RehabPhone: A Software-Defined Tool using 3D Printing and Smartphones for Personalized Home-based Rehabilitation

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ABSTRACT

Approximately 7 million survivors of stroke reside in the United States. Over half of these individuals will have residual deficits, making stroke one of the leading causes of disability. Long-term rehabilitation opportunities are critical for millions of individuals with chronic upper limb motor deficits due to stroke. Traditional in-home rehabilitation is reported to be dull, boring, and un-engaging. Moreover, existing rehabilitation technologies are not user-friendly and cannot be adaptable to different and ever-changing demands from individual stroke survivors. In this work, we present *RehabPhone*, a highly-usable software-defined stroke rehabilitation paradigm using the smartphone and 3D printing technologies. This software-definition has twofold. First, *RehabPhone* leverages the cost-effective 3D printing technology to augment ordinal smartphones into customized rehabilitation tools. The size, weight, and shape of rehabilitation tools are software-defined according to individual rehabilitation needs and goals. Second, *RehabPhone* integrates 13 functional rehabilitation activities co-designed with stroke professionals into a smartphone APP. The software utilizes built-in smartphone sensors to analyzes rehabilitation activities and provides real-time feedback to coach and engage stroke users. We perform the in-lab usability optimization with the *RehabPhone* prototype with involving 16 healthy adults and 4 stroke survivors. After that, we conduct a 6-week unattended intervention study in 12 homes of stroke residence. In the course of the clinical study, over 32,000 samples of physical rehabilitation activities are collected and evaluated. Results indicate that stroke users with *RehabPhone* demonstrate a high adherence and clinical efficacy in a self-managed home-based rehabilitation course. To the best of our knowledge, this is the first exploratory clinical study using mobile health technologies in real-world stroke rehabilitation.

CCS CONCEPTS

• **Human-centered computing** → *Ubiquitous and mobile computing*.

KEYWORDS

Mobile Health; Stroke Rehabilitation; Smartphone; 3D Printing.

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1 INTRODUCTION

Stroke is the fifth largest cause of death and a leading cause of long-term motor disability in the United States [1]. A direct effect of stroke involves either the right or left sides of the body being paralyzed - a mobility disorder called hemiplegia [2]. After stroke occurs, stroke survivors are recommended rehabilitation therapies with a stroke professional or are prescribed written exercises to be practiced at home [3]. The main effect of rehabilitation is to restore oxygen supply to the brain with the hopes that functional motor ability can be regained [4]. Thus, finding ways to augment functional mobility is important.

Nowadays, the general approach for home rehabilitation includes exercises using an elastic tubing band which has been clinically proven to augment functional mobility and reduce disability [5, 6]. However, the degree of motor disability limits the use of these bands [7]. A severely affected stroke patient, for example, may not even be able to adapt to the resistance offered by the band. Moreover, statistics show that exercises that mimic activities of daily living are more meaningful and produce significantly good outcomes, while elastic band exercises are boring cannot achieve the same effective outcomes [8].

In recent decades, technology including but not limited to the smartphone, augmented reality, and virtual reality has aided in providing rehabilitation solutions capable of mimicking activities of daily living over two decades [9]. However, two fundamental limitations pertain to existing technology-based in-home stroke rehabilitation solutions.

The first challenge is scalability. As an in-home rehabilitation tool, we expect it to be low-cost and accessible for most stroke survivors. Meanwhile, we expect it to address multiple levels of stroke prognosis. However, the fish and the bear's paw, you cannot have both at the same time (idiom, from Mencius). Most solutions are expensive or possess a high learning curve [10, 11], and universal deployability of tech-based rehabilitation solutions remains

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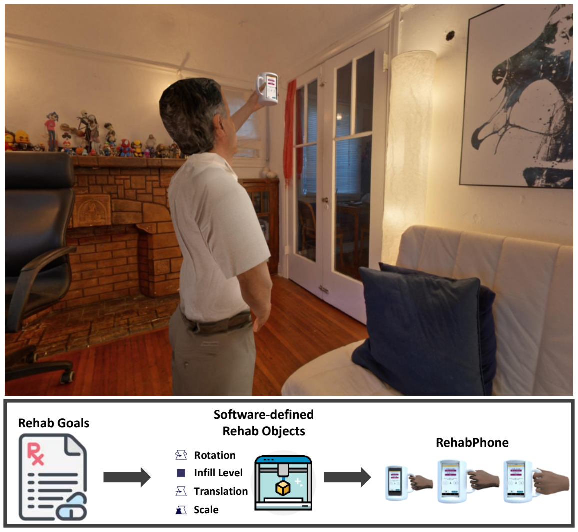


Figure 1: Top Figure: An example of *RehabPhone* in use. The rehabilitation object is structurally coupled with the user's smartphone. It allows to mimic daily-life activity and measure efficacy. Bottom Figure: *RehabPhone* can customize rehabilitation objects according to rehabilitation goals, hand size, smartphone size, and etc.

an open challenge [12]. In a six-year-long large regional study, Levine *et al.* [13] points out that stroke is associated with an acute decline in cognition and new learning. Instead of considering universal deployments, addressing multiple levels of stroke prognosis and different levels of cognitive ability are considered as the primary considerations [14]. On the country, a large-scale deployment would not adapt to different levels of stroke prognosis [15].

The second challenge is the usability. Stroke survivors will have disabilities in varying degrees, and they expect an in-home rehabilitation object that is easy to use. More specifically, they expect to acquire real-time feedback while performing a rehabilitation exercise. On the one hand, a system without proper feedback generates low user adherence. Stroke survivors progressively lose their interests and cannot meet their rehabilitation goals as compared to a check-in session in a clinical facility [16]. On the other hand, a patient can perform nonstandard exercises without feedback. Such nonstandard movement can further lead to unexpected damage.

However, our survey of the literature indicates that no technology-based solution addresses both ends of the spectrum together. Therefore, we ask a question: *"is it possible to have a scalable and usable solution to enable in-home stroke rehabilitation by leveraging ubiquitous technologies, such as smartphones and 3D Printing?"*

We know that stroke survivors are expected to mimic daily-life activities, such as opening the door, inputting the password and pouring the water, in order to help their brains to regain the skills. These built-in sensors (*e.g.,* touch screen, accelerometer, and gyroscope) and CPU in the smartphone provides the ability of real-time computation to recognize these activities and calculate specific metrics, such as smoothness and duration, to quantify the rehabilitation efficacy. Further, the smartphone enables human-computer interaction. The built-in speaker allows stroke survivors to perform rehabilitation exercises with acoustic guidelines, and GUI provides feedback. This objective feedback serves to inform the participant of their progress better and actively engage them in their rehabilitation, thus encouraging self-management of rehabilitation. To address the existence of multiple levels of stroke prognosis, we leverage 3D Printing technology to help produce rehabilitation objects according to various rehabilitation goals. As far as one rehabilitation object is concerned, 3D Printing technology can customize the products with different weights and sizes that adapt to stroke survivors with customized demand.

To this end, we design and implement *RehabPhone*, a smartphone-based software-defined stroke rehabilitation application, to enable in-home stroke rehabilitation (as shown in Figure 1). *RehabPhone* maps the given rehabilitation goal to pre-defined G-code, a language for 3D Printing. This G-code can produce requested rehabilitation objects via commercial 3D printers. The smartphone combines printed rehabilitation objects in a way that allows the stroke survivors to mimic daily-life activities, meanwhile measuring their behaviors. When a patient is performing rehabilitation exercise, *RehabPhone* captures and calculates four metrics, smoothness, accuracy, duration, and repetitions, in real-time. In meanwhile, voice guidance instructs the stroke survivors what to do in the next step. After each exercise session finishes, *RehabPhone* provides feedback via GUI. Moreover, at the end of each day, all raw data is uploaded to the AWS cloud, which allows clinician professionals to monitor and instruct the rehabilitation exercise in the next session remotely.

Through our continued efforts in application design and collaboration with stroke professionals, *RehabPhone* has included 13 different rehabilitation exercises. For each type of exercise, we design and implement the corresponding G-code files for rehabilitation objects and algorithms for activity recognition. We highlight that the *RehabPhone* is extendable. Different from traditional manufacturing pipelines, it allows a stroke professional to collaborate with a computer science researcher to quickly design and implement a rehabilitation exercise for a stroke survivor with a customized goal.

We highlight that we have evaluated *RehabPhone* on 32 real people. First, an in-lab validation study is conducted to establish the reliability of the metrics captured by the smartphone system. 12 young adults showing no signs of motor impairments are asked to perform repetitive exercises across 3 sessions in one week. The coefficient of variation for almost all exercises is validated to be around 10% coefficient of variation. Later, 4 healthy older adults and 4 stroke survivors are asked to provide possible usability refinement suggestions. The system is then distributed to 12 stroke survivors to access its' effectiveness in rehabilitating multiple levels of stroke prognosis. During the intervention, participants show self-motivated adherence to the *RehabPhone* without external coaching. For most of all 12 participants, the clinical Wolf Motor Function Test [17] results reveal significant improvements as compared to their baselines set in the first week.

The insights gained from this study indicate that a smartphone-based software-defined solution is possible for in-home stroke rehabilitation. The contributions of this work are three-fold:

- To the best of our knowledge, we perform the first study to investigate the 3D Printing technology coupling with the smartphone that can achieve in-home stroke rehabilitation.

3D Printing technology addresses multiple levels of stroke prognosis, and the smartphone serves as the sensors and computing unit.

- We design and implement *RehabPhone*, a software-defined 3D printing augmented stroke rehabilitation system. We have included 13 rehabilitation exercises in our application. For each exercise, we implement the G-code for stroke objects and algorithms for activity recognition. *RehabPhone* is scalable. A stroke professional can work with a computer science/engineering researcher to quickly define a new rehabilitation exercise.
- We evaluate *RehabPhone* on 32 real people, including 16 healthy people and 16 stroke survivors. Positive feedback from stroke survivors suggests that this software-defined solution shows the feasibility of deploying large-scale in-home stroke rehabilitation exercises in the future.

2 BACKGROUND AND PRELIMINARY

Stroke Rationale and Symptoms: To understand stroke, it helps to understand the brain. The brain controls our movements, stores our memories, and is the source of our thoughts, emotions, and language. The brain also controls many functions of the body, like breathing and digestion. To work properly, your brain needs oxygen. Although the brain makes up only 2% of the body weight, it uses 20% of the oxygen when breath. The arteries deliver oxygen-rich blood to all parts of the brain.

If something happens to block the flow of blood, brain cells start to die within minutes because they cannot get oxygen. This causes a stroke. There are two types of stroke (as shown in Figure 2), and both types of stroke damage brain cells.

Stroke is now the fifth largest cause of death and a leading cause of long-term motor disability in the United States [1]. As the baby boomer generation ages, 700,000 individuals are added to the stroke cohort each year [18]. A direct effect of stroke involves either the right or left sides of the body being paralyzed - a mobility disorder called hemiplegia [2].

Objective of Stroke Rehabilitation: After stroke occurs, individuals are recommended rehabilitation therapies with a stroke professional or are prescribed written exercises to be practiced at home [3]. The main effect of rehabilitation is to restore oxygen supply to the brain with the hopes that functional motor ability can be regained [4]. When rehabilitation is performed in the home context, it is shown to produce more *goal-orientedness* in individuals as compared to a check-in session in a facility [16]. The general approach for home rehabilitation includes exercises using an elastic tubing band, which has been clinically proven to reduce disability [5, 6]. However, the degree of motor disability limits the use of these bands [7]. A severely affected stroke individual, for example, may not even be able to adapt to the resistance offered by the band. Instead, exercises that mimic activities of daily living are more meaningful and produce statistically significant better outcomes as compared to elastic band exercises [8].

A Survey Study on Technology Use in Home Rehabilitation Programs : While evaluating rehabilitation experience, stroke survivors report that boredom and a desire for a more excellent fostering of autonomy. Technology has the potential to reduce these shortcomings by engaging survivors through entertainment and objective feedback. The research found that this objective feedback will result in improved outcomes and may assist the patient in learning how to self-manage rehabilitation.

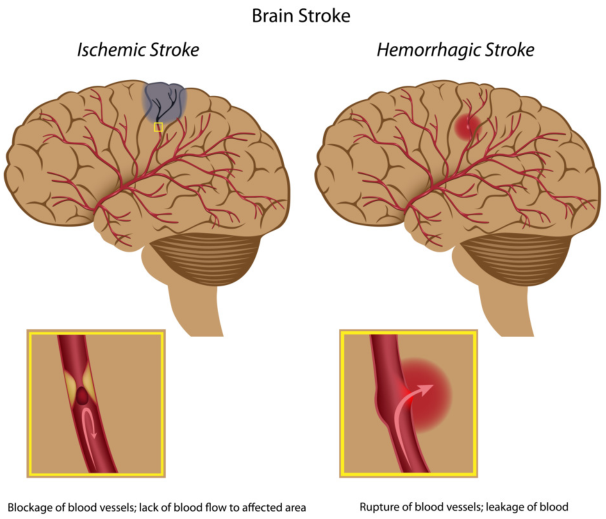


Figure 2: An introduction of two strokes. Ischemic stroke when the blood supply to the brain is blocked; hemorrhagic stroke when a blood vessel in the brain bursts. Both types of strokes require rehabilitation.

Our previous surveys [19] on physical and occupational therapists show that technology-based home rehabilitation is not widely used but urgently needed. Surveys are sent via mail, email, and online postings to over 500 therapists, and we get 107 responses. Results show that conventional types of equipment, such as stopwatches, are more frequently used compared to newer technology. However, less than 25% of therapists report using a stopwatch five or more times per week. Feedback to survivors is based upon objective data less than 50% of the time by most therapists. Therapists consider using technology, providing objective feedback in stroke rehabilitation to meet the needs of the stroke survivors better; however, a technology-based home rehabilitation is not there.

3 DESIGN CONSIDERATIONS

In this section, we identify key goals of *RehabPhone*. We first describe the goals from a perspective of the mobile health system. We then discuss goals that should be considered in every customized rehabilitation exercise.

3.1 RehabPhone Design Goals

Scalability: Since stroke can affect each person differently, stroke survivors will need diverse rehabilitation objects. Thus, an in-home rehabilitation application should be able to scale to different types of stroke according to clinical diagnosis. Moreover, for a stroke survivor in the different rehabilitation stages, the proposed in-home rehabilitation application should be able to adjust the rehabilitation program based on the instrument from occupational therapists.

Usability: Stroke survivors will have disabilities in varying degrees. Thus, we will expect an in-home rehabilitation application that is easy to use. More specifically, *RehabPhone* should give proper instruments in a rehabilitation program to allow survivors to be relatively independent. This goal is to ensure that a stroke survivor starts this application with proper user compliance.

Feasibility: As an in-home stroke rehabilitation application, it should be able to calculate rehabilitation efficacy automatically without an occupational therapist be there. Also, it should allow an occupational therapist to track any rehabilitation programs remotely and provide necessary feedback.

3.2 Physical Rehabilitation Rationale

Exercise adaption: *RehabPhone* includes a set of exercises for stroke rehabilitation. Different exercises have different purposes, for example, muscle enhancement exercises or balance exercises. These exercises usually rely on different sensing modalities (*e.g.,* touch screen, accelerometer, and gyroscope) for activity recognition and further health outcome measures. Whatever the rehabilitation exercise is, *RehabPhone* should be able to monitor the following components seamlessly. 1) occurrence of exercise: *RehabPhone* needs to detect if an activity happens or not; 2) duration of the exercise: *RehabPhone* needs to calculate how long each exercise exists; 3) repetitions: *RehabPhone* needs to count the number of actions is performed in each exercise; 4) smoothness of exercise: *RehabPhone* also requires to measure the smoothness of movement in each exercise, which is adopted to quantify the stroke efficacy.

External processing: For each type of exercise, *RehabPhone* should allow data streams to be passed through processing pipelines that are external to *RehabPhone*. This mechanism allows clinical researchers to analyze data streams and to provide stroke survivors feedback.

Figure 3: Left Figure: 3D visualization of the Mug in four different views. Smartphone is placed at the center to ensure the balance. Right Figure: Software-defined objects in use.

4 REHABPHONE OVERVIEW

In this section, we introduce the system overview to explain how will *RehabPhone* meet the goals we propose in Section 3. It contains two interfaces, as shown in Figure 4. The clinical researcher interface allows clinical professionals to assess health conditions and configure the rehabilitation program, and the user interface allows the users to receive the feedback.

4.1 A Software-defined Rehabilitation Tool

We design *RehabPhone* to include a smartphone and multiple rehabilitation objects. These rehabilitation objects are in the form of a software-defined method generated by 3D Printing technology. We can customize a rehabilitation object according to a user's rehabilitation goal, hand size, as well as smartphone size. These rehabilitation objects (as shown in Figure 3) structurally combined with a smartphone allow users to perform a set of exercises to enable rehabilitation. Since the objective of rehabilitation is to help survivors regain skills, these software-defined objects serve as household objects, for example, a doorknob, bowl, key, and a mug (see Figure 3). In this way, it allows users to mimic daily-life activities, such as pouring water and open the door. Meanwhile, these activities are detected and processed with smartphone in real time. Users then get feedback via APP GUI.

4.2 Clinician End

During a clinic visit, a medical team will first examine the stroke type with a series of tests (*e.g.,* physical examination, and blood test). Afterward, a rehabilitation professional determines the most appropriate at-home rehabilitation. *RehabPhone* maps this given prescription to pre-defined G-code, a language to tell computerized machine tools how to make something. A commercial 3D printer with this G-code file can generate required rehabilitation objects.

During a rehabilitation session, the rehabilitation professional is responsible for assessing rehabilitation efficacy and giving feedback. We integrate *RehabPhone* with a clinical team portal that analyzes four gold standard metrics for determining stroke rehabilitation efficacy. These analyses are carried out in real-time that allows a clinical team to closely follow up rehabilitation status and notify or adjust the probable rehabilitation program in the next stage.

4.3 User End

Rehabilitation with *RehabPhone* includes two parts, customized rehabilitation objects, and a smartphone APP. After a clinic visit, a stroke survivor can acquire the APP from the medical team and the customized rehabilitation objects by accessing commercial 3D printers with prescribed G-code files. During a rehabilitation program, the APP provides the acoustic instrument advising rehabilitation exercise. After completing one stage of a rehabilitation session, a stroke survivor receives the notification regarding the efficacy as well as the probable rehabilitation program in the next stage from the medical team.

5 REHABPHONE DESIGN AND IMPLEMENTATION

In this section, we detail the full system design and implementation. In Section 5.1, we justify the reason we choose 3D printing technology instead of traditional manufacture. In Section 5.2, we define and design the activity recognition approaches that will be implemented in a smartphone. In Section 5.3, we present our stroke patient manager to maintain multiple evens during a period of rehabilitation exercise. In Section 5.4, we present our implementation details.

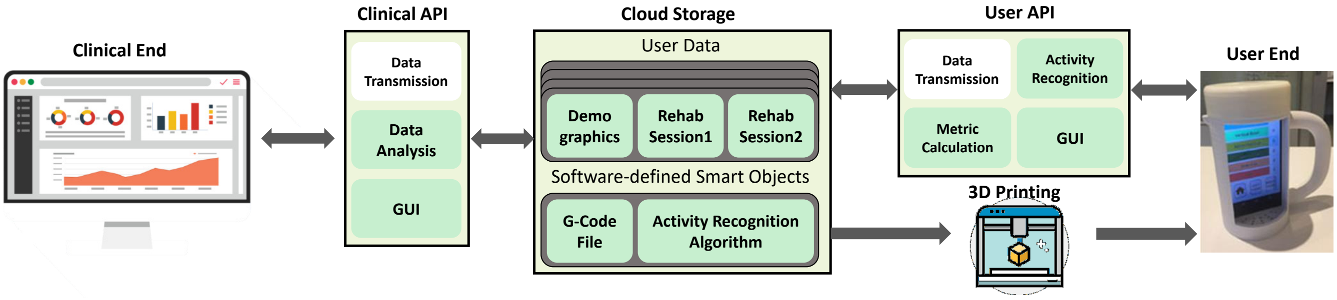


Figure 4: The overall system diagram including a clinician end, a user end, and a cloud storage. Sensory data are collected in the smartphone and analyzed by real-time computing unit to detect if an event happens and then measure the duration and repetitions of this event. After that, the raw data will be uploaded and stored in the cloud server. Clinical research is able to download the data, perform data analysis and give user feedback.

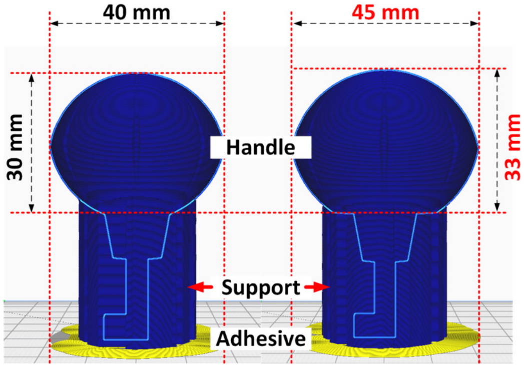


Figure 5: A closer look of two G code files preview for software-defined doorknob object. The size of the handle can be quickly adjusted according to the size of a patient's hand.

5.1 Software-Defined Rehabilitation Objects

As we introduced above, stroke can affect each person differently, thereby requiring different rehabilitation exercises. For the same rehabilitation exercise, stroke survivors would request customized rehabilitation objects due to discrepancies in age, hand size, upper extremity strength, and other health-related factors. It can take more than three months for a traditional manufacturing pipeline to customize a rehabilitation object, not to mention the financial cost.

As a consequence, we expect that a software-defined solution that is more efficient than traditional manufacture for deployment can be utilized to design the requested rehabilitation objects. In our work, *RehabPhone* determines rehabilitation objects according to user age, hand size, upper extremity strength, as well as smartphone model. These parameters direct inputs to the 3D object model data and allow automatic creation of user-specific rehabilitation objects. This tailored 3D model is then translated into a G-Code file, as shown in Figure 5, to allow offline commercial 3D printers to produce.

5.2 Activity Recognition and Metrics Measurement

Activity Recognition: As each rehabilitation object is structurally coupled with the smartphone while performing rehabilitation exercises, we design *RehabPhone* to leverage the various built-in sensors for activity recognition.

Gyroscope: For activities that require manipulating the physical orientation of the software-defined rehabilitation objects (*e.g.*, Sip from Mug, Quick Twist with Mug, and Slow Pour with Mug), we utilize rotational data from the smartphone's embedded gyroscope to determine the real-time changes that the user causes in the object's orientation.

Accelerometer: In activities that involve linear motion of the software-defined rehabilitation objects (*e.g.*, Horizontal Bowl, Vertical Bowl, Horizontal Mug, Vertical Mug, and Walk with Mug), we utilize data from the embedded accelerometer to detect user interactions with the objects.

Touch Screen: For activities that incorporate fine motor movement of the fingers (*e.g.*, Unlock with Key, Unlock with Doorknob, Type Numbers, and Quick Tap), we utilize touch screen sensing to track the user's motions.

Metrics Measurement: After recognizing an activity, *RehabPhone* extrapolates the metrics of repetition, duration, as well as smoothness to quantify the efficacy of exercise further.

Repetition: We adopt a threshold-based algorithm to detect the number of repetitions for an activity (as shown in Figure 6). This threshold can be either a reading from an accelerometer, a gyroscope, or a touchscreen, depending on the activity type. When sensor readings pass this threshold, a repetition is counted. Type Numbers and Quick Tap do not use threshold-based algorithms due to the binary input for these exercises.

Duration: We adopt the same threshold-based algorithm to detect the average duration of an activity. When an activity is detected, we calculate the difference in system clock between the end of the current repetition and the end of the previous repetition to get the duration of this repetition. At the end of the activity, we average the duration of all repetitions.

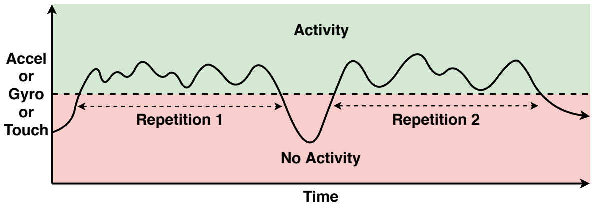


Figure 6: *Rehabphone* adopts a threshold-based algorithm to detect duration and repetitions of activities. It can be adopted with gyroscope, accelerometer, or touch screen measurements according to rehabilitation exercises.

Smoothness: We calculate Normalized Jerk Score (NJS) to quantify smoothness for accelerometer-based activities. NJS is highly correlated with the clinical Fugl-Meyer Upper Limb Motor Assessment Scale [20]. The calculation of NJS is:

$$NJS = \sqrt{\frac{1}{2}\int_{t1}^{t2}((\frac{da_x}{dt})^2 + (\frac{da_y}{dt})^2 + (\frac{da_z}{dt})^2)dt * \frac{\Delta t^3}{A^2}}, \quad (1)$$

where a_x, a_y, and a_z are the accelerometer readings in x-, y- and z-axes, respectively. The duration of the observation is $\Delta t = t_1 - t_2$ and A is the movement distance of the motion. The term $\frac{\Delta t^3}{A^2}$ is the normalization factor. The discretized integration between the limits Δt is generally performed after every sampling of the accelerometer. If NJS is close to 0, the motion is considered smooth [21]. To quantify smoothness for gyroscope-based and touchscreen-based activities, we calculate the Zero-Crossing Rate (ZCR), which is the rate at which the sensor data changes its numerical sign [22]. A ZCR closer to 0 is better, as this indicates less fluctuation during a movement. We highlight that smoothness does not apply to activities such as Type Numbers and Quick Tap, which have a binary input. Instead, those activities adopt an accuracy score, which is the percent of correct typings on a touch screen.

5.3 Stroke Rehabilitation Manager

One of the main challenges in the design of *RehabPhone* is maintaining the information flow in the state machine. Existing solution methodologies, such as Apple's ResearchKit [23], do not satisfy our design goals. Reasons are twofold: 1) The data collection methods of ResearchKit are based on the expectation that users self-report activity data, therefore having limited capability to detect whether activities are performed correctly or not. 2) The data analysis is done post-activity after data has been uploaded to a cloud server. This mechanism limits the patient's ability to receive real-time feedback.

For this purpose, we design a *Stroke Rehabilitation Manager (SRM)* to manage the data collection, data analysis, and exchange of information related to user performance across the modules of the app (as shown in Figure 7). This automated real-time collection, analysis, and exchange of information create an integrated and responsive user experience, allowing users to adjust and improve their interactions with the software-defined objects in each successive exercise session.

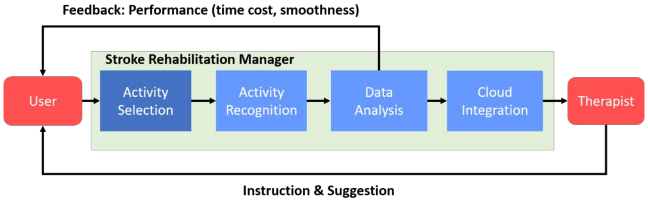


Figure 7: Stroke Rehabilitation Manager (SRM) manages the activity selection, activity recognition, performance analysis, as well as exchange of information related to user performance across the modules of the app. Arrows signify information passing flow.

Exercise Selection and Sensor Configuration: The Activity Selection module is triggered upon the user's initial interaction with the app. In this module, the user decides what exercises to perform for the current rehabilitation session. For each exercise, a user can choose the hand to perform with, as well as the number of repetitions.

Activity Recognition: The Activity Recognition module is triggered after the Activity Selection module, as the user interacts with the software-defined objects to perform the selected exercise activities. We implement the calculations from Section 5.2 in this module to extrapolate performance data from the smartphone sensors (gyroscope, accelerometer, touch screen), calculating the metrics of duration, repetition, smoothness. The specific implementations of these calculations depend on the activity-specific data that is determined in the Activity Selection module.

Feedback: After the activity is finished, the Feedback module is triggered, and the performance metrics from the Activity Recognition module are passed to it. We design the Feedback module to give auditory and visual feedback based on these performance metrics. The auditory feedback includes compliments and fanfare sounds; the visual feedback includes historical progress graphs and numerical scores. The combination of auditory and visual feedback further encourages the users to understand and improve their performances upon returning to the Exercise Selection and Activity Recognition modules.

Cloud Integration: We also design the SRM to include a framework for stroke professional intervention. The performance metrics calculated in the Activity Recognition module are written to a file and unobtrusively uploaded into an Amazon S3 bucket [24], where stroke professionals can access it. Based on stroke professionals' professional assessments of the performance metrics, clinical sessions can be adjusted, and advice can be given to users to improve their performance on the exercises further, as measured in the Activity Recognition module. Additionally, based on stroke professionals' assessments, users can choose appropriate exercises with appropriate intensities in the Exercise Selection module for future sessions.

5.4 Application Implementation

We implement the *RehabPhone* application in the real smartphone (as shown in Figure 8).

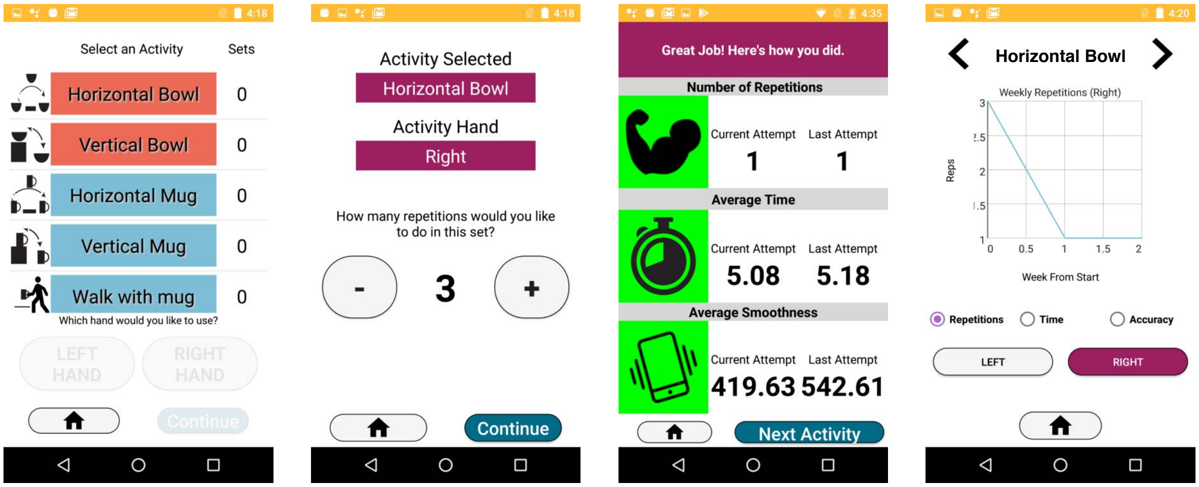
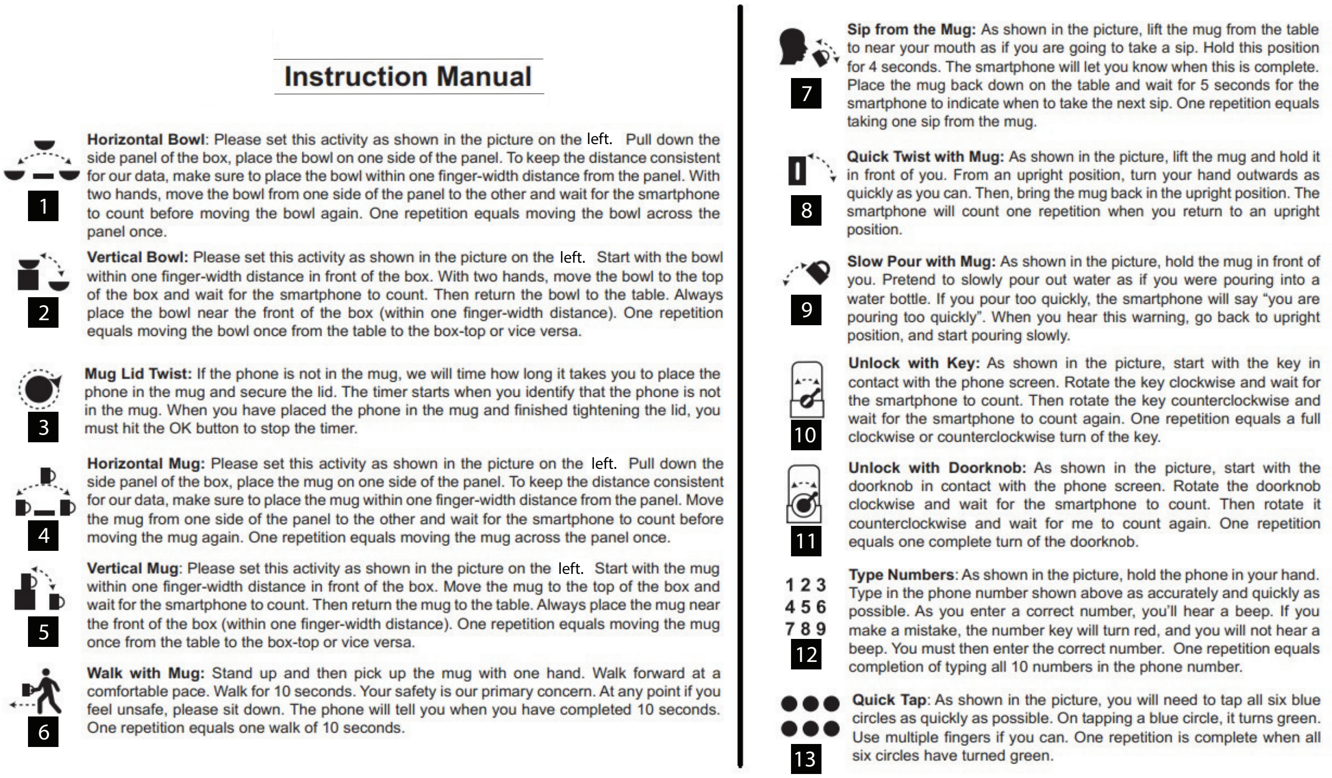


Figure 8: The implementation of *RehabPhone* at the smartphone end. It includes the exercise selection, real-time computation and feedback, and cloud integration.



Instruction Manual

Horizontal Bowl: Please set this activity as shown in the picture on the left. Pull down the side panel of the box, place the bowl on one side of the panel. To keep the distance consistent for our data, make sure to place the bowl within one finger-width distance from the panel. With two hands, move the bowl from one side of the panel to the other and wait for the smartphone to count before moving the bowl again. One repetition equals moving the bowl across the panel once.

Vertical Bowl: Please set this activity as shown in the picture on the left. Start with the bowl within one finger-width distance in front of the box. With two hands, move the bowl to the top of the box and wait for the smartphone to count. Then return the bowl to the table. Always place the bowl near the front of the box (within one finger-width distance). One repetition equals moving the bowl once from the table to the box-top or vice versa.

Mug Lid Twist: If the phone is not in the mug, we will time how long it takes you to place the phone in the mug and secure the lid. The timer starts when you identify that the phone is not in the mug. When you have placed the phone in the mug and finished tightening the lid, you must hit the OK button to stop the timer.

Horizontal Mug: Please set this activity as shown in the picture on the left. Pull down the side panel of the box, place the mug on one side of the panel. To keep the distance consistent for our data, make sure to place the mug within one finger-width distance from the panel. Move the mug from one side of the panel to the other and wait for the smartphone to count before moving the mug again. One repetition equals moving the mug across the panel once.

Vertical Mug: Please set this activity as shown in the picture on the left. Start with the mug within one finger-width distance in front of the box. Move the mug to the top of the box and wait for the smartphone to count. Then return the mug to the table. Always place the mug near the front of the box (within one finger-width distance). One repetition equals moving the mug once from the table to the box-top or vice versa.

Walk with Mug: Stand up and then pick up the mug with one hand. Walk forward at a comfortable pace. Walk for 10 seconds. Your safety is our primary concern. At any point if you feel unsafe, please sit down. The phone will tell you when you have completed 10 seconds. One repetition equals one walk of 10 seconds.

Sip from the Mug: As shown in the picture, lift the mug from the table to near your mouth as if you are going to take a sip. Hold this position for 4 seconds. The smartphone will let you know when this is complete. Place the mug back down on the table and wait for 5 seconds for the smartphone to indicate when to take the next sip. One repetition equals taking one sip from the mug.

Quick Twist with Mug: As shown in the picture, lift the mug and hold it in front of you. From an upright position, turn your hand outwards as quickly as you can. Then, bring the mug back in the upright position. The smartphone will count one repetition when you return to an upright position.

Slow Pour with Mug: As shown in the picture, hold the mug in front of you. Pretend to slowly pour out water as if you were pouring into a water bottle. If you pour too quickly, the smartphone will say "you are pouring too quickly". When you hear this warning, go back to upright position, and start pouring slowly.

Unlock with Key: As shown in the picture, start with the key in contact with the phone screen. Rotate the key clockwise and wait for the smartphone to count. Then rotate the key counterclockwise and wait for the smartphone to count again. One repetition equals a full clockwise or counterclockwise turn of the key.

Unlock with Doorknob: As shown in the picture, start with the doorknob in contact with the phone screen. Rotate the doorknob clockwise and wait for the smartphone to count. Then rotate it counterclockwise and wait for me to count again. One repetition equals one complete turn of the doorknob.

Type Numbers: As shown in the picture, hold the phone in your hand. Type in the phone number shown above as accurately and quickly as possible. As you enter a correct number, you'll hear a beep. If you make a mistake, the number key will turn red, and you will not hear a beep. You must then enter the correct number. One repetition equals completion of typing all 10 numbers in the phone number.

Quick Tap: As shown in the picture, you will need to tap all six blue circles as quickly as possible. On tapping a blue circle, it turns green. Use multiple fingers if you can. One repetition is complete when all six circles have turned green.

Figure 9: Instruction manual associated with 13 rehabilitation exercises. We (with stroke rehabilitation professionals and occupational therapist in our team) design these exercises and implement activity recognition algorithm for each exercise.

Exercise Selection and Sensor Configuration: To implement this module, we utilize the `Button`, `ImageButton`, and `RadioButton` classes in Android Studio's Java libraries. These buttons are triggered based on user interactions with the touchscreen interface. We set each button's `OnClickListener` to run a specific code branch for its corresponding activity selection, upon being triggered by the user. Each of these code branches uses a specific combination of built-in sensors for their respective activities.

Activity Recognition: In this module, we leverage the built-in accelerometer and gyroscope sensor modalities to monitor the user movement in the x, y, and z dimensions. Apart from that, we also utilize the touch screen sensors where the activity requires the user to interact with the screen. Although sampling rates for sensors vary from device to device, we typically set them as 100Hz in our experiment. Gathering this sensing information, this module generates individual parameters and runs the calculations to extrapolate information regarding duration, repetition, and smoothness for each rehabilitation exercise. In the end, we record the data regarding this activity to JSON files in the mobile file directory.

Feedback: To properly generate feedback to the users, we retrieve data from the previously written JSON files. Afterward, we parse this data into a human-readable format and display the long-term tracking performance on the GUI. We also utilize the built-in speakers to communicate the performance metrics to the user in an acoustic format.

Cloud Integration: Cloud service is a necessity for tracking data maintenance and synchronization across multiple mobile devices. Specifically, we develop this functionality with Amazon's AWS Mobile SDK. Using this SDK, we upload the workout data files from the Activity Recognition module to an AWS Bucket. The performance metrics can be further generated in each AWS bucket and available to stroke professionals in a human-readable format.

Rehabilitation Exercises Implementation: We collaborate with stroke professionals and design **13** rehabilitation exercises, as shown in Figure 9. For each exercise, we design its activity recognition algorithm and implement the framework in the smartphone application. Note that *RehabPhone* is extensible as we can enrich the exercises based on needs. A stroke professional who collaborated with a computer science/engineering researcher can quickly define a new rehabilitation exercise. Some exercises will need certain tools to achieve the best outcome. Particularly, we adopt a commercial off-the-shelf 3D printer, Ultimaker, to produce those rehabilitation objects. For the same object, its size can be customized with stepless regulation, and its weight can be customized with ten steps regulation by controlling the material density. Overall, *RehabPhone* is an effective solution because 1) it takes less than three hours, including the time for object design and for printing, for a stroke patient to get a customized rehabilitation object; 2) each object costs less than 5 dollars.

6 USABILITY STUDY

We conduct two in-lab studies to understand the usability of the system. In the first stage, we validate our system by testing the measurement consistency of the performance metrics. This part of experiment involves 12 healthy young adults who show no signs of motor impairments. In the second stage, we recruit four older adults and four stroke survivors to gather possible usability issues and optimization details. Eight participants are considered an appropriate sample size based on the 10 ± 2 participant rule for discovering 80% of usability problems [25]. Our organization's Institutional Review Board approves all procedures explained hereafter.

6.1 Evaluation of System Consistency

Benchmark Preparation: To test the consistency of performance metrics measurements reported by the system, a cohort of 12 young adults (mean age: 24.67, range: 21-30) are conveniently enrolled to participate in the study. We specifically choose young adults due to their consistency in performing functional motor exercises without much variation across days, repetitions, and sessions. These participants are asked to check-in to the lab for three sessions spread over a week. In each session, exercises shown in Figure 9 are requested to perform with ten repetitions each. The raw performance data is uploaded to the AWS cloud server at the end of each day. All the raw data is analyzed using Python.

Metrics: We adopt the coefficient of variation (CoV)[1] to evaluate consistency. CoV is a parameter commonly used in physical therapy to test whether a metric can measure the same phenomenon consistently [26].

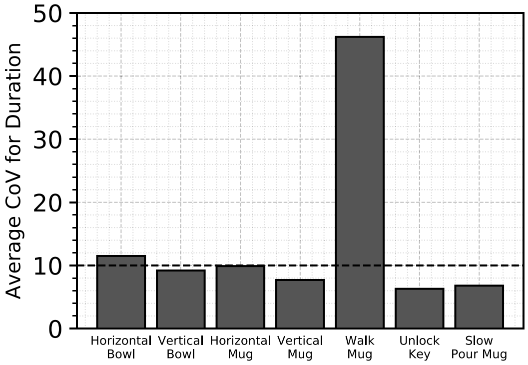


Figure 10: Average Coefficient of Variation in Activity Duration Measurements.

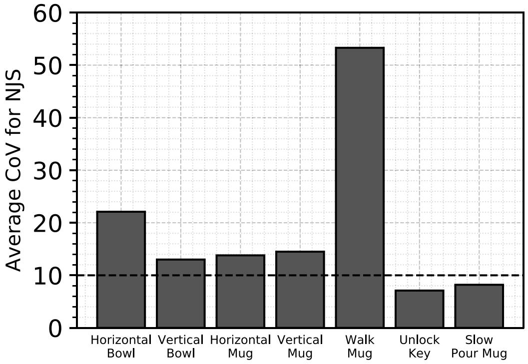


Figure 11: Average Coefficient of Variation in Normalized Jerk Score Calculations.

Results: Figure 10 and Figure 11 show CoV for average duration and normalized jerk score on application exercises, respectively. Our results reveal that, on average, most of the exercises show a CoV percentage of around 10%, which is considered good enough for human limb motion analysis [27]. We find that the CoV for the

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[1] CoV = mean/standard deviation

Walk with Mug exercise is considerably higher than other rehabilitation exercises. The reason is that related gait dynamics will affect the smartphone accelerometer readings. For other rehabilitation exercises such as Type Numbers, Quick Tap, and Mug Lid Twist, every finger tapping is correctly recorded and thereby it is not necessary to compute CoV.

6.2 Evaluation of Usability

Benchmark Preparation: To explore the usability, We validate *RehabPhone* on older adults who are more prone to stroke [28]. In detail, we enroll four healthy older adults (mean age: 72.5, range: 66-87) and four stroke survivors (mean age: 61.5, range: 54-68). After their usage, they provide usability feedback on our application for possible refinements before deployment of the in-home study. In one lab session, all 13 exercises are required to perform in as many repetitions as requested. Afterward, we adopt a modified version of the standard QUIS questionnaire [29] to receive feedback in a 0 (least favorable) to 9 (most favorable) Likert scale format.

Table 1: Usability questionnaire results of older adults (n=4) and stroke survivors (n=4) in the in-lab study.

Usability items	Mean ± SD
Frustrating to satisfying	6.60 ± 1.85
Dull to stimulating	6.50 ± 3.12
Ease of character reading on screen	7.88 ± 2.10
Clarity on the level of progress	7.43 ± 1.72
Ease of learning to operate	8.75 ± 0.46
Clarity of the sequence of screens	8.63 ± 0.74
Clarity of information organization	8.50 ± 0.76
Clarity of activity performance	7.57 ± 1.62

Results: Table 1 shows the usability questionnaire results. Based on verbal feedback, we modify our app to have less distracting audio and visual cues while adding more text (as shown in Figure 9) since older adults are more comfortable reading paper printed instructions. Also, we fine-tune the ergonomics of the software-defined rehabilitation objects, including modifying the doorknob to be more ellipsoidal rather than being perfectly spherical.

7 A HOME-BASED CLINICAL TRIAL ON STROKE SURVIVORS

In this section, we evaluate *RehabPhone* on real stroke survivors.

7.1 Participants

We enroll 12 stroke survivors (age: 62 ± 14.59, 5 females, 6 right hemiplegia, occurrence of stroke > 1 year). The enrollment criteria is that participants are not undergoing rehabilitation sessions with stroke professionals and also not on botulinum toxin injections or intrathecal baclofen to reduce their spasticity. The reason is that one out of three participants tends to have spasticity after a stroke [30], and therefore, medications are commonly used. We exclude participants with spasticity to avoid intervention caused by medication. 12 stroke survivors are divided into three groups of 4 participants each.

a) Performing 'Unlock with Key' Task b) Interacting with the Software-Defined Bowl

Figure 12: Stroke survivors are interacting with *RehabPhone* in their homes.

Table 2: Demographic characteristics of enrolled participants (n = 12).

Characteristics	Number
Age (Years), M (SD)	62 (14.59)
Male, n (%)	7 (58.3)
Right Hemiplegia, n (%)	6 (50)
Stroke Occurred Over 1 Year Ago, n (%)	12 (100)
Has Healthcare Provider, n (%)	12 (100)
Undergoing Rehabilitation Sessions, n (%)	0 (0)
Botulin Toxin Injections, n (%)	0 (0)
Intrethecal Bacoflen, n (%)	0 (0)

7.2 Procedures

12 stroke survivors are evenly divided into three groups (4 participants in each group). Each group conducts an 8-week long RehabPhone-based intervention program, including a 1-week baseline functional ability assessment, a 6-week in-home self-management intervention, and a 1-week follow-up functional ability assessment.

In the first week, stroke survivors come to our university lab. An occupational therapist in our team examines the baseline performance of every stroke patient using the standard clinical assessment (see Section 7.3). Then, rehabilitation objects are customized for each stroke patient, and the occupational therapist instructs the usage of the *Rehabphone*. After in-lab training, each patient is given a Nexus 5 phone installed the rehabilitation app, and a collection of requested software-defined objects are packaged into a 12"∗12"∗12" box and delivered to their home (as shown in Figure 12).

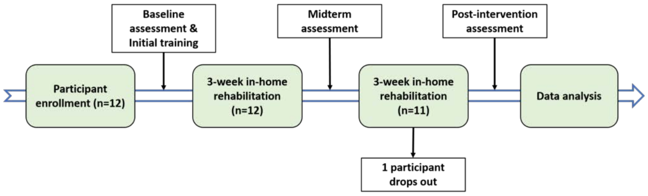

Figure 13: The flowchart of our rehabilitation program. 12 participants are enrolled and 1 participant drops out in the midterm. The total intervention last for 6 weeks. Occupational therapists conduct the clinical assessment at the baseline, midterm and post-intervention.

During the 6-week in-home self-management intervention period, participants are instructed to practice five sessions per week with the app guiding them to perform the embedded 13 exercises in 10 repetitions. Three exercises (*i.e.*, Horizontal Mug, Quick Twist

Mug, and Unlock Key) are required, whereas the remaining 10 exercises are highly recommended. Also, participants are encouraged to play more repetitions than they expected.

In the eighth week, a follow-up occupational therapist performs the clinical assessment for every patient to identify possible improvements or deterioration.

7.3 Data collection

Throughout the intervention program, two types of data are collected for assessing the functional status of these participants.

Smartphone-based Assessment: Smartphone provides a real-time efficacy assessment. The objective is to give participants feedback in time, thereby motivate the rehabilitation exercise. During each rehabilitation exercise with *RehabPhone*, on-board sensors collect data, and functional metrics such as duration, smoothness, and accuracy are calculated. At the end of each day, these metrics, as well as the number of repetitions, are uploaded to the Amazon S3 cloud server.

Clinical Assessment: While smartphone-based assessment provides timely feedback, a standard clinical assessment is required to provide a reference for clinical stroke rehabilitation professionals. An occupational therapist conducts this at the baseline in the first week (baseline) and the eighth week (follow-up). The applied clinical assessment is called the standard Wolf Motor Function Test (WMFT) [17]. WMFT is now the state-of-the-art motor function test leveraging a time-based method to evaluate upper extremity performance while providing insight into joint-specific and total limb movements. In total, it includes 17 tasks. For all timed tasks, participants are told to perform the tasks as quickly as possible. Timing is carried out using a stopwatch that records in milliseconds. The lower the total time costs, the better the functional ability is.

7.4 Evaluations

For each stroke survivor, we evaluate user adherence and clinical efficacy.

Analysis of User Adherence: Adherence to therapies is a primary determinant of treatment success. World Health Organization (WHO) defines user adherence as "the degree to which the person's behavior corresponds with the agreed recommendations from a health care provider. [31]" We define a participant (p_m) is adhering to the medication if the number of treatments (N_T) divided by the number of treatments prescribed (N_{PT}) in a given time period T is greater than 80% [32]:

$$p_m = \begin{cases} 1, & \frac{N_T}{N_{PT}} \times 100\% \geq 80\% \\ 0, & \text{otherwise} \end{cases} .$$

Then, we define the group adherence rate (R_A) as:

$$R_A = \frac{\sum_{m=1}^{M} p_m}{M},$$

where the M is the number of enrolled participants.

Figure 14 shows the number of exercises participants repeat during the 6-week intervention section. Recall that participants are requested to perform ten repetitions of three activities five times per week. That is, a number of 900 repetitions are requested for each participant. Participant (ID is 1) withdraws in this 6-week long intervention. Other participants (n = 11) except for the 7th participant adhere to our program. Therefore, user adherence in our study is over 90%. Most participants meet or exceed the prescribed number of repetitions. Two participants (ID is 2 and 5) show a high motivation to finish all 13 rehabilitation exercises. Some participants report that the real-time feedback of efficacy from *RehabPhone* helps to keep their motivation at a high level. Moreover, participants report that trust in this program plays an important role in keeping them motivated.

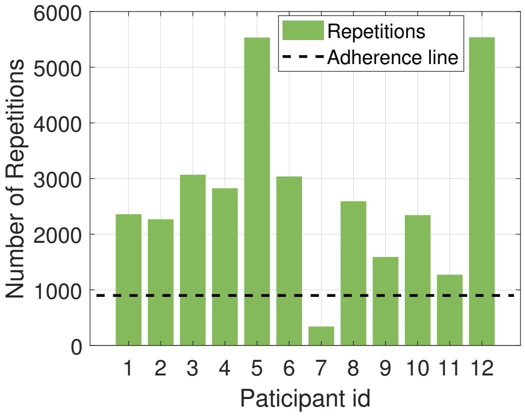

Figure 14: The number of rehabilitation exercises in the 6-week unattended intervention section. Participant 1 withdraws our program. 10 out of the remaining 11 participants adhere to our program.

Analysis of Functional Ability Improvement: Recall that two types of data measure the functional ability, where *RehabPhone* measures duration and smoothness in real-time, and a clinical assessment using the standard WMFT is conducted by an occupational therapist at the baseline and follow-up phase, respectively. For both assessments, improvement can be calculated as

$$\text{improvement} = \frac{F_b - F_f}{F_b} \times 100\%,$$

where F_b is the functional ability at the baseline phase, and F_f is the functional ability at the follow-up phase.

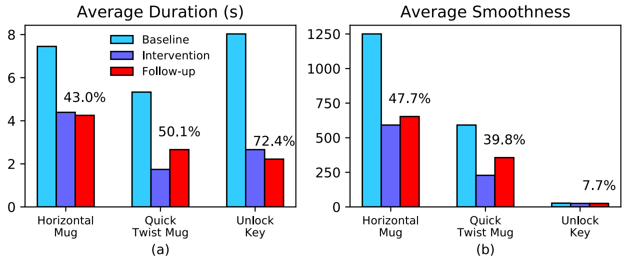

Figure 15: Average duration and smoothness for benchmark activities. In both metrics, the value will be the lower, the better. The value above the follow-up bars shows the improvement of functional ability.

Smartphone-based Assessment: Figure 15 shows the average duration and smoothness of three exercises on all participants. The follow-up values of all three exercises are less than the values of baseline, showing that *RehabPhone* can help participants regain daily-life skills. Besides, the intervention values of some exercises are observed lower than that of follow-up. The reason is that, in the follow-up section, a patient is supervised by an occupational therapist to make sure the whole procedure is standard. This off-field factor can make a small difference in results.

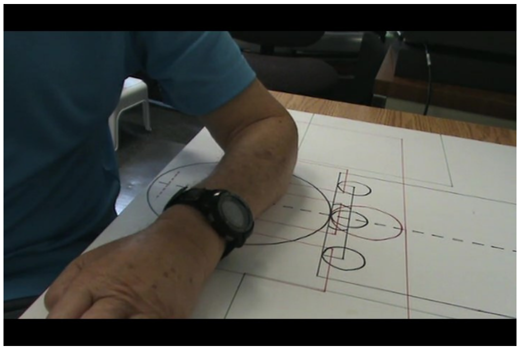

Figure 16: A stroke survivor is performing standard WMFT test instructed by an occupational therapist. The task in this figure is Extend Elbow.

Standard Clinical Assessment: Figure 16 shows a participant is doing the WMFT test instructed by our occupational therapist. A WMFT template is taped to the desk to assure a standard placement of test objects. The outline of each test object is traced on the template in the position in which it should be placed and further identified by corresponding task item numbers.

Table 3: Baseline Versus follow-up of total WMFT time over 17 tasks. Patient 1 dropped out mid-study.

ID #	Baseline (s)	follow-up (s)	Improve (%)
1	601.34	N/A	N/A
2	89.64	102.68	-14.55
3	206.66	188.59	8.74
4	176.76	197.68	-11.84
5	91.73	46.75	49.04
6	667.52	568.64	14.81
7	1444.14	1445.16	-0.07
8	573.52	467.67	18.46
9	29.62	24.74	16.48
10	390.94	354.59	9.30
11	99.94	44.77	55.20
12	35.82	30.74	14.18
AVG (SD)	346.03 (424.07)	315.64 (418.49)	14.5 (21.6)

Table 3 shows the comparison of functional ability between before and after an intervention. Results are recorded as the total time cost in the WMFT test. One participant withdraws our intervention program. The rest of stroke survivors can receive an average 14.5% improvement. The functional ability improves in 8 cases (72.7%) out of 11 cases. Two participants (ID is 5 and 11) improve more than 20% in the WMFT. A 20% change is less likely to be due to variability in performance. Specifically, participant 5 is diagnosed with limited movement in lateral or behind back and weakness in lifting weight at the baseline assessment. He reports that our program, to a certain extent, improves his lifting ability.

7.5 Feedback Collection and Summary

Feedback from Patient Users: During the whole intervention program, approaches, including email contact, home visit, as well as an interview with each patient, are carried out by an occupational therapist to explore the factors affecting user adherence. The results are generally positive. Some participants claim that they feel like interacting with their smartphones rather than some rehabilitation tools. They claim that this kind of interaction can motivate them better. There exist factors affecting user adherence. Some participants report that the APP is easy to use. Some software and hardware issues affect user adherence. One participant reports that key and doorknob breaks during the rehabilitation exercises, which stop the subsequent exercises. Some participants claim that the APP refuses to work sometimes, thereby prevent them from doing more repetitions. One participant withdraws our study with the explanation that although the system offers performance feedback after every trial, this feedback is not as effective as a person to keep them motivated to continue exercising. These factors motivate us to improve our application design in the future.

As a practical outcome of the study, participants can demonstrate abilities to recuperate to activities of daily living. One participant reports that the sip and slow pour make the scapula muscles work. One participant reports that slow pour and sip from the mug, and walk with mug help muscles working more. One participant can tie her shoe-lace, which she is not able to perform before the intervention. These results motivate us and provide us with first-hand inspiration that technology has an impact on improving the lifestyle of the disabled.

Feedback from the Clinician Community: *RehabPhone* has also been intensively demonstrated to healthcare professionals, including occupational therapists, physical therapists and physicians through national conferences, regional conferences, hospital grand rounds and individual meetings. The response to using technology to support therapeutic programs and enhance the patient's ability to take ownership of part of their rehabilitation is positive. As a result of presentations, physicians have reached out to the team group to adapt *RehabPhone* to fit other populations than individuals with chronic stroke. One physician summarized clearly the need for this tool. "This app is so needed! I think this has the potential to really help patients."

8 DISCUSSION

Recent surveys indicate that technology penetration among physical therapists is minimal - greater than 87% practitioners do not use technology in their practice [19, 33]. The reasons pertain to technology failure [34], steep learning curve [35], high cost [36], or non-scalable solutions [37]. However, stroke survivors exhibit high adherence in our pilot study. Some positive feedback says that they feel like interacting with their smartphones rather than a rehabilitation tool. This result is consistent with a previous survey of 91 stroke professionals, which reveals that 89% *intend* to use smartphone technology in practice [33]. *RehabPhone* marks a closer step towards in-home stroke rehabilitation. However, it exhibits some limitations.

Usability Issues: We notice issues of stroke survivors misplacing the instruction manual, calling the research team to re-explain the exercises, or trying to fit the 3D printed key into the notches meant for the smartphone. Considerations for easy assembly is important in developing a stroke rehabilitation system. A short video of the intended exercises embedded in the smartphone app would help.

Software-defined Objects Shortcomings: The objects have a tendency to be broken due to the jerky forces applied by stroke survivors. Time devoted to good craftsmanship and durable setup results in less in-home support. Objects are sanded down for a good finish. For objects that have joined parts, such as doorknob and key holder, the epoxy coating made the joints sturdier. These learnings are validated on stroke survivors in the first group and incorporated in the following groups. We believe this issue can be addressed when 3D printing technology becomes more accessible. Stroke survivors can quickly re-print their damaged objects.

Smartphone Related Shortcomings: The *RehabPhone* depends on the faculties provided by a smartphone. Developer orient considerations include lowering the power consumption of the smartphone and finding optimum time points in a day when raw performance metrics measurements could be uploaded to the cloud server. Among older adults, internet disconnectivity is prevalent, with outreach being just under 67% [38]. Therefore, a deployment adaptation such as an AB test [39] may enable better practical usage of the smartphone system. We leave such considerations as extensions to our system.

Scalability Issues: We expect the workflow of *RehabPhone* looks as follows. After visiting a rehabilitation team, the stroke patient receives the G-Code in his/her smartphone for rehabilitation objects. Then, he/she can select any accessible 3D Printers online. The printed customized rehabilitation objects will be delivered to the home. However, a lack of accessible 3D printers would affect this workflow. Currently, each software-defined object is pre-printed in the lab. Then, all the objects are packaged into a 12" ∗ 12" ∗ 12" box that is delivered to homes of the participants. This issue can also be addressed when the 3D printer is popularized in the future.

9 RELATED WORK

9.1 Mobile Health System

Mobile health is an emerging area of interest for researchers in recent years [40–46]. Stresssense [47] recognized stress from the human voice using smartphones. Pho_2 [48] measured the blood oxygen level of a person with a built-in camera. iSleep [49] leveraged embedded microphone to monitor events related to sleep quality, such as snoring and body movement. Farhan *et al.* [50] applied data from GPS and accelerometer of the smartphone to perform depression screening. Healthaware [51] utilized the embedded accelerometer to monitor daily physical activities and the built-in camera to analyze food items to control obesity. SymDetector [52] employed the built-in microphone to detect respiratory symptoms, such as coughs, sniffles, and sneezes. PDMove [53] achieved the medication adherence monitoring through gait assessment using a smartphone. PDVocal [54] utilized non-speech body sounds to enable privacy-preserving Parkinson's disease detection. HealthSense [55] developed a platform to enable software-defined clinical trials. Different from all existing work, *RehabPhone* utilizes the smartphone and 3D Printing technology to augment in-home stroke rehabilitation.

9.2 Smartphone-based Stroke Rehabilitation System

Smartphones have been used to facilitate motor rehabilitation [56–58]. Most approaches rely on the smartphone being a gateway to connect body area network [59, 60] devices to the internet. Such approaches require patients to attach sensors/smartphones onto their bodies [56–58, 61] or would require patients to hold the smartphone [62]. Sensorless approaches using auditory cues of a smartphone have also been studied to teach and train motor exercises for chronic pulmonary obstructive disease rehabilitation [63]. Although efficient, these systems have not been designed with a consideration towards scalability. Most existing works leverage the smartphone as a gateway or a sensor. *RehabPhone* leverages 3D Printing technology to augment smartphone. The smartphone is structurally coupled with rehabilitation object. It will serve as a computing unit, sensor as well as a human-computer interface.

9.3 Smartphones Making Objects Smarter

Previous work have demonstrated the ability of using smartphones to enhance daily life objects in the form of augmented reality [64–66]. Also, embedded approaches such as smartphones inserted into toys and learnable robots have been proposed to help children learn effectively [67–69]. Works such as these, utilize the built-in sensors such as speakers, vibrators, cameras, or the screen to make daily life objects smarter. In this work, we embed smartphones into 3D Printed objects to transform them for stroke rehabilitation.

10 CONCLUSION

This study demonstrates our pilot study of deploying a 3D printing augmented smartphone system, *RehabPhone*, to facilitate in-home stroke rehabilitation. *RehabPhone* is scalable to fit the multiple level needs of stroke rehabilitation. An in-lab validation on 12 young adults and 8 old adults shows the good usability of the *RehabPhone*. An in-home program on 12 stroke survivors reveals that our system is capable of recuperating stroke survivors to mimic daily life activities once again. Through this pilot study, we believe that *RehabPhone* demonstrates a promising step in the real-world deployment of a universal but scalable stroke rehabilitation system in the future.

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