Unity assets that were acquired in order to expedite development time*: Hands VR* by Tschirgi Games and *Table Tennis* by David Villa. VRehab's BLE functionality was developed using Android Studio (Google LLC, USA) and Thalmic Labs' Myo Android SDK.

D. Application Content

The VRehab system was designed to be used by individuals with upper limb impairments, and require little setup time. To use the system, users open the VRehab application and connect to their Myo armband. Once a connection is established, the user then selects the level, as well as the number of trials they wish to complete, from the VRehab home screen. Once these selections are made, the user places the smartphone inside the VR headset and the rehabilitation session begins.

At present, there are three levels in the VRehab application, each of which targets a specific upper limb joint and motion. The target exercise of the first level involves creating and holding a fist for a period of three seconds (Fig. 3). From a biomechanical and anatomical perspective, that requires a sustained contraction of the forearm (i.e., flexor pollicis longus, flexor digitorum superficialis, flexor digitorum profundis, and brachioradialis), extrinsic finger (i.e., flexor digitorum superficialis, and flexor digitorum profundis), and thumb muscles (i.e., adductor pollicis, flexor pollicis brevis, and opponens pollicis). When the application detects a fist gesture, the virtual hand picks up and squeezes a table tennis ball. If the user contracts the requisite muscles for the entire three second period, the user will be provided with both visual (the virtual hand will release the ball) and haptic feedback (a short vibration pulse) indicating that the trial was performed successfully. The system will then begin the next trial and the number of completed repetitions will be incremented by one. However, if the user is unable to maintain muscular contraction for three seconds, the virtual hand will release the ball and the user will feel a longer vibration pulse. A new trial will begin, allowing the user to continue to work towards reaching their goal number of trials for that particular session. The level 1 exercise is completely controlled by Myo armband EMG, which is processed by the Myo armband software and results in a plain text prediction of the type of gesture being created. This information is then passed via BLE to the smartphone application.

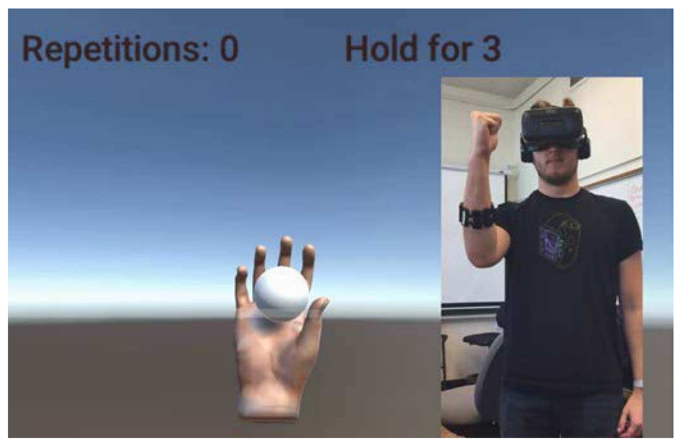

Fig. 3. Virtual environment and corresponding physical movement required (inset) to successfully complete Level 1 Target Exercise trial.

The target exercise of the second level involves a table tennis game in which the user controls a virtual table tennis paddle to hit a table tennis ball served toward them. From a biomechanical and anatomical perspective, this action requires shoulder external rotation (i.e., infraspinatus, posterior head of the deltoid, and teres minor) to hit the oncoming ball and shoulder internal rotation (i.e., subscapularis, sternal head of the pectoralis major, latissimus dorsi, and teres major) to bring the arm back to the start position (Fig. 4). At the start of each trial, the application prompts the user to position their arm with the forearm parallel to the chest and an approximate 90° elbow flexion. The system gives the user three seconds to maintain the starting position during which the application records the IMU data produced by this position. Once the system has registered this initial orientation of the arm, the virtual environment responds by serving a ball across the table towards the user. The user is required to perform >90°

external rotation of the shoulder, which will result in the virtual table tennis paddle hitting the ball back across the table. If the trial is performed successfully, the user will feel a short vibration pulse, and the system will increment the number of successful trials by one. The next trial will begin once the user brings their arm back to the starting position.

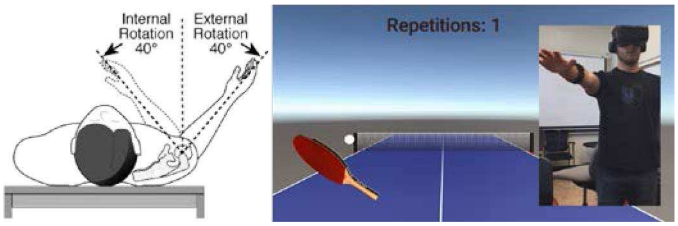

Fig. 4. Virtual environment and corresponding physical movement (i.e., 40° shoulder internal and external rotation) required to successfully complete Level 2 Target Exercise trial. Image on left retrieved from [26]

The smartphone application evaluates the user's movements by constantly polling the Myo armband for IMU data and comparing it to the prerecorded starting position and the desired change in orientation. The actual data passed to the VRehab application consists of a quaternion which itself is constructed from the accelerometer and magnetometer data from the IMU. Thus, the VRehab application simply receives three values that represent right-handed rotations in radians about each of the x, y, and z axes of the Myo armband (Fig. 2). Because the second level of the application captures the y-axis rotational data at both the starting position and throughout the movement, the determination of a successful trial can be calculated by evaluating the change in angle from an arbitrary starting position to a dynamic end position (currently set to 90°, but can be adjusted to any value). In addition, because the application compares the current rotational data to the previously recorded starting position, it was possible to enforce a rule stating that a new trial will not begin until the arm is placed back in the starting position.

The target exercise of the third level involves bouncing a ball on the table tennis paddle, and requires elbow flexion (i.e., biceps brachii, brachialis, and brachioradialis) and extension (i.e., triceps brachii). As in level 2, each trial begins when the user has placed their arm in the starting position. Once the system has recorded the initial orientation of the arm, the virtual environment responds by dropping a ball down towards the virtual paddle. The user is required to perform >180° elbow flexion, which will result in the paddle contacting the ball and sending it upward in the virtual environment. If the trial is performed successfully, the user will feel a short vibration pulse, and the number of successful trials will increment by one. User performance is evaluated in a similar manner as the second level. In this case, the application monitors the rotation of the armband around its x-axis. From the starting position, the application waits for an angular change of >180° before recording a completed trial and the application will not allow the user to start another trial until it detects that the arm has returned to the initial starting position.

For each level, the user is provided with visual information regarding intended to inform and guide them through the exercises. All levels display the total number of successful trials that have been completed so far. The first level includes written cues telling the user how much longer they must hold the exercise in order to complete a successful trial. The second and third levels begin with written cues instructing the user to place their arm in the starting position for a specific amount of time. When these instructions disappear from the screen, the session starts with the movement of the virtual ball. In all levels, the exercises can be performed while seated, standing on a solid surface, or on a compliant surface. The latter two conditions would increase the complexity of the task, as the user would need to exert control over the supraspinal balance mechanisms while performing the upper limb task. In addition, the user may introduce a stress ball to level 1 or a hand weight to levels 2 and 3 to integrate upper limb muscular strength and endurance to their rehabilitation program.

In summary, the virtual environments created by the VRehab application are intended to be as intuitive and realistic as possible, opting to mimic outdoor spaces with natural horizon lines and lighting as compared to static backgrounds of a single color. The application tracks head movement, allowing the user to explore their environment by simply looking around, just as they would in real life. While auditory feedback is not currently implemented, future incorporation of ambient and responsive noises (e.g., the ball hitting the paddle or the table) would be simple and straightforward

V. Usability Experiments

A. *User Expectations*

A central aspect that engineers need to consider when designing a product is the requirements of the product from the perspective of the end-users. Given the numerous barriers that exist for medically underserved stroke patients, we conducted an online survey (Qualtrics) to ascertain people's expectations for a VR system for upper limb physical rehabilitation that would not be reimbursed by private insurance or Medi-cal/Medicare (i.e., the user would have to pay for the VR system out-of-pocket). The survey queried people's expectations on the price of the VR system, acceptable setup time, content of the rehabilitation games, as well as people's familiarity with VR, familiarity with VR for rehabilitation, and their age.

73 individuals responded to the survey. Participant age (18-24 years = 17.8%, 25-34 years = 46.6%, 35-44 years = 20.5%, 45-54 years = 2.7%, 55-64 years = 6.9%, 65-74 years = 5.5%) and familiarity with virtual reality (extremely familiar = 6.9%, very familiar = 9.6%, moderately familiar = 38.4%, slightly familiar = 28.8%, not familiar at all = 16.4%) spanned a broad spectrum. In contrast, participants familiarity with virtual reality for rehabilitation purposes (extremely familiar = 4.1%, very familiar = 1.4%, moderately familiar = 16.4%, slightly familiar = 21.9%, not familiar at all = 56.2%).

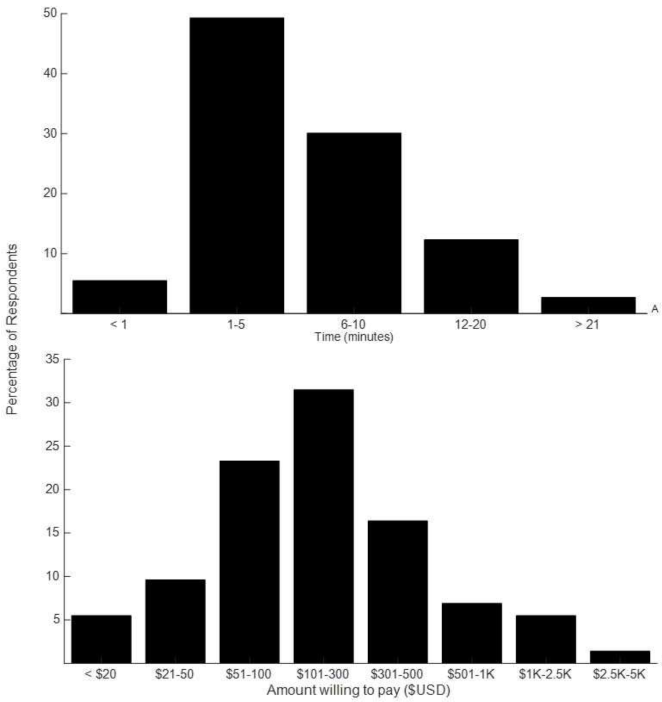

Fig. 5. Responses of online survey for acceptable system setup time for a 30-45 minute rehabilitation session (left) and the amount people would be willing to pay for a home-based virtual reality rehabilitation system (right).

As can be seen in Fig. 5A, the majority of respondents stated that 1-5 minutes (49.3%) and 6-10 minutes (30.1%) would be an acceptable amount of time to set up the system before a 30-45 minute rehabilitation session. With respect to the amount people would be willing to pay for a VR rehabilitation system that would allow them to continue rehabilitation in the home environment (Fig. 5B), 31.5% responded that they would be willing to pay $101-300, 23.3% would be willing to pay $51-100, and 16.4% would be willing to pay $301-500 for a VR stroke rehabilitation system. Regarding VR content, 46.6% of respondents stated that sports games would be the most motivating, whereas activities of daily living were ranked as least motivating content (50.7%). Fictional games and hobbies were equally distributed across motivation levels.

B. *System Usability*

Six individuals familiar with post-stroke upper limb impairments (who also participated in the online survey) were interviewed in order to elicit feedback on the usability of the VRehab system for home-based rehabilitation. During each session, participants were first provided with an overview of the VRehab system and then allowed to interact with the system and play all three target exercise levels. After the experimenter answered any questions that arose, the participant was asked to provide feedback regarding the system design and usability. During this phase, participants were encouraged to discuss problems that they encountered and possible changes that could be implemented, as well as their impressions on the usefulness of the system for stroke rehabilitation. Subsequently, individuals were presented with three different commercially available VR headsets (ETVR 3D VR, Oculus Rift, Merge VR/AR Goggles) and asked to rank them in terms of their suitability with VR for stroke rehabilitation, and note whether any of the headsets were not appropriate for this context. To determine which VR headset was most suited for stroke rehabilitation in medically underserved communities, we assigned numerical values to each response (1st choice = 3 points, 2nd choice = 2 points, 3rd choice = 1 point), with higher total points reflecting a greater headset preference across participants.

TABLE I. COMPARISON BETWEEN THREE VR HEADSETS

VR Headsets	ETVR 3D VR	MERGE VR/AR	Oculus Rift
Price	$19.99	$19.99	$399
Weight	0.92 lb	0.75 lb	1.04 lb
Material	Plastic case with soft rubber pads inside	Soft foam	Plastic case with soft rubber pads inside
External components required	4.7"-6.2" Smartphone	4.7"-6.2" Smartphone	High-end PC

Usability testing indicated that all participants were able to successfully and independently use the VRehab system. Participants also expressed satisfaction with the setup process for the VR system application, and were able to connect the device and place the headset in the correct position in less than 60 seconds (mean = 40.5, SD = 13.1). After a single tutorial, none of the subjects felt the need to ask follow-up questions for the rest of the session about how to navigate through the application. All subjects stated that they would enjoy using the system as part of a rehabilitative program, either at home or in a clinic setting, and that its inclusion would be preferred over executing the same exercise routine without the VRehab system. In addition, all individuals remarked that they felt comfortable with the game content presented to them, that the content of each level was comfortable and engaging, without being intimidating.

That said, some aspects of the VR system were found to be problematic for users. Participants expressed frustration about the control of Level 1 (creating and holding a fist), which required the head (and not the hand) to move the virtual hand (i.e., the virtual hand is determined by head movement, rather than arm movement). Fortunately this usability issue can be easily modified by adjusting the software algorithms to allow the hand to mirror the movement of the arm rather than the head. Because this issue was not present in Level 2 and 3, they were rated more positively by users than Level 1. That said, participants stated that levels requiring a prescribed range of motion (i.e., Level 2 and 3) would benefit from additional visual feedback to indicate how close the user is to reaching the prescribed range of movement. For example, a visual scale

TABLE II. COMPARISON BETWEEN EXISTING PLATFORMS AND THE VREHAB SYSTEM

Feature	***VRehab System***	***Existing Platforms***
Required Hardware	Myo armband, Android smartphone, Google Cardboard compatible headset	High-power PC, expensive headset; Nintendo Wii; motion capture cameras
Portability	Fully mobile – can be used anywhere	Tethered to a single location: clinic, house, etc.
Target Audience	Patients with varying stroke severities	Specific subset of stroke patients
Supervision Requirements	No supervision required	Supervision required
Estimated Cost	VR system: $35 (excl. smartphone) VR & motion input: $235	VR system: >$1300 (PC & headset) VR & motion input: >$2000

showing what percentage of the full range of motion has been achieved can be incorporated into the existing user interface. This would provide the user with a more detailed and complete view of their performance, allowing them to adjust their movements more efficiently in order to reach a successful trial.

While the VRehab system currently have simple instructions for each level, participants suggested that more in-depth instructions should be provided. Specifically, users felt that the system should provide them with the goals of the level (i.e., more direct instructions that describe the starting position and at what time they must place their arm in this position before each level). In addition, the current system requires that the smartphone be removed from the headset to switch levels. Users commented on the relative inconvenience of this design feature, noting that it would be particularly frustrating for stoke patients who have limited use of a single limb. The usability issue can be resolved by using having mildly impaired stroke patients use the Myo armband gesture controls (i.e., tapping fingers together, waving your hand right or left, and opening and closing your fist) to toggle between the home screen and the individual activity levels, or using audio and/or button-based controls for stroke patients with distal impairments and will not be able to use the gesture controls. In the current iteration of the VRehab system, the user is immediately directed back to the home screen (2D GUI) after completing the required number of trials for a given level (3D). Participants found the combination of a 2D menu GUI and 3D activity level GUIs particularly jarring, and suggested that all game content be rendered in 3D, as these is believed to create a more immersive environment.

When asked to compare the three VR headsets, participants felt that the ETVR 3D VR headset was most appropriate for this context (14 total points), but also reported that the headphones could be easily broken, that the mechanism for inserting a smartphone into the device was not durable, and may be too heavy for a stroke patient. The Merge VR/AR Goggles were the easiest to put on, and the soft foam structure gave the headset a low profile, but hurt the cheek bones of one participant (11 total points). Four participants rated the Oculus Rift their third choice (9 points), with two participants stating that it would not be an appropriate headset for medically underserved stroke patients because of the tethered nature of the headset, its weight (1.1 lbs., 0.84 lbs. for the ETVR 3D VR, 0.75 for the Merge VR/AR), and frustration when adjusting the head strap. Thus, the current VRehab system headset (ETVR 3D VR) was found to the most suitable for the current context, followed by the Merge VR/AR Goggles, and the Oculus Rift.

VI. DISCUSSION

In this paper, we described the VRehab system, and evaluated user expectations, and the usability of the current system. Results of the user expectation survey indicated that a VR system for home-based stroke rehabilitation should not take longer than 5 minutes to set up, and cost more than $300USD. The present instantiation of the VRehab system is $235USD (excluding Android smartphone), but could be significantly reduced by using input sensors that are more economical than the Myo armband. Future work will investigate whether commercially available input sensors (e.g., the Leap Motion universal VR development bundle, available for $89.99 [Leap Motion, USA]) or custom-built low-cost intelligent wearable sensors (e.g., the outREACH embedded sensor developed by our labs [i.e., the Intelligent Computing & Embedded Systems Laboratory and the Health Equity Institute NeuroTech Lab) are more appropriate for integration into the VRehab system.

Moreover, there are currently only three levels in the VRehab application, which is insufficient for use in a stroke rehabilitation program. In consideration of the results indicating that sports-related VR content would be most motivating (and that activities of daily living content is the least motivating), future work will focus on building a larger repository of 3D contexts and levels that feature different sports, hobbies, and fictional game content. Last, after technical development of the system, we plan to test the utility and effectiveness of the system to improve upper limb function in stroke patients from medically underserved areas. Given the barriers to quality stroke rehabilitation services that these individuals face, it is likely that this population would greatly benefit from the development of a low-cost VR system that would allow them to continue their rehabilitation program in the home environment.

In this paper, we introduced a low-cost, portable, flexible, and interactive VR system for medically underserved stroke patients who exhibit upper limb motor dysfunction, and reported on the results of a usability study. While the VRehab was considered usable, there were a number of key improvements required in order to enhance the usability of the system. Future research will incorporate the feedback of end-user in system refinement in order to ensure uptake of the VRehab system by medically underserved populations.

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