A Hardware and Software Prototype of the CTAR All-Star

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Abstract

The CTAR All-Star is a system consisting of a rubber ball, a pressure sensor, and a bluetooth transmitter paired with a cross-platform mobile application. The device is used as a rehabilitation tool for people with dysphagia in a similar fashion to the traditional chin tuck against resistance (CTAR) exercise by squeezing a ball between the chin and upper chest. The mobile device monitors and displays the pressure inside the ball on a real-time graph allowing the patient to follow exercise routines set by Speech-Language Pathologists. Additionally, the application stores exercise data that can be used to both monitor the patient's progress over time and provide objective data for future research purposes.

keywords: chin tuck against resistance, dysphagia, rehabilitation.

1 Introduction

Dysphagia is a medical symptom with a neurological underpinning that is characterized by difficulty swallowing. Primarily seen in stroke victims and the elderly, this condition is estimated to affect roughly 9 million adults of which approximately 37 percent are diagnosed with dysphagia in the US [3]. Therefore, it can be estimated that the number of people undergoing medical treatment for dysphagia is around 3.3 million people each year. For the purpose of this paper the focus will be on dysphagia, which is caused by upper esophageal sphincter dysfunction. Dysphagia is caused by sphincter (UES) dysfunction and lack of bolus flow into the esophagus and can result in serious health consequences including malnutrition, dehydration, aspiration pneumonia, and death [8].

One common exercise for strengthening the suprahyoid muscles and improving oral feeding is the chin tuck against resistance (CTAR) which has been reported to be an effective treatment for dysphagia. [11] This exercise involves squeezing a ball between the chest and chin in order to strengthen the muscles in the neck, and improve bolus flow into the esophagus. Furthermore, it is known that patients perform better and work harder with visual feedback. The CTAR All-Star aims to improve on the traditional rehabilitation experience for patients and Speech-Language Pathologists (SLPs). The system capitalizes on the increasing prevalence of mobile smartphones and tablets in modern society to create a package that is both affordable and feature-rich. The CTAR All-Star is composed of a cross-platform mobile application and a wireless exercise device that can be used by both parties for creating, assigning, and performing exercise routines as well as monitoring the results of rehabilitation sessions. Using this system, the SLP can create personalized exercise routines and assign the exercises as home practice to the patients. During the home practice exercise routines, the application guides the patient through the exercise step by step while plotting progress, pressure, and pressure thresholds inside the ball in real time.

The rest of this paper is structured as follows: Section 2 discusses the software design of the mobile application, Section 3 goes over the hardware design of the exercise device, Section 4 walks through the implementation of the CTAR All-Star, and Section 5 reviews the conclusions and future work associated with the CTAR All-Star.

2 Software Design

This work began with a brainstorming meeting between several of the co-authors of this paper. During this meeting we wanted to leverage our previous work on tool development for doctors in the field of Speech Pathology and Audiology. Our previous work had led to an open source game for dysphagia therapy [7]. We came up with the idea of constructing the hardware and software for the device described in this paper.

The requirements detailed in the following subsections include descriptions of the functional and nonfunctional requirements used by the system. The construction of these requirements was developed through interviews with stakeholders that had a hand in the project. Besides the requirements we also present use cases, the traceability matrix, and the database design of the application. The requirements and use cases for the application were realized through interviews with multiple stakeholders including SLPs.

2.1 Stakeholder-Client Interviews

Once the development team was put together, the first process was constructing the requirements. This was done by interviewing several of our clients. These were interviewed in person and via email. In order to collect consistent information

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we put together a set of questions to ask. The first ten questions we asked of all clients are as follows:

1. How would your profession benefit from this project?
2. What in your view would make this a successful project?
3. What functions are desired?
4. What is the priority of each feature or function?
5. What are the business requirements?
6. What results are required/desired?
7. What are the metrics to define success?
8. Are there any other requirements we should be aware of?
9. Are there any products/projects related to this one?
10. Is there anything we didn't discuss?

Additionally we asked Client 1 several more questions:

- What is the current process?
- What type of exercises would this project be used for?
- What kind of people will the primary users be?
- What are the pitfalls/what is inhibiting success with the current process?
- What's been done to solve this already?
- How much history would you like stored & who should have access to it?
- What level of security is required?
- What kind of training do you anticipate needing?
- Is there anyone we need to speak with who isn't on our list?

Client 1: Our first client spoke about the need for an effective way to measure the results of the chin tuck against resistance exercise. Currently, they have no way of knowing if the patient is actually putting any amount of force into the exercise. With proper measuring techniques, they can gather better data for research and determine if the exercise is indeed an effective rehabilitation technique.

She said her profession would benefit in several ways from this project. It will help speech pathologists know more about swallowing conditions and rehabilitating them. Additionally, it will help a speech pathologist give more specialized treatment to patients. She also said several times that patients perform better with visual feedback.

The business requirements she spoke about are a product that works and works reliably. Data gathered from the device should be repeatable and precise. She would also like the price point to be low enough that a patient can pay cash for it, no more than $200 dollars, making it affordable and accessible. This price would not include the phone or tablet required to run the application.

The functions she would like the project to encompass are a visualization of the exercises, a way to set thresholds, a hold time with a target, and a repetition counter. She would like separate training and exercise modules, with different modules for isometric and isotonic exercises. She would also like the visualization neutral enough to appeal to multiple demographics, although a large part of our users will be older and many of them under long term care.

As for security, in order to meet HIPAA requirements we can't use any identifying information. She said we can use their medical records number for our application, and can upload a pdf or histogram to their electronic medical record (EMR). Currently, there are no competitors in the CTAR exercise devices. However, there are several for similar rehabilitation exercises. These exercises include sEMG, surface electromyography, with the leading competitor being Synchrony by ACP (Accelerated Care Plus), and an exercise that strengthens the tongue using a bulb, which is led by IOPI Medical. Both of these companies have effective ways to measure rehabilitation results and somewhat interactive visualizations.

Client 2: Our second client was a graduate research assistant at the University of Nevada, Reno. She works as a clinician for the Northern Nevada Voice and Swallow Clinic. She treats patients with dysphagia and will be a user of our product when it is available, which makes her a good person to interview. We asked her the same first ten questions we asked Client 1. We interviewed her via email and the following is a summary of her answers.

Like Client 1, she expressed the need for a measurable system, to broaden their understanding and research, which will lead to improved patient outcomes. She said they currently use a rolled-up towel or an inflated ball under the chin. They have no way to quantify the resistance. They also cannot change that resistance. Her measurement of our success is if we are able to create something that she will be able to use in practice. Integrating a way to change the resistance would be helpful as well. As for business requirements, she suggests that it has to be portable and cost effective, and depending on our target audience, the cost can vary.

The primary function she would like to see is a way to measure how much pressure the patient is exerting. In addition to measurement, she is interested in knowing what level of pressure a healthy person is capable of exerting as a baseline. Some additional functionality requirements are portability, accuracy, data storage, visual representation, and sterilizability or disposable parts to prevent spreading of infections. She also commented that we need to consider the constant changes of the medical field. We should be able to easily update our software, possibly remotely, when the products are out in the field.

Client 3: Our third client is a Lecturer in Speech Pathology and Audiology at the University of Nevada, Reno. She is a clinician at the Northern Nevada Voice and Swallow Clinic, which makes her an ideal candidate to interview. We gathered her answers via email and asked her questions 1-10.

She expressed that her profession would benefit from this device because it would allow them to integrate additional objective data into their rehabilitation program. She would like the device to measure pressure and provide visual feedback as well as track duration. She would consider us successful if we can achieve these functionalities.

For business requirements, she said the most important thing to consider is cost. The product should be inexpensive so that each patient can purchase one. If we aren't able to keep the cost down, we should incorporate materials that are tolerant to a high level of disinfecting or integrate the use of disposable covers. She mentioned that there is research and data that support the use of the CTAR ball, and there is an ideal size for the ball that we should look into. She is unaware of any competitors that quantify the pressure component.

2.2 Functional Requirements

Functional Requirements are "statements of services the system should provide, how the system should react to particular inputs, and how the system should behave in particular situations. In some cases, the functional requirements may also explicitly state what the system should not do"[9]. The following functional requirements describe the behavior of the CTAR All-Star. There are several more than the ones listed, but these are the most critical and give a good sense of the design.

1. The CTAR All-Star stores a user profile.
2. The CTAR All-Star identifies users only by EMR numbers.
3. The CTAR All-Star forces the user to log in for the first time.
4. The CTAR All-Star connects via Bluetooth 4.0 using an HM-10
5. The CTAR All-Star measures the gauge pressure between the ambient air and the inside of the ball.
6. The CTAR All-Star broadcasts pressure readings at least once every 100ms.
7. The CTAR All-Star allows the user to drop/change the current bluetooth connection.
8. The CTAR All-Star allows the user to start a new session.
9. The CTAR All-Star allows the user to stop the current session.
10. The CTAR All-Star offers Isometric and Isotonic exercise routines.
11. The CTAR All-Star provides a visual representation of the pressure during an exercise.
12. The CTAR All-Star stores the 1-Rep Max value used for calculating a threshold.
13. The CTAR All-Star stores a repetition count value.
14. The CTAR All-Star allows the user to view data from previous sessions.
15. The CTAR All-Star provides a countdown timer.
16. The CTAR All-Star timer pauses and restarts if the pressure falls below the threshold.
17. The CTAR All-Star allows the user to view aggregate data.

2.3 Non-functional Requirements

Non-functional requirements are "constraints on the services or functions offered by the system. They include timing constraints, constraints on the development process, and constraints imposed by standards. Non-functional requirements often apply to the system as a whole rather than individual system features or services"[9]. The following list contains the Non-Functional requirements for the CTAR All-Star application.

1. The CTAR All-Star runs on Android and iOS platforms.
2. The CTAR All-Star communicates between the device and ball via Bluetooth 4.0.
3. The CTAR All-Star is implemented using the Xamarin framework.
4. The CTAR All-Star is written in C, C#, XAML
5. The CTAR All-Star provides Visual feedback in real time.
6. The CTAR All-Star has a user friendly interface.
7. The CTAR All-Star protects the security of each user.
8. The CTAR All-Star visualization is neutral to appeals to multiple demographics.

2.4 Use Cases

Use cases describe on a high-level how the users should interact with an application. Figure 1 shows the interaction between the CTAR All-Star and the patient or doctor. The major use cases for this application are as follows:

1. **CreateUser:** Patients and medical professionals should be able to make a patient user account from a mobile device using the patient's EMR number. Medical professionals should be able to make an account which allows them to view their patient's information.
2. **LogIn:** Patients should be able to log in to the mobile app the first time the app opens. The home screen is displayed after successful login.
3. **PairDevice:** Users should be able to connect their mobile device to the exercise ball by selecting from a list of available Bluetooth devices. The app will prompt this when a device is not connected or allow the user to change the connection through settings.
4. **CreateExercise:** Medical professionals should be able to make a patient exercise plan that the patient can work on between appointments. Plans would include specifying the

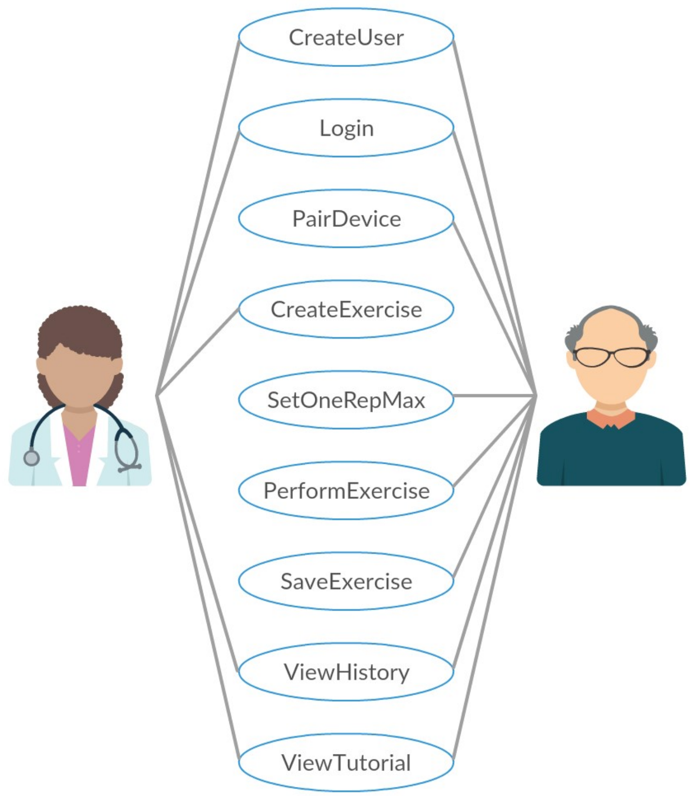

Figure 1: The Use Case Diagram shows the patient and doctor interactions with the CTAR All-Star.

exercise module and the number of times or frequency that the module should be completed during a specified time period.

5. **Set1_RepMax:** The app guides the patient through setting a 1-rep max at the beginning of each exercise session. The app prompts the user to squeeze the ball as hard as they can and stores the maximum pressure inside the ball.
6. **PerformExercise:** Patients should be able to follow an exercise routine. The program sets various pressure thresholds based on the patients 1 rep max. The program then guides the patient through the exercise routine where the patient squeezes and releases the ball while a counter counts the repetitions for a certain threshold.
7. **SaveExercise:** The patient's exercise should be saved at the end of a session so that the results can be viewed at a later date.
8. **ViewHistory:** Patients and medical professionals should be able to view historical exercise data.
9. **ViewTutorial:** The patient or medical professional should be able to view various tutorials with screenshots instructing them on how to use the various features of the app.

Each Use Case had a detailed template that described several items. An example of this detailed use case for the Create Exercise use case can be seen in Figure 2.

Use Case: CreateExercise	
Use Case ID	UC4
Brief Description	Medical professionals should be able to make a patient exercise plan that the patient can work on between appointments. Plans would include specifying the exercise module and the number of times or frequency that the module should be completed during a specified time period.
Primary Actors	Clinician/Medical Professional
Secondary Actors	Patient
Precondition(s)	1. Clinician/Medical Professional has an account 2. Patient has an account
Main Flow	1. Medical Professional selects one or more modules to be completed 2. Medical Professional selects the frequency or number of times the exercise should be completed 3. Medical Professional saves the exercise plan 4. Medical Professional assigns the exercise plan to selected patients
Postcondition(s)	1. The user is reminded about new or incomplete exercises through push notifications
Alternative Flow	None

Figure 2: Detailed Use Case for Create Exercise

2.5 Traceability Matrix

Traceability policies "define the relationships between each requirement and between the requirements and the system

Requirements	Use Cases							
	1	2	3	4	5	6	7	8
1	X	X						
2	X							X
3	X	X						
4			X					
5					X	X	X	
6						X	X	
7			X					
8					X	X	X	
9					X	X	X	
10				X		X	X	
11					X	X	X	
12					X			
13				X		X	X	
14								X
15						X	X	
16						X	X	
17								X

Figure 3: The Traceability Matrix shows the relationships between each functional requirement and use case.

design that should be recorded.[9]" The CTAR All-Star Traceability Matrix, as seen in Figure 3, is the tool used to track these relationships. Organizing these connections is essential in analyzing proposed changes and the impact they have on other parts of the system.

2.6 Database Design

The main data structures used for the CTAR All-Star are tables in a SQLite[5] local database. Each patient is only identifiable by their Electronic Medical Record (EMR) number to avoid any HIPAA violations. The EMR is used along with their password to login when the patient initially opens the application. Table 1 depicts the class tables, the primary keys, and the class attributes. The User class is role-based with their role being stored in the userType attribute. The UserName is the patient's EMR or another unique identifier for the doctors. An auto generated unique Id serves as the primary key. The DocID identifies the patient's corresponding SLP.

There is a one-to-many relationship between the User table and the Workout table. In the Workout table, there is a WorkoutID, WorkoutName, PatientEmrNumber, DoctorID, and several other attributes that allow the details of the workout to be stored, such as the number of reps, sets, and the duration of each step in the exercise. The WorkoutID specifies and uniquely identifies the workout number. The PatientEmrNumber is used to link each workout to the corresponding patient. The DoctorId corresponds to the proper medical professional. Additionally, there is a measurement table. This table is used to record the measurement data from each exercise session. The measurement table contains the Id, UserName, DocID, SessionNumber, a timestamp with various display formats, Pressure, and OneRepMax. The Id is the primary key which is auto generated and uniquely identifies measurements from the ball. UserName and DocID are linked to the User table in a one-to-many relationship. The pressure field is used to record the pressure reading as an integer. The OneRepMax is used to track the patient's current capabilities at the time the exercise was completed.

The tables are related to display the history inside the application for both the patient and the medical professionals to review. If a medical professional's UserName is linked with a patient's DocID, then they have access to that patient's session history. The Patient class is designed to assist in this linkage, specifically for allowing a doctor to create workouts for a patient before they have created their own account. By linking the tables, the medical professional is able to analyze a patient's data and determine if they are making positive progress. If the patient is not making progress, a workout adjustment may be needed.

The remaining tables, GraphMeasurement, NativeDevice, and Tutorial, are used for various other specific features in the application. The GraphMeasurement stores the data that will be displayed in the graph on the exercise screen. The NativeDevice stores the available bluetooth devices used when connecting to the hardware. Finally, Tutorial contains the individual instruction guides for the Tutorial's page.

3 Hardware Design

A major goal of the hardware was to make it affordable. A cost-effective device will enable patients to purchase their own personal device and perform exercises from within their home. Figure 4 shows the initial prototype and the hardware design can be seen in Figure 5. The patient uses the device by squeezing the pneumatic ball between the chin and upper chest. A pressure transducer outputs an analog voltage to the Arduino before the analog reading is converted to digital and transmitted over Bluetooth 4.0.

There are several articles which were consulted in Bluetooth software design. [2] explores the needs of wireless medical sensors. [4] gives an introductory tutorial on how to configure an arduino to communicate with an iOS device via Bluetooth. It lists the hardware needed, a great deal of information relating to code on the arduino side, details on wiring, and some information on development of the mobile app for iOS.

The hardware components used in the prototype include the following:

- **Pneumatic ball:** This ball is appropriately sized to fit between an adults chin and upper chest. It has a valve for an inflation needle which makes probing the internal pressure simple.
- **Inflation needle and plumbing:** The inflation needle and plumbing allow the pressure sensor to read the pressure inside the ball.
- **Pressure Transducer:** The pressure transducer reports the gauge pressure inside of the ball as an analog voltage value between 0 and 4.5 volts. The pressure transducer used in the prototype has a range of 0 to 7.25 psi.
- **Arduino Uno:** The Arduino Uno[1] reads the analog pressure from the pressure transducer every 50 ms.

Table 1: Data Structures

Class	Key	Attributes
User	Id	Username, Password, userType, isLoggedIn, OneRepMax, Session, DocID
GraphMeasurement	Id	Time, Pressure
Measurement	Id	UserName, DocID, SessionNumber, TimeStamp, DisplayTime, DisplayDate, Pressure, OneRepMax
NativeDevice	Id	Name
Patient	PatientId	PatientEmrNumber, DoctorName
Tutorial	Id	Topic, Description, ImageName, isVisible, URL
Workout	WorkoutId	WorkoutName, PatientEmrNumber, DoctorID, NumReps, NumSets, ThresholdPercentage, HoldDuration, RestDuration, Type

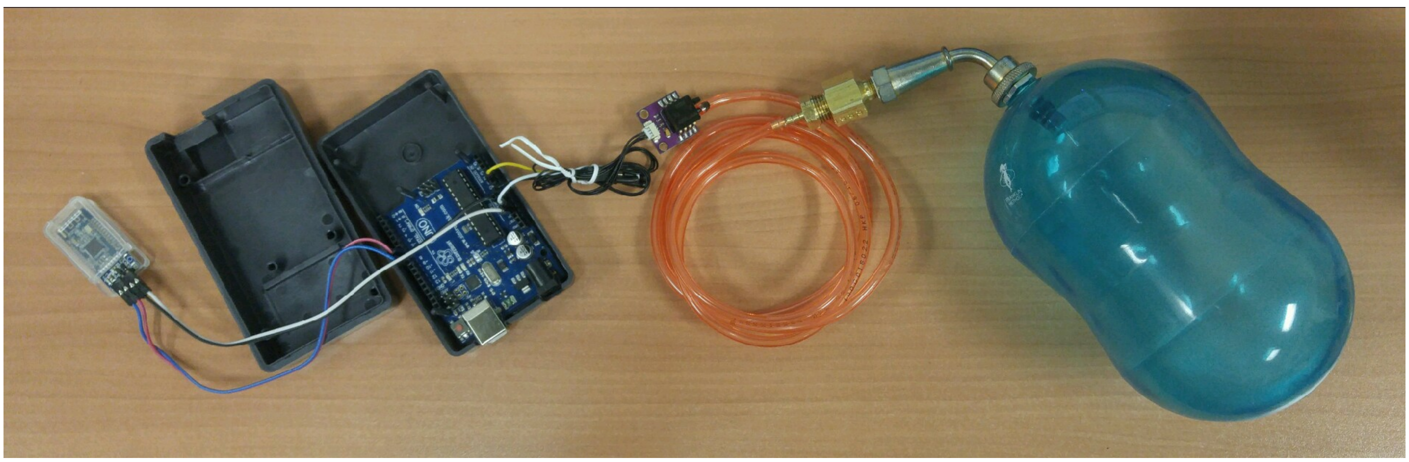

Figure 4: The initial prototype of the CTAR All-Star was powered by a PC through a USB cable.

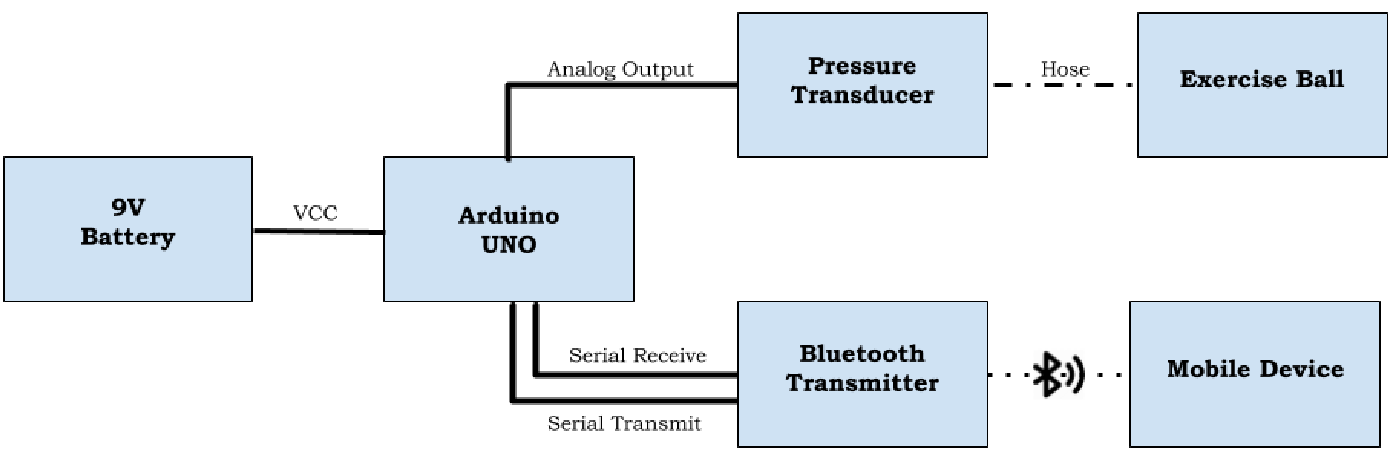

Figure 5: The Hardware Diagram defines how the components connect and interact.

Figure 6: A patient learns how to use the CTAR All-Star.

The analog value is converted to digital and then sent to the Bluetooth transmitter via universal asynchronous receiver/transmitter (UART).

- **Bluetooth Transmitter:** The Bluetooth transmitter receives readings via UART and then transmits them to the mobile device.

The pressure inside the ball is sampled continuously and each reading is transmitted over Bluetooth 4.0 to the mobile app where the pressure is recorded and displayed for the user. Figure 6 shows the device in action.

4 Software Implementation

The implementation of the CTAR All-Star was built around various classes in C#. These classes can be seen in the Class Diagram in Figure 7. The application was designed with a user friendly interface. It allows doctors to create or modify exercise plans (Figure 8) while patients can complete their prescribed exercises with visual feedback (Figure 9). The exercise history is stored for monitoring improvements and will additionally be used for future research purposes (Figure 10). It is a cross platform application, working on both Android and iOS tablets and mobile devices (Figure 11).

The mobile application is built using the Xamarin.Forms [6] framework in the Microsoft Visual Studio IDE. All of the code is written using a combination of C# and XAML, the Plugin.BLE package is utilized for management of Bluetooth 4.0 connections, the Syncfusion[10] plugin is utilized for plotting the ball pressure, and the mobile app is built for use on both iOS and Android devices.

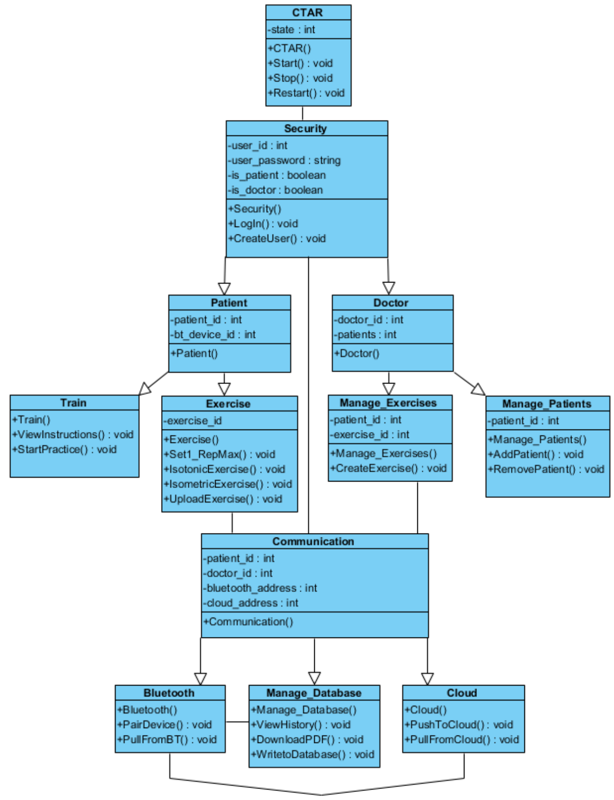

Figure 7: Class Diagram for CTAR All-Star

5 Conclusions and Future Work

5.1 Conclusions

The CTAR All-Star allows medical professionals and patients with dysphagia to track CTAR workouts over time. This application is significant because with technology incorporated into the ball, doctors are able to accurately track patient progress. The real time graph is interactive, gives instant feedback, and guides patients through their workouts. This first-of-it's-kind cross-platform application is necessary to gauge the success of both the CTAR exercise and the rehabilitation progress of the patient. With future work such as an online server and embedding the hardware inside of the ball, the CTAR All-Star can become a marketable product.

5.2 Future Work

This software can be modified to be used with different types of devices such as expiratory/inspiratory muscle trainers, IOPI®, or SEMG. Although aimed at medical rehabilitation

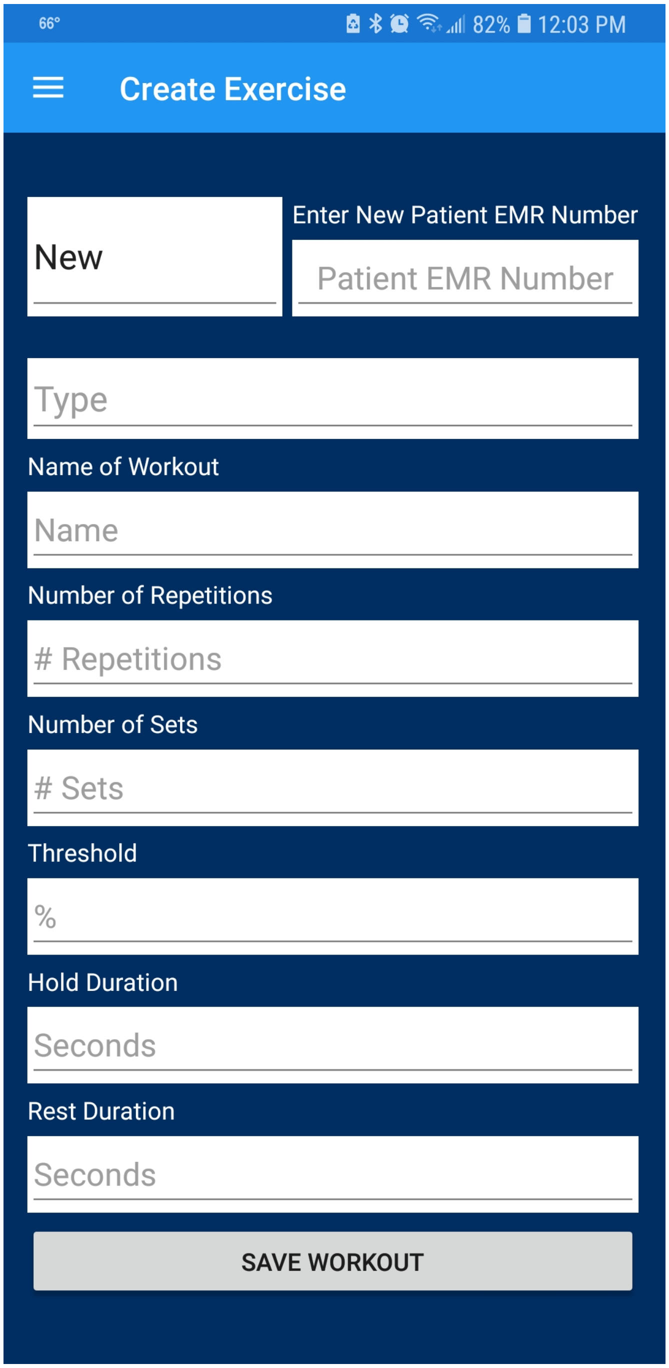

Figure 8: Doctors can create an exercise.

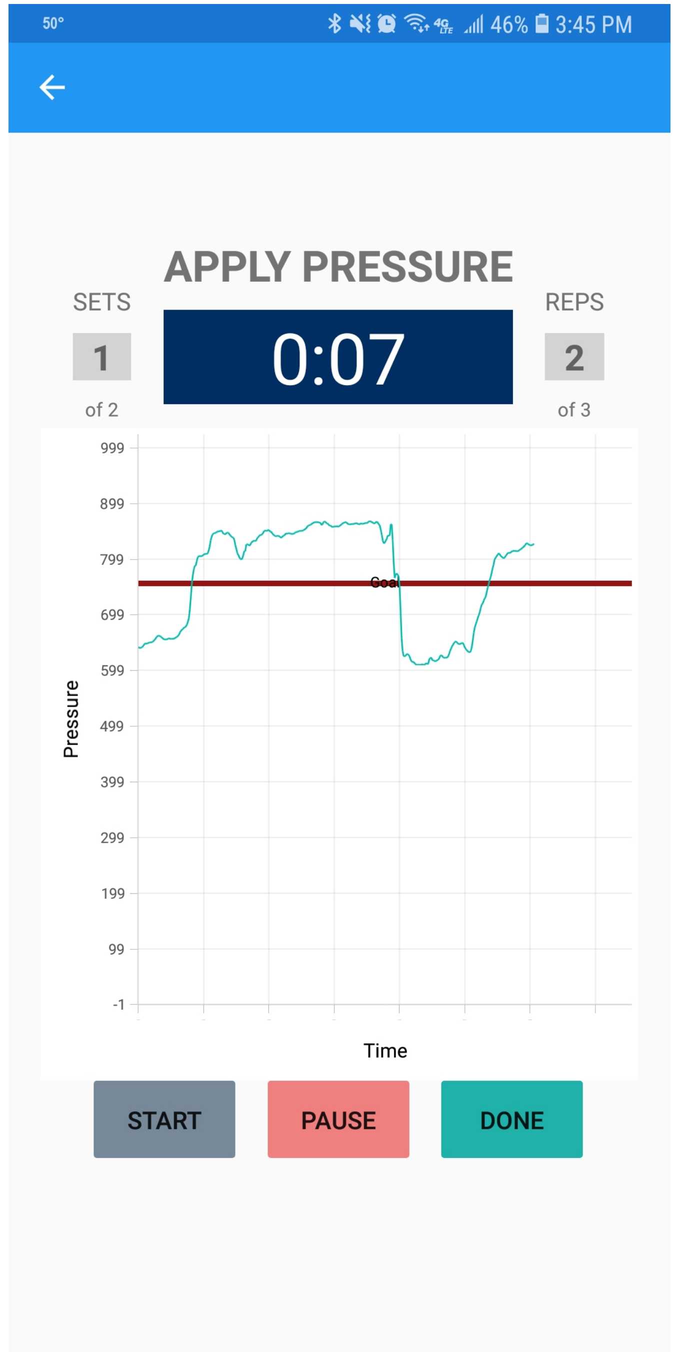

Figure 9: Patients are led through the exercise.

exercises, it may also be useful in other fields. This specific project could also integrate a game to make rehabilitation exercises more fun and interactive. Creating a mobile game, or incorporating a game already created for dysphagia rehabilitation, such as Avaler's Adventure, to work inside the CTAR mobile application would be a great option [7]. Additionally, a server hosted database back end with an API would make communication across multiple devices possible. Finally, refining the design of the hardware so that the electronics can be embedded inside the ball would greatly improve the reliability and ease of use of the device.

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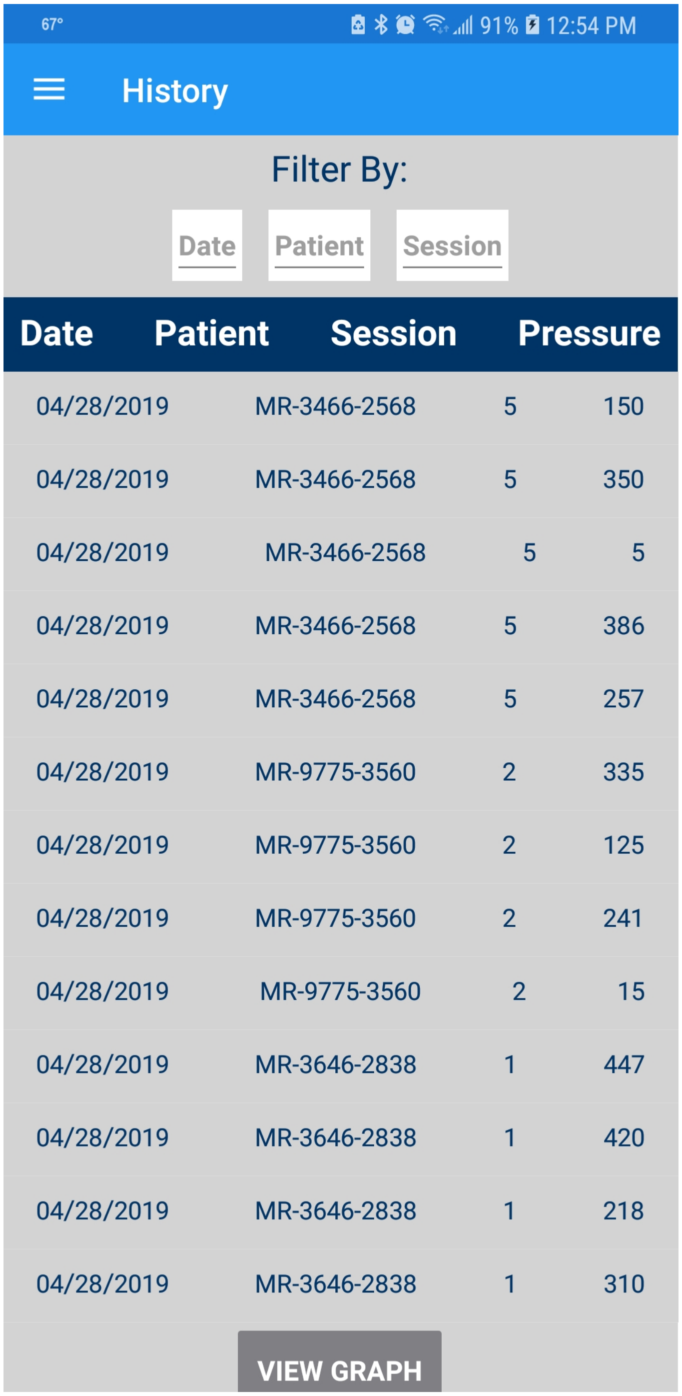

Figure 10: History is stored for future research.

necessarily reflect the views of the National Science Foundation.

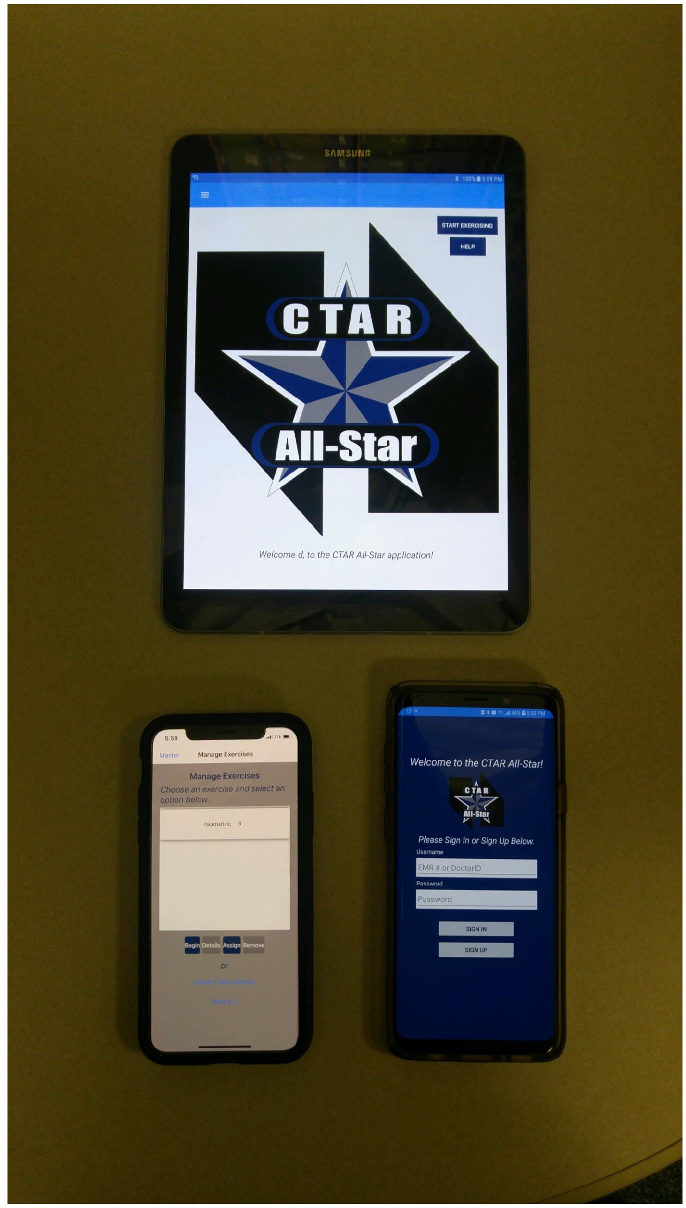

Figure 11: The CTAR All-Star can be run on multiple devices and operating systems including Android and Apple's iOS.

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