HAPTICDIVE: AN INTUITIVE WARNING SYSTEM FOR UNDERWATER USERS

An Undergraduate Research Scholars Thesis

by

SNEHA SANTANI and LESLIE ESCALANTE-TREVINO

Submitted to the Undergraduate Research Scholars program at
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by Research Advisor: Dr. Tracy Hammond

May 2018

Major: Computer Science and Engineering

TABLE OF CONTENTS

Page

ABSTRACT

HapticDive: An Intuitive Warning System for Underwater Users

Sneha Santani and Leslie Escalante-Trevino
Department of Computer Science and Engineering
Texas A&M University

Research Advisor: Dr. Tracy Hammond
Department of Computer Science and Engineering
Texas A&M University

All divers—regardless of skill or activity—are constantly at risk of decompression sickness; mild symptoms can often go ignored, and can also be deadly if left untreated. Currently, divers receive training and carry a dive computer or a combination of a depth gauge and a depth watch for checking to avoid such situations. However, this equipment does not warn a user if they are in danger of decompression sickness, since users have to keep track of their ascension rates and since shallow-water divers often carry minimal equipment. This work proposes an application called HapticDive to keep track of a user's depth in relation to the time passed underwater. The application paces their ascent to the surface by providing "stop" signals to users as an audio-visual combination, so that users avoid experiencing "the bends" (i.e., decompression sickness symptoms). HapticDive aims to provide the foundation for a cost-effective application that warns divers—especially surface supported divers, free divers, and general shallow-water divers—when they are at risk of decompression sickness, so they may avoid symptoms.

ACKNOWLEDGMENTS

We would like to thank our faculty advisor Dr. Tracy Hammond of the Department of Computer Science and Engineering, and our graduate student mentor Larry Powell of the Department of Computer Science and Engineering for their guidance and support throughout the course of this research and thesis creation.

We would also like to thank teaching assistant Josh Cherian of the Department of Electrical and Computer Engineering and teaching assistant Paul Taele of the Department of Computer Science and Engineering for their assistance throughout the semesters that we took the AggiE_Challenge course.

IRB compliance for our user studies is numbered IRB2017-0157D. We were included in this existing IRB and approved on February 6th, 2018 with reference number 071315. For our studies, we submitted an amendment to conduct diving user studies and retroactively added previously missed details on March 19th, 2018.

A special thanks to scuba diving instructor Mr. James Woosley of the Texas A&M Recreational Center for his help in coordinating preliminary and haptic user studies. All other work conducted for this thesis was independently completed by undergraduate students Sneha Santani and Leslie Escalante.

NOMENCLATURE

AGE	Arterial Gas Embolism
ATM	Atmosphere (unit of pressure)
BCD	Buoyancy Control Device
DCI	Decompression Illness
DCS	Decompression Sickness
ECG	Electrocardiograph
IRB	Institutional Review Board
ISO	International Organization for Standardization
mm	Millimeter
ms	Millisecond
SPG	Submersible Pressure Gauge
SCUBA	Self Contained Underwater Breathing Apparatus
USD	United States Dollar

1. INTRODUCTION

Certification is a vital part of scuba diving; divers must learn to maneuver underwater, build a diving plan, signal to fellow divers, and review the health risks associated with diving and pushing limits such as decompression illness. Decompression illness (DCI), encompasses decompression sickness (DCS), and arterial gas embolism (AGE) both of which are illnesses caused by a sudden change in the ambient pressure a body experiences [1, 2, 3]. Although scuba divers must undergo training to get their certification, other types of diving are less stringent, namely those restricted to relatively shallow waters. Since these divers remain in shallower depths, the amount of equipment and training time is reduced [4, 5]. However, all divers are vulnerable to a range DCS symptoms if they inappropriately handle their underwater descent, ascent, or duration [2, 3].

1.1 Diving

Drift diving, night diving, rescue diving, and open water diving represent a handful of the many types of diving activities that exist. Before going underwater, scuba divers have to receive training and acquire certification, which is currently divided into three general levels as agreed by the European Standard and International Standard (ISO): supervised diver, autonomous diver, and dive leader. Similarly, there are free divers, who depend on their trained lung capacity during dives; and surface supported divers, who receive air via a type of umbilical cord to the surface; both types of divers train with minimal equipment to dive successfully [5, 6]. Although some diving types follow specific certification levels, the first of the general division is a supervised diver (level one), described as a diver with sufficient knowledge to dive in open waters—to a maximum depth of 12 meters—while supervised by dive leader. An autonomous diver (level two) can reach maximum depths of 20 meters, unsupervised, as long as conditions are equal or better than when training. Lastly, a dive leader (level three) can plan and conduct dives—including any specialized recreational activities—or emergency procedures that they have trained for [7, 8, 9]. The type of equipment these different types of divers need also varies, although deeper dives tend to need more complex equipment. Free diving, as an example, has no mandatory equipment, but most divers tend to wear masks, fins, and some sort of wetsuit or swimwear [6]. Surface supplied air recreation diving requires a basic breathing hose connected to a scuba regulator at the surface, which serves as an air source, along with the mask, fins, and wetsuit [5]. Typical scuba diving equipment includes a mask, snorkel, fins, wetsuit, buoyancy control device (BCD), weight system, regulator, submersible pressure gauge (SPG) and dive watch or dive computer, among other choice accessories [10]. The SPG and dive watch are used to track descent and ascent rates manually, while a dive computer calculates and displays these, and can even provide time of day, warning signals, and other measures [11].

1.2 Decompression Sickness

Dive computers perform a basic but vital function: automatically calculating a safe rate of ascent for a diver that can save them from experiencing "the bends" (i.e., decompression sickness). DCS occurs over time and with pressure, which is a direct result of inadequate decompression of the body after exposure to pressures higher than normal. Essentially, as divers descend, they experience an increase in pressure over their entire body. The lungs especially become pressurized, forcing the nitrogen inside them to travel from the high pressure system (i.e., the lungs) to the low pressure system that is the blood stream, which results in nitrogen absorption by the body tissues. This nitrogen migration, or saturation, happens as the body is exposed to increased amounts of pressure, so a diver who remains at certain depths remains unaffected. A hurried ascension denies the body time to stabilize and reduce nitrogen saturation in the body tissues, which creates bubbles in the tissues and blood stream and triggers DCS symptoms [2, 12, 13]. Depending on the situation and the sensitivity of the diver, these symptoms can manifest as mild symptoms, severe symptoms, injuries which appear fully with time, or even death [13]. To mitigate sensitivities and prevent experiencing the symptoms and signs of decompression sickness, many divers equip themselves with knowledge and hardware. Divers know to pace their descent—around every 3 meters, divers should equalize—and to follow their diving plan and safety measures [2, 14]. Scuba divers require equipment, which includes the dive computer or manual equivalent. Free divers and surface-supplied air divers are free to also use either option.

1.3 Motivation

This work aims to use the various sensors included in modern smartphones—particularly the barometer—to create an application that measures depth, collects data when diving underwater, and calculates safe ascension rates for the user. For this research, we will focus on the following subgroup of divers: free divers, surface supplied air recreational divers, and beginning scuba divers who might be looking into reducing equipment costs. These divers all tend to swim in shallower depths that range from a few meters to a typical maximum of 30 meters, which is a suitable range for most waterproof or water-resistant smartphones in combination with waterproof pouches [2, 15].

Dive computers are not an inexpensive purchase: most begin at USD$200 and generally top off at USD$1,300. The more expensive devices will often come with a variety of extra features that are useful during dives. Some devices offer features necessary to certain types of diving, such as those using mixed gases [16]. In recent years, smartphones have become ubiquitous and come equipped with a varied selection of sensors, which make smartphones with a barometer sensor more prevalent [17, 18, 19]. Our application can provide a cost-effective alternative for displaying warnings to users for avoiding decompression sickness, as well as displaying a variety of other readings and useful information or at least serve as a foundation for such alternatives.

2. RELATED WORK

Prior to starting the project, existing commercial products and similar research work were investigated. We discovered that warning systems that informed users against rapid rates of ascent or descent and also notified them of risk of decompression sickness were lacking. As a result, we explored the different types of swimming and diving wearables that focused on those using smartphone sensors, especially the barometer sensor in an underwater environment on whether it collected data, signaled, or only assisted on other functionality. Afterwards, we explored different types of feedback provided by smartphones and their contexts. Finally, we investigated the treatment methods currently available for decompression sickness, including its symptoms.

2.1 Underwater Wearables

A restricted subset of wearable technology is suitable for underwater use, as the requirements for waterproofing a wearable narrow down the field. Since the wearable or sensing system will be used around water, waterproofing must be addressed in the early stages of investigation. However, we also briefly considered research efforts that used the smartphone's barometer sensor in dry conditions. An improved floor localization algorithm for 3D spaces, for example, used the barometer sensor to successfully predict the current floor a user stands in, as well as floor changes, by first establishing a reference point during the learning period and then filtered the data to gather floor transition information with 99% accuracy [20]. This research demonstrated that a smartphone's barometer sensor data was sensitive enough to be used for tracking changes in elevation experienced by the device as it was handled by a user.

2.1.1 Swimming Wearables

An anti-drowning flotation device was keyed to the sensor information relayed by the accelerometer and barometer sensors in a smartphone to detect potentially dangerous drowning events. The smartphone was placed under a swimming cap, and would trigger an airbag if it sensed the swimmer had remained motionless or under the water's surface for an extended period of time. The device sensed increased pressure fluctuations to know if a swimmer was underwater for an extended period of time, since the device was underwater so too would the swimmer's head. Once the signal was sent, the airbag would then fill and float the endangered swimmer to the surface so that the swimmer could be visible and receive aid [21]. This research demonstrated that a smartphone could be used underwater to gather shallow depth data, signal another device, and act as a general warning system.

2.1.2 Diving Wearables

A common diving wearable is the dive computer, used by scuba divers to automatically track current depth and elapsed time spent underwater. The dive computer can even calculate the user's ascent rate, which can then be followed for their safe ascent. Unfortunately, current dive computers have no standardization for feedback regarding a safe ascent beyond displaying the rate. Generally, device designers expect users to be trained and be sufficiently aware in routinely checking the device's display. However, more advanced models offer programmable functionalities, audible warnings for various circumstances—including warning for a hasty ascent—and can even give audible vibrating alarms [22, 23, 24]. Dive computers are typically worn on the wrist and can display various important information, depending on the model. However, the more features a dive computer has, the more expensive it is. Price ranges from approximately USD$200 to more than USD$1,300. The price tag may not be insubstantial, especially for recreational divers or amateur divers who do not dive very often. Insights from the dive computer's design allowed us to develop features that we would like to provide in our warning system [25, 26].

While the dive computer aims to keep the diver safe by providing depth diving information, other diving wearables aim to monitor health or train during dives. One such wearable monitors a diver's ECG signal in real-time and compares with that diver's known input health conditions to create an emergency alert system when scuba diving [27]. Similarly, the Diving Coach Monitor streams inertial motion data to direct a user with vibrotactile feedback through a diving training session [28].

Other researchers focused on enhancing the dive experience provided by commercial dive computers by creating a simplified version that still maintained necessary features to keep the diver safe. The minimalistic wearable device attached to the wrist and provided visual feedback—from unlit, blue, to increasing shades of red—to depict danger, and intensified this with vibrations and audio cues as the danger increased [29]. Our approach provides similar feedback in dangerous situations by displaying the color red for danger in the application background, but our focus is on the user's reaction to the vibrational cues.

2.2 Smartphone Feedback

Most dive computers provide feedback visually via their displays, and some give non-visual feedback cues such as through audible or haptic feedback. However, visual feedback can be ignored by the diver [22, 23, 24]. Haptics has been shown to be a discernible [30, 31] and effective mode of communication for paratroopers [32, 33], motorcylists [34, 35], assistive technology [36], and physical therapy [37]. Increasingly, smartphone vibrations have been used as haptic feedback to guide users through tasks. Research has proven that vibrations were successful 96% of the time in nonvisual wayfinding, and were successful in guiding persons with visual impairment through challenging or unfamiliar routes [38, 39].

2.3 Decompression Sickness Treatments

As previously mentioned, decompression sickness is caused by an increase in environmental pressure followed by a rapid decrease, such that the body not allowed time to stabilize in between the changes. Research has stated that repeated daily diving can lead to acclimatization, reducing the amount of post-dive bubbles formed in the bloodstream from four days to by nearly half [40]. Beyond preventive measures, there are several methods for the treatment of DCS. A diver can slow their ascension in a series of timed stages, thereby giving their body the time to stabilize. Once the diver is above the surface, they can receive treatment in a recompression chamber. These chambers re-pressurize an individual to a certain degree as they breathe in a gas mixture of mostly oxygen to accelerate stabilization [1]. However, treatment success depends on an appropriate diagnosis, as decompression sickness is classified into two categories: Type I, pain-only DCS; and Type 2, DCS with symptoms beyond pain. Recent research uses a neuroimaging technique to detect lesions in the brain or spinal cord and damage to the central nervous system resulting from the rapid development of bubbles in the bloodstream and tissues in an individual experiencing DCS [41].

3. MATERIALS

The primary equipment list utilized of our research project consisted of the following: a water-resistant smartphone device and several types of waterproof pouches.

3.1 Smartphone Device

One of the pieces of equipment used in this project was a smartphone device, specifically the Huawei Nexus 6P [42]. This smartphone was chosen for the following two features: water resistance and a built-in barometer sensor. The water resistance ensured the phone survived minimal water exposure if the waterproof pouch allowed some water in. The barometer sensor was a necessity for our research, so we used this version of the phone, as opposed to its more inexpensive Lite version. In addition, this device was chosen because of its price point, since the potential for accidental water damage was of high risk. We also wanted to ensure that the device could be replaced without sacrificing much expense and it proves to be a cost-effective solution [43].

3.2 Waterproof Pouches

A combination pack of touch-sensitive waterproof pouches were chosen for their ease of use and modification potential. Ideally, we wanted to place the smartphone in an unobtrusive place, so modification would be necessary to secure the phone and pouch to the user's forearm. Figure 3.1 demonstrates how the device is attached to the forearm for our studies.

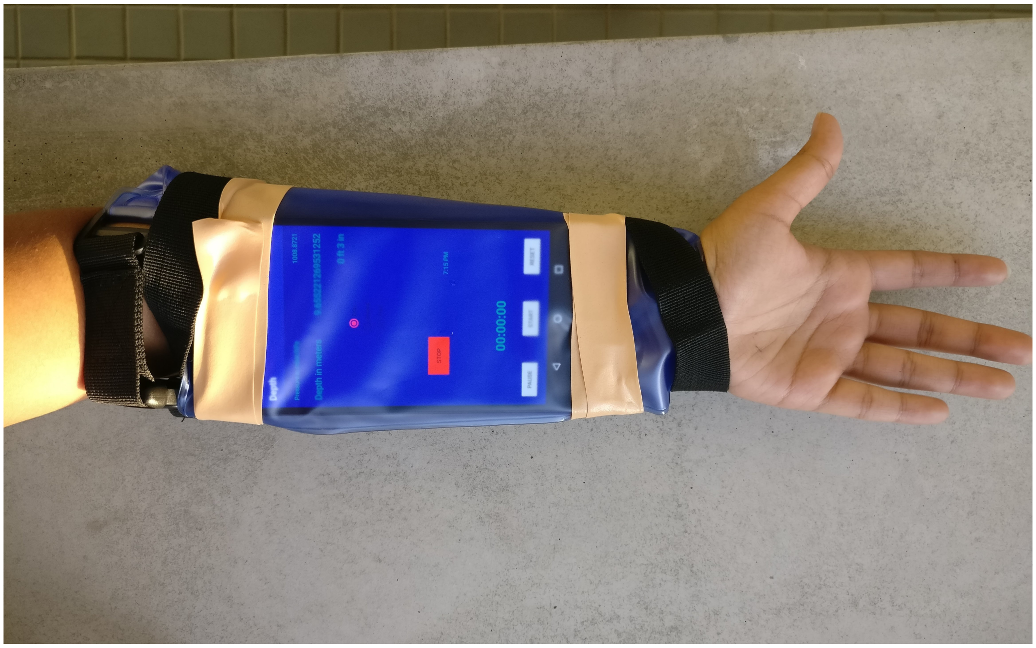

Figure 3.1: Smartphone inside a waterproof pouch attached to a user for assessing its wearable feasibility and its durability during testing.

4. METHODOLOGY

It is critical for our application to have a user-centered design to prevent a disconnect with the user. Ideally, a user should first become comfortable with the application and attempt a few practice attempts above water or in non-threatening underwater depths. Since not all users may have this preparation time, we want to ensure the application functions adequately and intuitively in case a user tries to use the application for the first time while underwater. A diver has a variety of things to keep track of both above water and under water, especially during a dive. We want to ensure that our application aids the user by providing an external device that handles some of the computationally-heavy aspects of a dive, thereby reducing their user's mental load and hopefully improving their focus.

4.1 Phase I: Preliminary User Study

For the initial user study, our primary motive was to refine the features that our application would provide, since we the investigators lacked such diving experience. To do this, we gathered information and suggestions from potential users who had experience as rescue divers in-training. We conducted a semi-structured interview with a focus group that presented our idea and vision, and then questioned the group on the current situation of diving and their thoughts on the relevance of the application. We asked several questions to an undergraduate course titled "Advanced Scuba Diving," which was taught at the Texas A&M University's Student Recreation Center. The interview itself was conducted during the first ten minutes of class time with the permission of the course's instructor. Although we were not able to conduct any personal one-on-one interviews we gathered some useful information.

4.1.1 Demographics

The users we interviewed for the preliminary user studies were aged between 19 to 23 years with diving experience of 1 to 3 years because they were working to become rescue divers. This is why a lot of the features they suggested were related to safety and ease for rescuing.

4.1.2 User Study Questions

To remain true to our user-centered design, we gathered a list of useful features for the application by conducting a preliminary user study. The questions asked were:

1. What is the age range of the participants?
2. What is the most inconvenient part of calculating depth during the participant's dive?
3. What is the diving experience range of the participants?
4. What is the most convenient position for a diver to carry a cellphone or similar device during their dive?
5. What information other than depth and a decompression sickness warning would a diver want to be given by the application?
6. How much would the participant be interested in an application version of a dive computer?
7. What are some things divers mentally keep track of while diving?

These questions helped us gauge interest and gather the user's perspective and expectations regarding the behavior of our application, especially considering general needs. Some of the features the users were looking for were:

1. The application should display the current time as it is difficult to sense the time-of-day underwater.

2. A stopwatch that can be started when the user starts their dive and can be used to time the entire time. After the stopwatch is stopped, the application should display total elapsed time.

3. A dive table reference picture [44].

4. Display current GPS coordinates.

5. Display a functioning compass that points to north.

6. The application should have the ability to receive incremental weather alerts or other general weather forecast. This data could be collected before the descent and not underwater. This feature would be useful to warn the user in case of a storm that would affect the dive and be dangerous.

7. A feature where the diver can build a dive profile. This profile would include critical information like:

    (a) Before the dive the user inputs diving profile, including the dive plan. This includes "checkpoints" or "check markers" which help indicate the rate of descent, remind users about total elapsed time, and any other conditions the user may want to achieve.

    (b) During the dive the inputted progress points are validated.

    (c) After the dive the user can check and see how they fared compared to what they expected to do.

    (d) Inputting general diving profile information would help a rescue diver gather important information about the dive and diver's condition if a diver experiences anything that leads to an emergency and are unable to communicate or unconscious.

8. Another suggested feature was the ability to send and receive a general emergency signal in times of danger. The users also suggested this emergency signal could be sent to the closest emergency center in addition to the closest diver in the same diving team.

9. The users also suggested a feature where the application displayed the GPS position of where the user would have started their descent underwater and where the user resurfaces above water.

10. The last feature that was suggested was enabling communication between the members of the diving party. This could include:

    (a) Some preset general responses like "Follow me," "Meet up," or "Start ascent" that could be readily available as push buttons.

    (b) The ability to have microphones inside the oxygen mask so that people can communicate underwater.

After taking into consideration all the suggested features and what the users would like to see, we came up with a list of features that we would be able to accomplish and would be relevant for our research. The features we plan to incorporate in the android application are:

1. Display time with a digital clock.

2. Stop watch that has the ability to pause and reset. This would be used to time the dive or make any necessary resets if needed.

3. Display the current depth in feet and inches.

4. Display the rate of descent of the user. This would be done by calculating the rate of change of depth underwater.

5. Have warning signals in case the user has rapid rate of descent because this puts them in danger of decompression sickness. If time permits we plan to also incorporate weather alerts and emergency signal functionality. However, these two features are not our primary goal as of now.

4.2 Phase II: DCS Recognition Study

For the second phase of the research project, we developed and manually tested the recognition algorithm. The recognition algorithm works by making the decisions shown in Figure 4.1 when executed:

4.2.1 Calculating Depth

To correctly compute the smartphone's depth when submerged underwater, we used the barometer sensor data. That is, we converted the current pressure the smartphone was experiencing into depth. The deeper the smartphone was underwater, the more pressure it experienced. We used the following formula to convert the pressure sensed to depth submerged:

$$P = R \cdot G \cdot H$$

- P is pressure on an object that is submerged in a fluid
- R (rho) is the density of the fluid. For this experiment, we set the fluid density to $1024kg/m^3$, as we are mostly testing in saltwater environments of chlorine filled

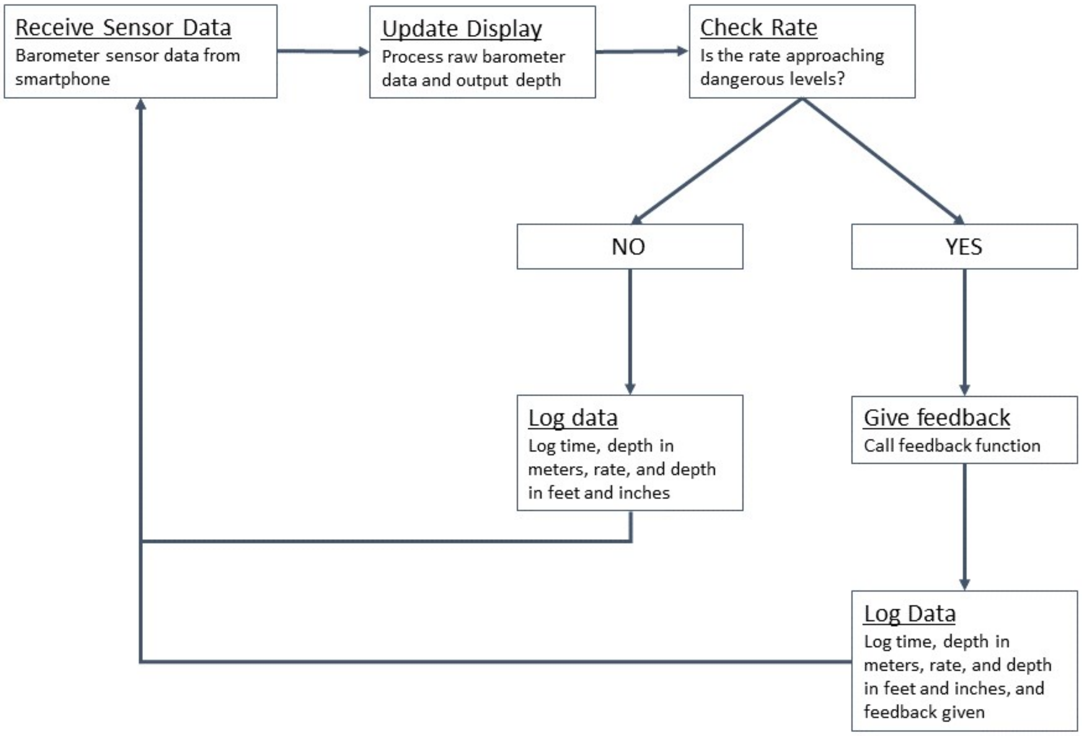

Figure 4.1: Decision tree for the HapticDive application, which focused on the logic for sensor change response.

pools [45].

- H is the height of the fluid above the object (depth).
- G is the acceleration of gravity [46]. For research purposes, it was set to $9.8m/s^2$.

With this in place, we carried out our first set of testing to verify the smartphone could accurately measure the depth in shallow waters. This was done by first putting the smartphone in a waterproof bag, as shown in Figure 4.2, and then tying it to a long string. The phone was then dipped into water parallel with a ruler to check the true depth and the depth calculated by the smartphone. Various depths were tested in a regular swimming pool, ranging from 3.5 feet in depth to 4 feet in depth, and later in a diving pool to 17 feet in depth.

After verifying the depth recognition provided accurate results, discussed in the results section, we proceeded with the next stage of the algorithm development. We then added some of the features that were recommended by the preliminary study users. We integrated a stop watch, clock, and dive table button into the application.

4.2.2 Calculating Rate of Change in Depth

The last step in developing the recognition algorithm was to calculate the rate of change of depth. This calculation would then enable us to perceive if the user is at risk of facing any decompression sickness symptoms. The safe rate of ascent is no more than 30 feet (9 meters) per minute, a standard adopted by the US Navy [40, 47].

In order to calculate the rate of change of depth, we tracked the change of depth as compared to the last sensor changed by first tracking a previous depth and time, and then calculating the difference:

$$R = \frac{D_f - D_i}{T_f - T_i}$$

.

Figure 4.2: Smartphone inside the small waterproof pouch used for when testing the recognition algorithm.

- R is the rate of ascent/descent, underwater.
- D_f is the current (final) depth.
- D_i is the initial depth or the depth previously sensed.
- T_f is the current time that corresponds of the current depth.
- T_i is the initial time that corresponds with the previous depth sensor change.

The application was then tested to see if it could satisfactorily trigger various feedback with dangerous ascent or descent rates. Similarly to before, the string test method was used to submerge the device and mimic quick ascension rates. Data received was output to a log file for later verification, which we discuss in the next chapter.

According to Zanchi et al., a safe ascension rate is generalized to be 9 meters per minute [40]. We simplified this threshold rate to millimeters and milliseconds, as those were the units of the application used.

We therefore establish the safe rate of ascent to be below $0.15mm/ms$. Since our device would be muffled by the waterproof pouch and would be tested in shallower depths over short periods of time, we decided to amplify the sensitivity of this threshold. After testing rate sensing at 100% amplification (rate of $0.0015mm/ms$) and rate sensing at 1000% (rate of $0.00015mm/ms$), we found the sensitivity amplification at 100% to be too insensitive, and at 1000% to be overly sensitive as it would constantly provide feedback. A rate of three-quarters between 100% and 1000% proved to be most stable, giving a rate of $0.00825mm/ms$. Figure 5.2 in Results demonstrates the stability of rate $0.00825mm/ms$.

4.3 Phase III: Haptic Feedback Study

For the last phase of the research project, we conducted a usability test to find out which haptic feedback system is the most intuitive for users underwater. We conducted the last user test by asking users from differing diving backgrounds to react to various haptic and visual feedback. We tested the following feedback to find the most intuitive:

- Short, continuous vibrations (set of three).
- One long continuous vibration.
- Vibrations of increasing length (set of three).

Each warning was accompanied by a flashing background animation, where the screen color changes from white to red. We chose the color white, because it is the brightest color and the easiest one seen underwater; and the color red, because it is universally acknowledged as the color for danger. Combining visual and haptic feedback would ensure that the user receives an adequate warning and would potentially slow down or stop ascending, thereby reducing their risk of experiencing decompression sickness symptoms.

The process of carrying out the usability test involved the following:

1. Gear up participant, instruct them to swim 50 meters in a lap pool: slowly for the first 25 meters, then quicker for the second half, and react however they feel, then exit the pool.
2. Start HapticDive application, testing a single feedback.
3. Observe participant as they swim and react to device, note start times and any notes.
4. When participants reach the other end of lap pool, have them exit pool and ask post-feedback questions.
5. Repeat Step 2, 3, and 4 for other two feedbacks.
6. Ask follow-up questions to correlate observed behaviors with diver's instinctual reactions, focusing on what feedback worked best to warn the users.

The usability test results were used to determine the most intuitive haptic feedback that can be used to warn users underwater. There were three sets of questions for the participants: the pre-study questionnaire, the post-feedback questionnaire, and the post-study questionnaire. The questioned are detailed in the following.

4.3.1 Pre-Study Questionnaire

1. What is your age?
2. How many years have you been diving?
3. How many years have you been swimming?
4. What type of diving do you usually do?
5. Do you have any diving certifications? If so, what certification(s) do you have?
6. Are you familiar with decompression sickness, its causes, and symptoms?

4.3.2 Post-Feedback Questionnaire

1. Could you briefly describe the feedback you experienced?
2. How noticeable was the feedback? (On a scale of 0 to 5, where 0 is "I didn't notice" and 5 is "unavoidable.")
3. How many times did you feel the feedback?
4. After experiencing the feedback, (if you did) what was your intuitive reaction?

4.3.3 Post-Study Questionnaire

1. Out of all three feedbacks, which is the most memorable?
2. Out of all three feedbacks, which is the least memorable?

3. What would you say each feedback was meant to signal? What was its purpose?
4. Out of all three feedbacks, was there one which signaled you to stop swimming?
5. Out of all three feedbacks, was there one which signaled you to slow down?
6. Out of all three feedbacks, was there one which signaled you to do nothing?

In the section five, we discuss the answers recorded and compare it to data received to reach an intuitive feedback combination that successfully signals “stop” to the user.

5. RESULTS

Throughout testing, users became familiar with the Haptic Dive application interface. For ease of testing and feedback anonymity, the specific types of feedback were labeled arbitrarily. To begin collecting data, a user must pick a feedback type then hit the Start button. Figure 5.1 shows the startup process in action, as well as the stopwatch:

Pressure in mbar/hPa 1000.95825
Depth in meters 9.579483251953127
0 ft 0 in
○ First
● Second
○ Third
7:41 PM
0:10:743

Pressure in mbar/hPa 1000.9782
Depth in meters 9.579674179687501
0 ft 0 in
○ First
● Second
○ Third
7:41 PM
0:35:895

Figure 5.1: Screenshots of the HapticDive application, on the left: the second feedback is picked, but data collection has not started. On the right: data collection in process.

We decided to display the raw pressure measurement, depth in meters, and depth in feet and inches for testing purposes. The stopwatch was added to help a diver time their elapsed time when testing, and similarly, current time was displayed.

Next, we discuss the results of the various tests performed. We begin by describing the string test done to prove recognition of dangerously quick ascension rates. Then, we discuss the haptic user studies: first a single user's rate and depth data, then all the users combined.

5.1 Phase II: DCS Recognition Study

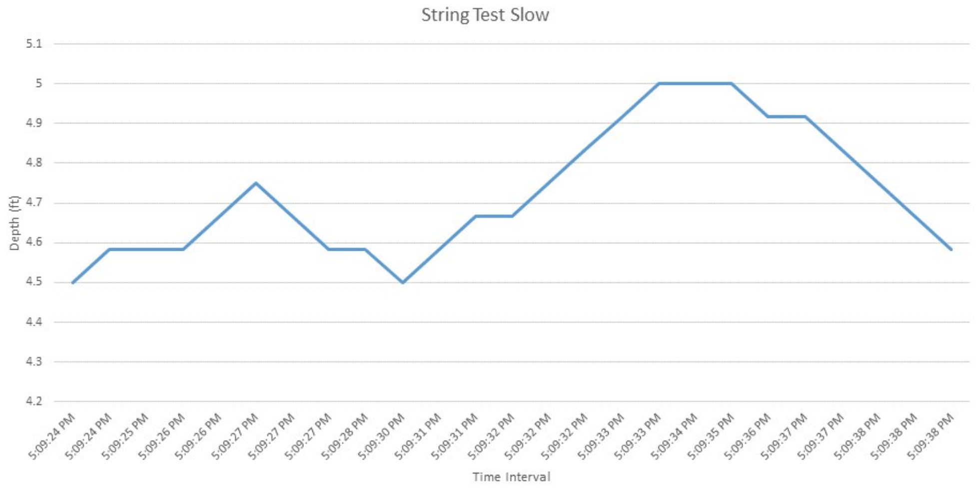

Figure 5.2: 15-second interval shown for a string test where the descent and ascent rate were correctly paced (termed: slow) such that no feedback was triggered.

Figure 5.2 shows a sample set of data that was collected during Phase II of the research project. The depth data did not provide any feedback because the rate did not surpass the established rate $0.00825 mm/ms$, which is a simplified, more sensitive version of the accepted dangerous rate of $9m/minute$. This slow string test was measured to stay within the limit, to gauge any misfired feedback and correlate logged data with expected depth in the swimming pool. The recognition algorithm accurately measures depth data, providing feedback when the measured rate surpasses the established threshold.

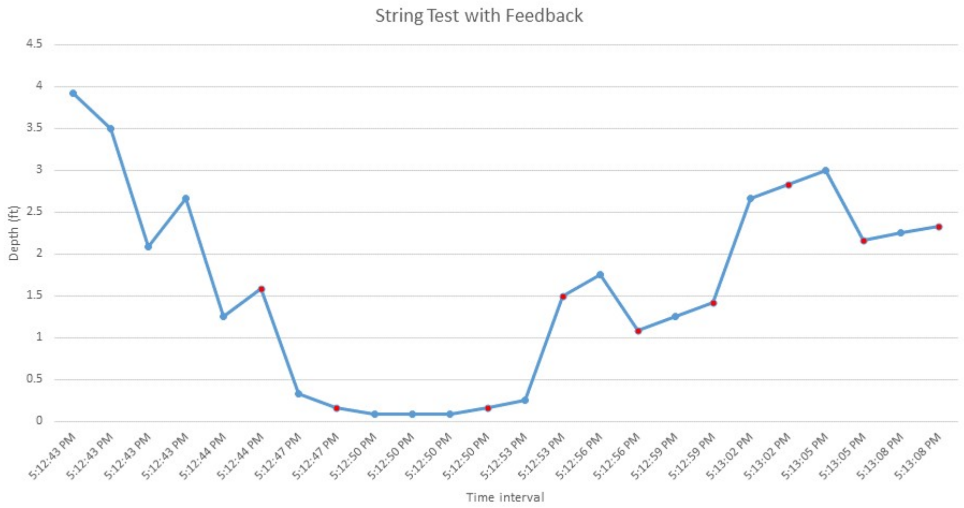

Figure 5.3: Graphical representation of a 15-second interval from a string test with sufficient rate of change, so as to provide feedback. The red data points specify when feedback was given.

Figure 5.3 shows a sample set of rate of change of depth data collected during Phase II, the DCS recognition algorithm. In Figure 5.3, feedback was produced when the rate of change in depth exceeded our established $0.00825mm/ms$, sans the initial lift from the pool floor, which did not trigger feedback during the entire 43rd second at 5:12:43 p.m. Although the depth change displays as a smooth curve in the interval between the 47th and 50th second, the smartphone broke the surface of the pool at 5:12:47 p.m. and re-entered at 5:12:50 p.m., which explains why the feedback triggers twice: the jolt from underwater to open air distorts the depth measurements. After re-entry, the device descends at an uneven pace, which triggers feedback response at various points after the 50th second. Overall, Figure 5.3 can be broken down into three sections: a smooth ascent with hasty end, pool exit and re-entry, and an uneven descent.

5.2 Evaluation Details

5.2.1 Baseline

Current dive computers have no concrete measure for standardization. Therefore, many patents exists for dive computers with a variety of functionalities and features. In essence, a dive computer is used to keep track of a diver's depth, time elapsed underwater, oxygen tank air pressure, etc. Some dive computers give audible alarms, and others do give haptic feedback: a combination of vibrations and audible signals to warn a diver when their oxygen tank reaches critical levels of air pressure [22, 23, 24].

Other diving wearables exist, but these focus on monitoring a diver's health, or on efficiently training a diver by guiding a user with haptic feedback.

5.2.2 Conditions

Dive computers seem to be quite a specialized piece of equipment that is a requirement for scuba divers. When searching for affordable options, we quickly realized dive computers tend to be expensive. In addition, some shallow water divers —like freedivers, surface-supported divers, and recreational divers— often dive with minimal equipment, as a body can usually withstand dives in shallow waters (above 30 feet) [6, 1, 5].

Knowing a good subset of divers remained in shallow waters and possibly overlooked the option of buying and using dive computers, a result of analyzing cost to use, gave us the idea to use smartphones with barometer sensors as an economical option. The barometer sensor can gauge pressure, so detecting depth would be made simple by knowing geographic and water density information [48, 21]. From this, we decided to build a haptic system by creating an application for a smartphone with an integrated barometer sensor, and test how users reacted to different feedbacks given by the smartphone. As decompression sickness is such a risk to inexperienced divers, we shifted the focus of our system to help reduce the risk of decompression sickness in a user by helping them pace their ascent with warning signals. With our system, we wanted to see how far a smartphone could lend itself to becoming a dive computer, or in the very least a stripped down version. If we were successful, shallow water diers could possibly enjoy the safety benefits of a simple dive computer by paying a fraction of the price, close to nothing if their devices already had a barometer sensor built-in.

5.2.3 Metrics

For our haptic system, we hoped to measure two things. Firstly, we wanted to ascertain our system can recognize an accelerated rate of ascent when diving so as to reduce the risk of decompression sickness in a user. Secondly, we wanted to see which feedback could best fit the system to intuitively warn the users to slow down or stop their quickened ascent. To test for the best fit, we wanted to have users experience the feedback as they maneuvered in water so as to gauge their reactions. However, our system was made to be hyper-sensitive to protect the users from any discomfort: the device would go off easier so users could exert less effort.

5.3 Phase III: Haptic Feedback Study

5.3.1 Purpose

The haptic feedback study aims to test a combination of three feedbacks —a long continuous vibration, three short vibrations, and an incremental vibration, each paired with a flashing white and red background— to find which feedback system most intuitively tells users to slow or stop their rate of ascent, as described in section 4.3.

5.3.2 Demographics

We tested HapticDive on 6 participants of varying skills in swimming and diving. Before each test, we asked our participants the pre-study questions listed in section 4.3.1 to help us gain insight into their responses and understand their behavior. The age range of our participants was between 20 to 26 years, with 33% female and 67% male participants i.e. 2 female and 4 male participants. Figure 5.4 shows the majority of users were male, their age range varied between 20 to 26 years, whereas females were 21 years of age. The average age of the users was 22.66 years old.

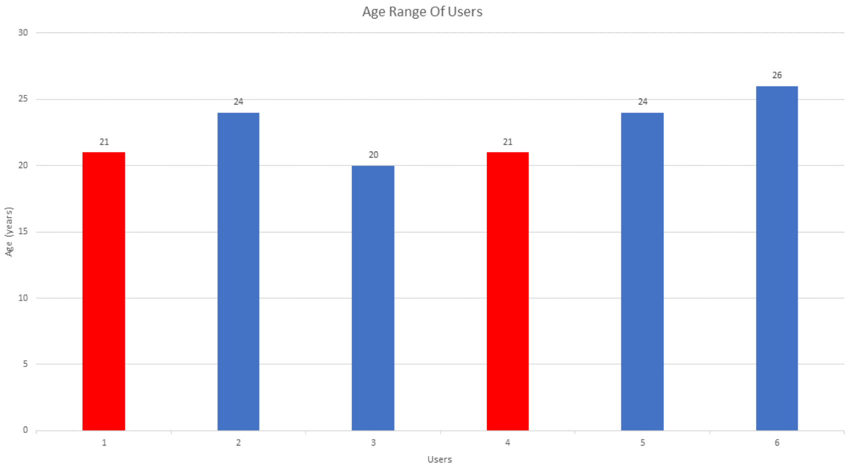

Figure 5.4: Age range of all the users part of the study. The red column indicates that the user is a female and blue indicates that the user is a male.

Some of our participants had been swimming for as little as a month, others going onto 20 years. Similarly, we had divers with little to no dive training and others with 12 years of diving. We grouped our participants by their reported skills in swimming and diving in Figure 5.5, and demonstrate the difference in experience between the amateur participants and more experienced participants. The two inexperienced participants in diving and swimming, as they had just began to learn to swim. One participant was and advanced swimmer and diver, with years of experience in both areas. Three participants were good swimmers, but had little to some experience diving.

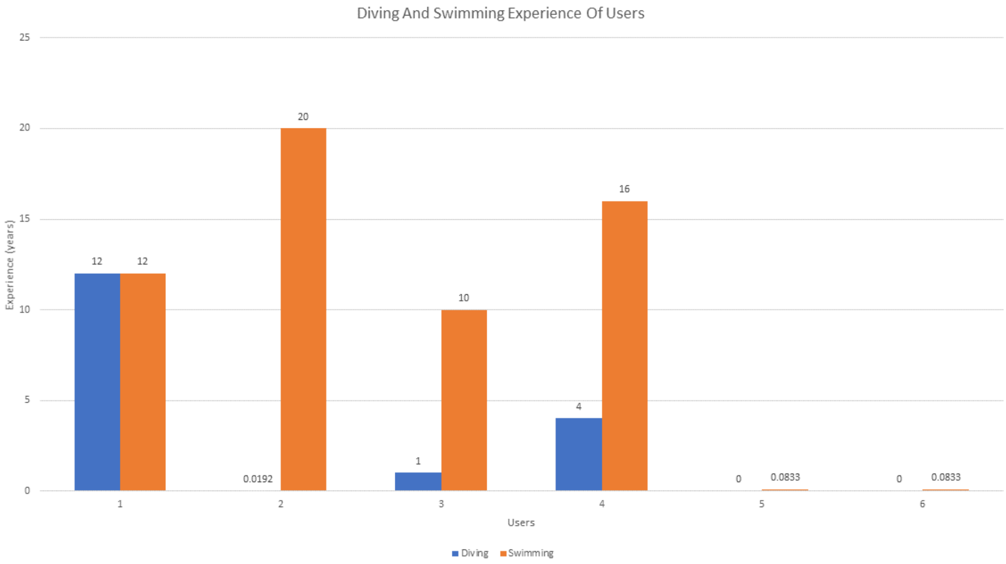

Figure 5.5: Diving and Swimming Experience of the users part of the study.

Only one of our participants had certifications (Open Water, PEAK Performance, Underwater Photography), but another would be taking the PEAK Performance assessment within a week. In addition, 67% of our participants knew of decompression sickness, its causes, and symptoms. Of those, 100% of the females were familiar with DCS. 50% of the male participants were familiar with DCS and 50% were unfamiliar, as they had just started swimming. The participants familiar with DCS all had some diving experience or years of swimming experience, including a certified female and a to-be certified male.

5.3.3 Depth Pattern of an Advanced Swimmer

The first user we tested was an advanced swimmer who had been swimming for 12+ years and diving sporadically throughout that time.

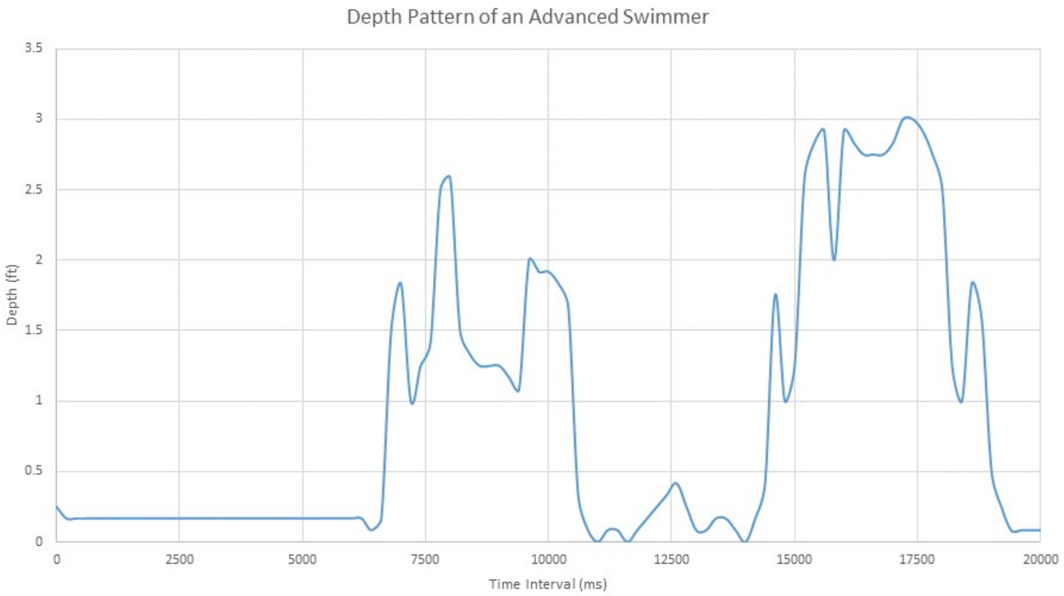

Figure 5.6: Depth pattern of an advanced swimmer, whose technique allowed different depths to be logged.

Figure 5.6 shows the depth pattern of the user, who we found notable as their expertise allowed them to dip-dive further underwater as they swam. Because of this, the advanced swimmer logged different depths in each lap for all three feedbacks. Following our instructions to swim the first half slow and the second quicker, Figure 5.6 demonstrates two curves with sharp changes in depth, first for the dive's descent and then for the dive's ascent. The first dive, however, is less drastic than the second. Figure 5.6 had feedback at time intervals: 6600, 9400, 12600, 15800, and 18800, which match up with the major rate changes explained by the dives.

5.3.4 Analyzing Depth and Rate Data for a User

Figure 5.7 shows this user typically takes about 15 seconds to begin swimming after the application began logging data. Since the data brings no further insight for the first 15 seconds, we focus on the latter half for Figure 5.8.

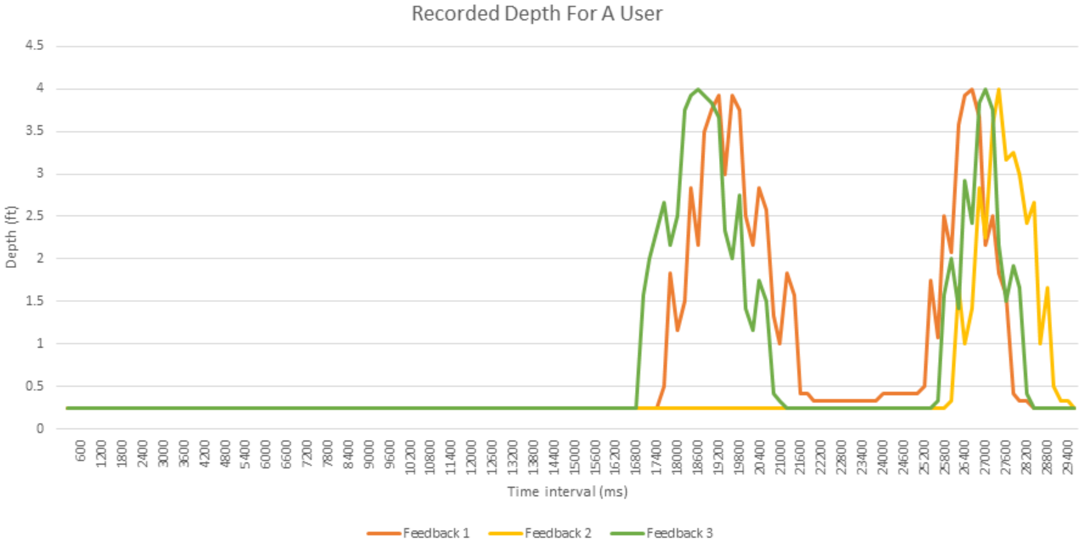

Figure 5.7: Sample set of depth data gathered from user who experienced all three feedback.

Similar to the advanced swimmer from Figure 5.6, we see the results of change in depth for a slow dive and a faster dive. The first dives form a softer curve as compared to the curve formed by the second dives, which have greater slope. Notice that for both instances, the user was able to go reach a depth change from 0 feet to 4 feet and back. However, more feedback is received when the user goes faster, because the rate is increased, so the barometer sensor received more data and updated frequently.

Next, we analyze the rates created by the same user over a time interval of 10 seconds in Figure 5.8. The same user is analyzed so there is no discrepancy in the data presented. As previously stated, the user takes about 15 seconds to begin swimming, so we also present a second figure which depicts the latter interval in detail.

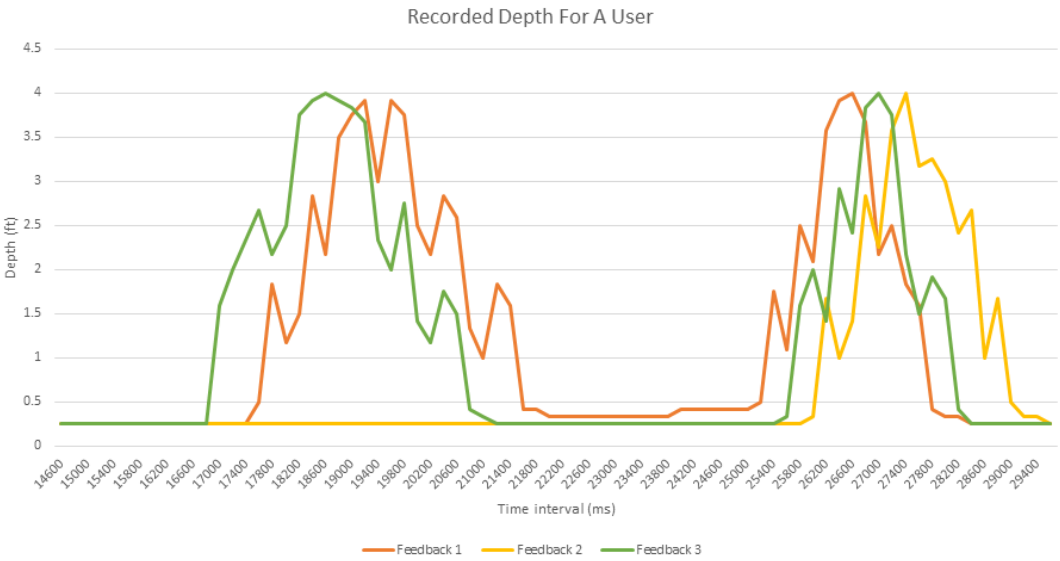

Figure 5.8: Sample set of depth data gathered from a user who experienced all three feedback, starting slightly before the 15th second.

When we correspond Figure 5.8 and Figure 5.9, which present matching time intervals, we see there is not much adjustment in the rate of depth for the slow dive because the user was asked to go slow. However, when we consider the second half, we see the rate increases sharply as the user dove quickly.

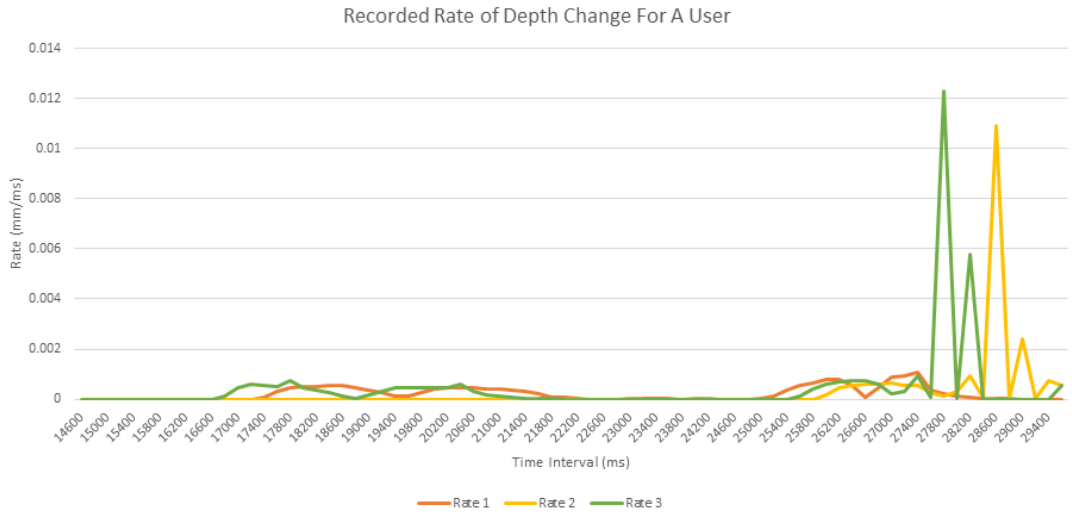

Figure 5.9: Sample set of rate of change of depth data gathered from a user who experienced all three feedback, starting slightly before the 15th second.

As mentioned in section 4.2, we use the rate $0.00825 mm/ms$ as the threshold rate to trigger a warning feedback. In Figure 5.9, feedback was given for times 27,600 and 28,400, times which correspond to the sharp peaks.

5.3.5 Discovering the Most Intuitive Feedback

From section 4.3, Feedback 1 was a continuous vibration, Feedback 2 was three short vibrations, and Feedback 3 was an incremental vibration.

When considering memorability in Figure 5.10, 67% or the majority of the users found the three short vibrations to be the most memorable one. The user who found the incremental vibration to be the most memorable was participant 5 who did not feel Feedback 1 or 2. Therefore, the only feedback they responded to was Feedback 3. Participant 4 found the continuous vibration to be most memorable.

Figure 5.12 shows the data gathered from four users for the three short vibrations —

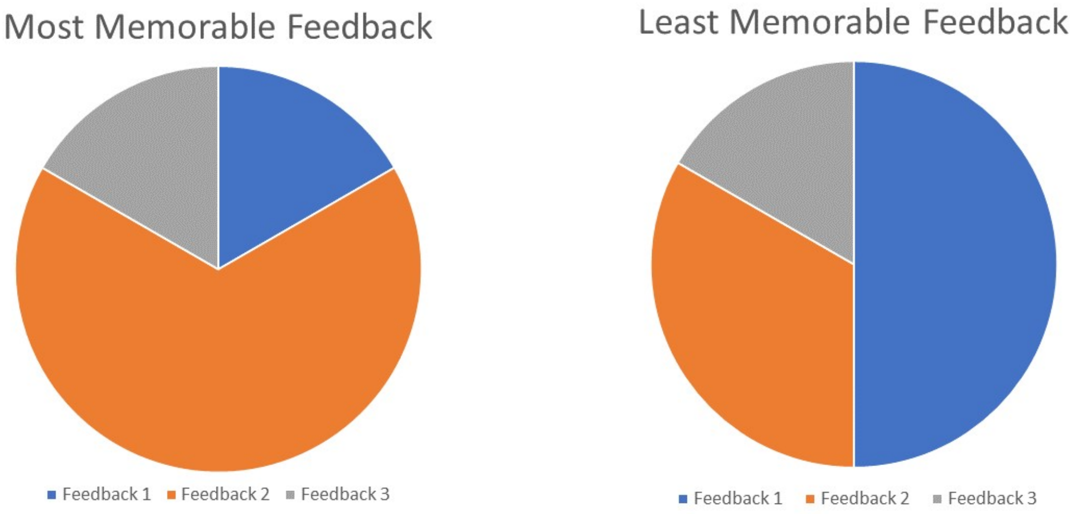

Figure 5.10: User's perception on the memorability of the feedback. On the left: most memorable feedback. On the right: least memorable feedback. Feedback 1 was a continuous vibration, Feedback 2 was three short vibrations, and Feedback 3 was an incremental vibration.

Feedback 2. Two participants were exempted because of their swimming techniques; this is reviewed in section 5.3.

Similar to the data collected and illustrated in Figure 5.7 to Figure 5.9, the initial data does not bring any insight for at least 15 seconds, so we focus on the latter half for Figure 5.12. Participant 2 in Figure 5.12 stayed underwater as they swam for each feedback, and they were able to change depth, triggering the feedback. Participant 1 also stayed mostly underwater as they swam for each feedback. They were only able to experience feedback in the end when they went faster and quickly changed their depth levels. Participant 3 and 4 did not change depths as often in Figure 5.11. They only trigger the feedback once or twice as can be seen in Figure 5.12.

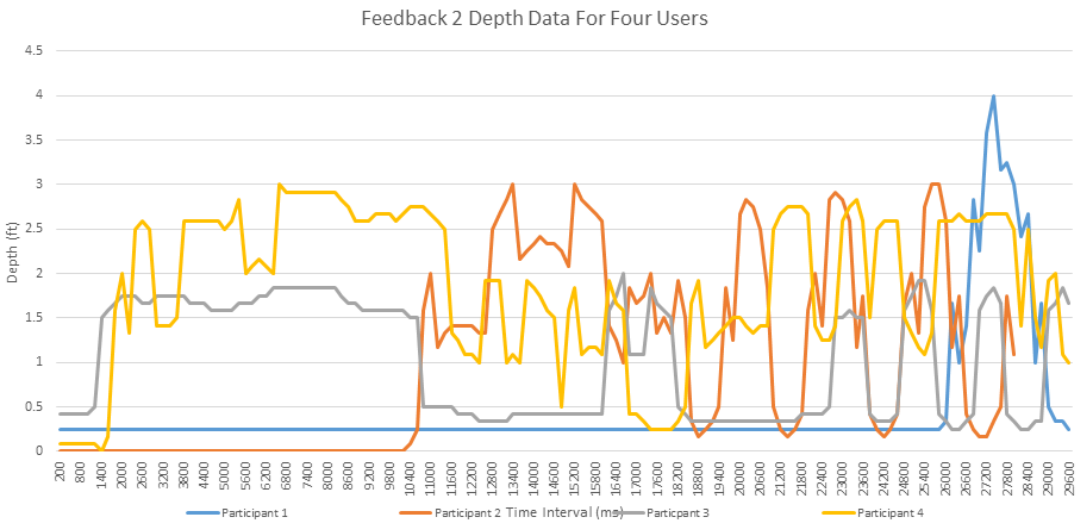

Figure 5.11: Depth data collected by four users.

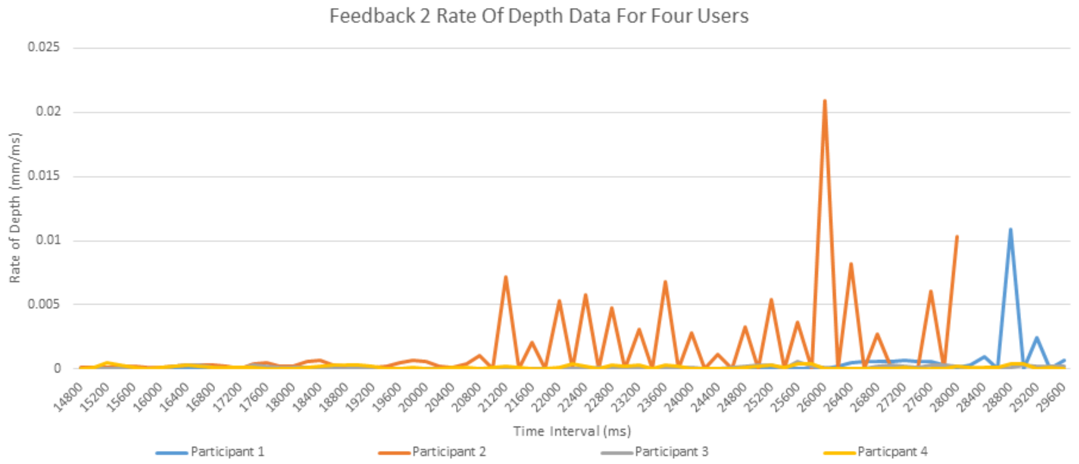

Figure 5.12: Rate of depth data collected by four users. Collected data started shortly before the 15th second.

6. DISCUSSION

6.1 Insights

We believe users found the three short vibrations most intuitive because it is a common haptic feedback given by smartphones. These vibrations are often used to alert incoming calls, notifications, alarms and all the users had been exposed to some sort of vibration from their smartphones.

As we continued with the the user studies, the users realized that they were receiving haptic feedback and should be more alert of the device. We believe that is one of the primary reasons that Feedback 1 or the long vibration is the least memorable feedback as we can see in Figure 5.10. For every user, the first round of user studies that were carried out by the long vibration (Feedback 1), majority of the users were concentrating on swimming as opposed to the smartphone.

Therefore, even though we needed the user to be completely unbiased. This could not be helped due to human nature.

6.2 Intuitive Feedback

From section 4.3, Feedback 1 was a continuous vibration, Feedback 2 was three short vibrations, and Feedback 3 was an incremental vibration.

As mentioned in section 5.2.4, majority of the participants preferred three short vibrations (Feedback 2) and considered it to be the most intuitive one. Participants mentioned the following regarding their intuitive reaction to the three short vibrations (Feedback 2): “To look at it and stop,” “Look at the phone or be alert,” and “Come up.” Two of our participants actually noticed that a quick rate of change in depth caused more feedback, stating “When I was going slow, there was less vibrations.” Additionally, one of them believed the feedback meant to signal ascent rates, warning the user about coming up to the surface. In this manner, HapticDive was able to replicate the depth and change in depth calculations, as well as provide feedback when rates reached dangerous levels.

6.3 Error Analysis

The majority of the participants followed the study instructions as directed. All the other users were able to go to the maximum depth of the pool which was 4 feet. None of the participants looked at the device while they were swimming because the visual feedback was not noticeable enough in the well-lit indoor pool. In low light situations the visual feedback might play a larger role in warning a user.

6.3.1 Swimming Strokes

Every user used a differing swimming techniques, depending on experience. Participants 5 and 6, however, used beginner swimming strokes which kept the arms largely stable and straight to break the water and used their feet to propel them forward. Additionally, they did not dip-dive as their inexperience made them uncomfortable with going underwater as they swam. Because of the swimming strokes and lack of diving, there was little to no depth change recorded by the device, causing a uniform rate and triggering little to no feedback for these participants. We notified participant 6 to dive and go deeper for the second and third feedback types which they then successfully did, but only for a shorter distance.

6.3.2 Study Limitations

Our research project primarily focuses on shallow water type diving, but our approved IRB allows only swimming user studies, where users are still mainly above or around the surface as opposed to diving to great depths. Additional testing must be carried out to better represent the diving perspective. Swimmers tend to stay close to the surface, which caused some of our users to cover a small range in depth differences, such that the haptic feedback was not triggered at all.

6.3.3 Equipment Exchange

Unfortunately, Some of the equipment we were working with broke down in the beginning stages of the user study. Creativity was exercised to attach the smartphone to the user in such a way that the smartphone remained waterproof but the user was still able to swim without hindrance and feel the feedback. This also caused discrepancies in the quantitative data, as some users were unable to feel the feedback given by the smartphone because there was insufficient contact between the device and the user for them to feel the vibrations.

7. FUTURE WORK

HapticDive set out to provide an application to track a user's rate of change in depth and provide intuitive feedback that would pace their ascension by giving signals which would tell the user to slow down or stop. As of now, the recognition algorithm can signal users in saltwater or chlorine-water mixtures common to pools, and in geographical areas similar to College Station, Texas. However, the recognition algorithm developed could made more accurate by considering all the variables that impact depth: changes in water density, temperature, and altitude, among others. Water salinity creates a big impact in calculating depth, but temperature and altitude also impact depth calculation in smaller ways, so they must be considered.

When conducting our user studies, we realized our harness approach to strapping the device to the user needed to be reconsidered, as some of our users required the waterproofed device to be reattached after one or two feedback tests. Future testing can be done to create a more secure harness that also works well with divers. Additionally, feedback given during the user study by the participants helped us realize there was still more fine-tuning we could do for the rate sensitivity. Additional tests with different participant instructions could be carried out to cover more underwater situations. For example, testing with stationary dives were users sink and ascend at their own safe pace could provide valuable feedback regarding how sensitive the system really needs to be.

Due to time constraints with research compliance and the safety concerns for the study participants, we were unable to test out the application with a user submerged underwater for a substantial amount of time and at various depths. These tests could be performed again with users in deeper waters, so as to capture a deeper dive profile with the data logging in our application. Future studies could also re-focus the types of feedbacks tested, by expanding the combinations tested to include audio and visual signals as feedback for a more robust data analysis.

A goal for this research was to help provide a base for additional features and detection in the future. Further work can refine the features provided by the application by expanding the sensors used. The application could also be modified to include the following:

1. *Group Communication:* Accelerometer and gyroscope data could be used, in addition to barometer data, to recognize gestures given by a diver and propagating them to other divers inside the communication network [48]. Users could perform quick actions to relay group messages like "Let's regroup," "Lost," or "Danger!," to name a few. This would benefit those who dive in groups, those who dive at nighttime or in low-light situations, and could even be used by instructors to track everyone during a dive. They could be done using hand posture [49] or hand motion [50, 51, 52, 53]
2. *Body Positioning:* Gyroscope and magnetometer data could be used to sense how the body is positioned relative to the known surface [48, 54]. Divers who are anxious about releasing air supply to rediscover the surface (by following the bubbles created) might appreciate an application which can track which way is up. This would also benefit divers with low visibility, like nighttime divers, or those who deep dive.
3. *Underwater Navigation:* A combination of the features mentioned above in addition to GPS information could be used to help navigate users to a destination, in case divers become disoriented or lost [48].

8. CONCLUSION

This research set out to establish a foundation to produce a functioning warning system, HapticDive, using a smartphone and its barometer sensor data that alerts a diver using noticeable feedback. The primary motivation for this research was to distinguish which feedback, among a selection of haptic and visual feedback combinations, would serve best to signal a diver to slow or stop their ascent. HapticDive detects whether a user correctly paces their descent or ascent by calculating the rate of change in depth and providing a haptic and visual warning when the user might be at risk of decompression sickness, or any of its symptoms, in depths of 33 feet or less [15]. Decompression sickness is easy to ignore, as symptoms typically begin presenting themselves 10 to 30 minutes after a diver surfaces, at which point they correlate their ailments to other causes. This allows the symptoms to escalate, which left untreated can be deadly [1, 2]. Currently, divers commonly use a dive computer to display their rate of change in depth, but these tend to be expensive. No prior work has sought to provide a warning system using haptic feedback and smartphone sensors to mitigate DCS.

We began our research by conducting preliminary studies to understand the basic requirements experienced divers expected, and the features they would like to see. In this manner, our approach would consider expert opinion, ensuring a user-centered design. To test our prototype's DCS recognition algorithm without risking DCS symptoms, we developed the string test. After evaluating correctness using data logged, we conducted user studies as the last phase research. User studies helped us find a combination of haptic and visual feedback which most intuitively signaled "Stop" when underwater to a diverse set of users. Of those studied, the most intuitive feedback for the majority of users was three short vibrations with a flashing white-and-red background.

HapticDive can be incorporated into future smartphone —based warning systems to warn against the risk of DCS, or can be expanded to consider other features important to divers. By making DCS warning systems more accessible, shallow-water divers and recreational divers may experience safer dives and less decompression stress.

REFERENCES

[1] J. How, D. West, and C. Edmonds, "Decompression sickness in diving," *Singapore Medical Journal*, vol. 17, pp. 92–97, July 1976.

[2] M. Yehuda, A. Shupak, and H. Bitterman, "Medical problems associated with underwater diving," *The New England journal of medicine*, vol. 326, pp. 30–5, 02 1992.

[3] E. Thalmann, "Decompression illness: What is it and what is the treatment?." `https://bit.ly/2GNSshj`, March 2004.

[4] Professional Association of Diving Instructors, "Becoming a certified PADI freediver faq." `https://bit.ly/2uDXGaB`, 2018.

[5] C. Davis, "Hookah surface supplied air for recreational divers." `https://bit.ly/2GvZZBZ`, October 2016.

[6] E. Farrell, "What is freediving and types of freediving." `https://bit.ly/1TfZBrJ`, May 2016.

[7] European Underwater Federation, "En 14153-1 / iso 24801-1." `https://bit.ly/2GL9P2n`, October 2013.

[8] European Underwater Federation, "En 14153-2 / iso 24801-2." `https://bit.ly/2Iox3bw`, October 2013.

[9] European Underwater Federation, "En 14153-3 / iso 24801-3." `https://bit.ly/2GrSUCo`, September 2013.

[10] Professional Association of Diving Instructors, “About scuba gear.” `https://bit.ly/2snEfAY`, 2017.

[11] Professional Association of Diving Instructors, “Choosing a dive computer.” `https://www.padi.com/gear/dive-computers`, April 2017.

[12] Sarah, “The bends — decompression sickness.” `https://bit.ly/2Ef1DSN`, April 2013.

[13] R. Philp, “A review of blood changes associated with compression-decompression: relationship to decompression sickness,” *Undersea Biomed Res*, vol. 1, pp. 117–150, June 1974.

[14] S. Whelan, “20 safety rules for freediving.” `https://bit.ly/2Ef32IP`, April 2003.

[15] J. Palmer, “Top 5 waterproof phone cases of 2016.” `https://bit.ly/2H5WjUN`, March 2016.

[16] Scuba Diving, “Your first set of scuba gear: A buyer’s guide.” `https://www.scubadiving.com/training/basic-skills/your-first-set-gear-buyers-guide`, January 2018.

[17] S. Dahiwadkar, “Different kind of sensors available on a smartphone.” `http://thehappylearning.com/different-kind-sensors-available-smartphone`, December 2016.

[18] M. Pesce, “Sensors, not cpus, are the tech that swings the smartphone market.” `https://bit.ly/2GM4ec5`, January 2016.

[19] X. Su, H. Tong, and P. Ji, “Activity recognition with smartphone sensors,” *Tsinghua Science and Technology*, vol. 19, pp. 235–249, June 2014.

[20] D. Banerjee, S. K. Agarwal, and P. Sharma, “Improving floor localization accuracy in 3d spaces using barometer,” in *Proceedings of the 2015 ACM International Symposium on Wearable Computers*, ISWC ’15, (New York, NY, USA), pp. 171–178, ACM, 2015.

[21] M. Kharrat, Y. Wakuda, N. Koshizuka, and K. Sakamura, “Automatic waist airbag drowning prevention system based on underwater time-lapse and motion information measured by smartphone’s pressure sensor and accelerometer,” in *2013 IEEE International Conference on Consumer Electronics*, ICCE ’13, (Washington, DC, USA), IEEE, 2013.

[22] R. Hollis, M. S. Hollis, and J. C. Holman, “Dive computer with free dive mode and wireless data transmission,” Feb 2016. Patent US9254900B2.

[23] L. B. Hales, “Field of view underwater dive computer system,” March 2002. Patent US6360182B1.

[24] K. W. Juergensen, “Enhanced dive computer functionality and associated features,” Feb 2015. Patent US20130257621A1.

[25] Leisure Pro, “Dive computers.” `https://bit.ly/2pWGPen`, 2018.

[26] Scuba.com, “Dive computers.” `https://bit.ly/2GwMrCi`, 2018.

[27] T. Cibis, B. H. Groh, H. Gatermann, H. Leutheuser, and B. M. Eskofier, “Wearable real-time ecg monitoring with emergency alert system for scuba diving,” *2015 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, pp. 6074–6077, 2015.

[28] E. M. Kidman, M. J. A. D’Souza, and S. P. N. Singh, “A wearable device with inertial motion tracking and vibro-tactile feedback for aesthetic sport athletes diving

coach monitor," in *2016 10th International Conference on Signal Processing and Communication Systems (ICSPCS)*, pp. 1–6, IEEE, Dec 2016.

[29] E. Jacob and J. Jacobsson, "Development of a new dive computer and enhancing the experience of scuba diving," Master's thesis, Chalmers University of Technology, 2017.

[30] M. Prasad, M. Russell, and T. Hammond, "A user centric model to design tactile codes with shapes and waveforms," in *Haptics Symposium (HAPTICS)*, (Houston, TX, USA), pp. 597–602, IEEE, February 23–26, 2014. ISBN: 978-1-4799-3131-6.

[31] M. Prasad, M. Russell, and T. Hammond, "Designing vibrotactile codes to communicate verb phrases," *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, vol. 11-1, pp. 11:1–11:21, September 2014. ISSN: 1551-6857, `http://doi.acm.org/10.1145/2637289`.

[32] D. Cummings, M. Prasad, G. Lucchese, C. Aikens, and T. Hammond, "Multi-modal location-aware system for paratrooper team coordination," in *CHI'13 Extended Abstracts on Human Factors in Computing Systems (CHI)*, (Paris, France, France), pp. 2385–2387, ACM, April 27–May 2, 2013. ISBN: 978-1-4503-1952-2.

[33] D. Cummings, G. Lucchese, M. Prasad, C. Aikens, J. Ho, and T. Hammond, "Haptic and AR interface for paratrooper coordination," in *Proceedings of the 13th International Conference of the NZ Chapter of the ACM's Special Interest Group on Human-Computer Interaction (CHINZ)*, (Dunedin, New Zealand, New Zealand), pp. 52–55, ACM, July 2–3, 2012. ISBN: 978-1-4503-1474-9.

[34] M. Prasad, P. Taele, A. Olubeku, and T. Hammond, "Haptigo: A navigational 'tap on the shoulder'," in *Haptics Symposium (HAPTICS)*, (Houston, TX, USA), pp. 339–345, IEEE, February 23–26, 2014. ISBN: 978-1-4799-3131-6.

[35] M. Prasad, P. Taele, D. Goldberg, and T. Hammond, “Haptimoto: Turn-by-turn haptic route guidance interface for motorcyclists,” in *Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems (CHI)*, (Toronto, Canada, Canada), pp. 3597–3606, ACM, April 27–May 1, 2014. ISBN: 978-1-4503-2473-1.

[36] V. Rajanna and T. Hammond, “Gawschi: Gaze-augmented, wearable-supplemented computer-human interaction,” in *Proceedings of the Symposium on Eye Tracking Research and Applications (ETRA ’16)*, (Charleston, South Carolina, USA), ACM, March 14-16, 2016.

[37] V. Rajanna, P. Vo, J. Barth, M. Mjelde, T. Gray, C. Oduola, and T. Hammond, “Kinohaptics: An automated, wearable, haptic assisted, physio-therapeutic system for post-surgery rehabilitation and self-care,” *Journal of Medical Systems*, vol. 40-3, pp. 1–12, March 2016. ISSN: 0148-5598, `https://doi.org/10.1007/s10916-015-0391-3`.

[38] S. Azenkot, R. E. Ladner, and J. O. Wobbrock, “Smartphone haptic feedback for nonvisual wayfinding,” in *The Proceedings of the* 13^{th} *International ACM SIGACCESS Conference on Computers and Accessibility*, ASSETS ’11, (New York, NY, USA), pp. 281–282, ACM, 2011.

[39] S. Kammoun, T. Jouffrais, H. Nicolau, and J. Jorge, “Guiding blind people with haptic feedback,” *Pervasive 2012 Workshop on Frontiers in Accessibility for Pervasive Computing*, 2012.

[40] J. Zanchi, M. Ljubkovic, P. Denoble, Z. Dujic, S. Ranapurawala, and N. Pollock, “Influence of repeated daily diving on decompression stress,” *International Journal Sports Medicine*, vol. 35, no. 6, pp. 465–468, 1976.

[41] J. Kamtchum Tatuene, R. Pignel, P. Pollak, K. A. Lovblad, K.O., and M. Vargas, “Neuroimaging of diving-related decompression illness: Current knowledge and perspectives,” *American Journal of Neuroradiology*, vol. 35, no. 11, pp. 2039–2044, 2014.

[42] Huawei, “Nexus 6P.” https://consumer.huawei.com/en/phones/nexus-6p/, 2018.

[43] G. Arena, “Huawei Nexus 6P.” `https://www.gsmarena.com/huawei_nexus_6p-7588.php`, September 2015.

[44] R. Rogers, “The recreational dive planner and the PADI experience,” *Journal of the South Pacific Underwater Medicine Society*, 1992.

[45] A. Poisson, C. Brunet, and J. Brun-Cottan, “Density of standard seawater solutions at atmospheric pressure,” *Deep Sea Research Part A. Oceanographic Research Papers*, vol. 27, no. 12, pp. 1013–1028, 1980.

[46] C. Hodanbosi, “Fluids pressure and depth.” `https://go.nasa.gov/2uGESHA`, August 1996.

[47] ScubaDiving, “10 rules of scuba diving.” `https://bit.ly/2EffIj4`, October 2006.

[48] A. Developers, “Sensors overview.” `https://developer.android.com/guide/topics/sensors/sensors_overview.html`, March 2018.

[49] B. Paulson, D. Cummings, and T. Hammond, “Object interaction detection using hand posture cues in an office setting,” *International Journal of Human-Computer Studies (IJHCS)*, vol. 69-1, pp. 19–29, January 2011. ISSN: 1071–5819, `https://doi.org/10.1016/j.ijhcs.2010.09.003`.

[50] J. Cherian, V. Rajanna, D. Goldberg, and T. Hammond, "Did you remember to brush? : A noninvasive wearable approach to recognizing brushing teeth for elderly care," in 11^{th} *EAI International Conference on Pervasive Computing Technologies for Healthcare*, (Barcelona, Spain), ACM, May 23–26, 2017. DOI: 10.1145/3154862.3154866, `https://dl.acm.org/citation.cfm?id=3154866`.

[51] J. Bartley, J. Forsyth, P. Pendse, D. Xin, G. Brown, P. Hagseth, A. Agrawal, D. Goldberg, and T. Hammond, "World of workout: a contextual mobile RPG to encourage long term fitness," in *Proceedings of the Second ACM SIGSPATIAL International Workshop on the Use of GIS in Public Health*, (Orlando, FL, USA), pp. 60–67, ACM, November 5, 2013. ISBN: 978-1-4503-2529-5.

[52] P. Taele and T. Hammond, "Adapting surface sketch recognition techniques for surfaceless sketches," in *Proceedings of the Twenty-Third International Joint Conference on Artificial Intelligence (IJCAI)*, (Beijing, China, China), pp. 3243–3244, AAAI Press, August 3–9, 2013. ISBN: 978-1-57735-633-2.

[53] P. Taele and T. Hammond, "Initial approaches for extending sketch recognition to beyond-surface environments," in *CHI'12 Extended Abstracts on Human Factors in Computing Systems (CHI)*, (Austin, TX, USA), pp. 2039–2044, ACM, May 5–10, 2012. ISBN: 978-1-4503-1016-1.

[54] A. Developers, "Position sensors." `https://developer.android.com/guide/topics/sensors/sensors_position.html`, March 2018.