AN INTRAORAL CLOSED LOOP MONITORING AND STIMULATION SYSTEM FOR TREATMENT OF SWALLOWING DISORDER

A Thesis

by

SIDDARTH BIYANI

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Hangue Park
Committee Members,	Steven M. Wright
	Kamran Entesari
	Rainer Fink
Head of Department,	Miroslav Begovic

May 2019

Major Subject: Electrical Engineering

ABSTRACT

One in every 25 Americans suffer from swallowing disorders, referred to as Dysphagia. Problems in the pharyngeal phase of swallowing are hard to treat because of the neuromuscular complexity in the region and the quick passage of food (< 1 s) through the pharyngeal region. The pharyngeal phase of swallowing is also involuntary and involves coordination among various parts of the brain to execute which results in variation of efficacy of treatments administered to patients

The proposed medical device uses a closed-loop neural stimulation approach for treating swallowing problems. This approach monitors the start of involuntary phase of swallowing by detecting tongue-tip pressure. The lesser palatine nerve is located on the soft palate where most of the food makes contact before swallowing. The nerve is also known to be involved in sensorimotor loop of swallowing function. After detecting the start of involuntary phase of swallowing, we timely stimulate the soft palatal area inside the 2^{nd} molar, potentially lesser palatine nerve, as a closed-loop. We hypothesize that the closed-loop stimulation on lesser palatine nerve augments the sensory feedback and strongly triggers the pharyngeal swallowing phase, which would result in stronger swallowing.

Two experiments were performed to test the hypothesis. A prototype system built using Arduino DUE was used to perform these experiments. In the first experiment, the swallowing time and acceleration of laryngeal excursion was recorded without any stimulation. In the second experiment, stimulation was provided to the lesser palatine nerve for 500 ms when tongue tip is detached from the incisors, and the swallowing time and acceleration of laryngeal excursion was recorded. Two human subjects participated in the study. Without stimulation, both subjects showed consistent swallowing in both duration and amplitude. Stimulation reduced the peak-to-peak duration of laryngeal excursion but the peak-to-peak amplitude of laryngeal excursion was not changed by stimulation. This study found that closed-loop stimulation onto the palatal area inside the 2^{nd} molar, timed with the onset of the pharyngeal swallowing, can reduce the duration of the pharyngeal swallowing.

The idea of the proposed medical device was validated in the market as part of NSF I-Corps Site program organized by Texas A&M University. Additional research has been done to build a wireless prototype of the proposed device using a CC2640R2F microcontroller which uses Bluetooth Low Energy(BLE) for communication.

DEDICATION

To Mumma, Pappa, Divesh, Niyati and Anushree. Thank you for your constant support and motivation.

ACKNOWLEDGMENTS

I would like to thank Dr. Hangue Park for his constant guidance and support through the duration of my thesis.

I would also like to thank Dr. Saurabh Biswas for helping me broaden my perspective for this project.

A big thank you to my friends Aalhad, Mei, Sudhanshu, Ishan, Shubham and Mahesh for being my home, here in the United States. Thanks are also due to Udhaya, Neeharanshu and Chirag for all the technical discussions related to my research. Thanks to Yaqub, Ronak, Maulik and Abishai for their constant support.

Thanks to Nikhil and Gokul for helping me take my first steps in the field of electronics and training me to think critically.

Special thanks to my fiancee, Anushree, for supporting me through my uncertainties. Lastly, but most importantly, my parents, siblings and family for being my rock and without whom, none of this would have been possible.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a thesis committee consisting of Dr. Hangue Park [advisor], Dr. Steven Wright and Dr. Kamran Entesari of the Department of Electrical and Computer Engineering and Dr. Rainer Fink of the Department of Engineering Technology and Industrial Distribution.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

All funding for this project was provided by the Integrated Neuro-Prosthetics Laboratory at Texas A&M University which is under the supervision of Dr. Hangue Park

NOMENCLATURE

I/O	Input and Output
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
UART	Universal Asynchronous Receiver/Transmitter
USART	Universal Syncronous/Asynchronous Receiver/Transmitter
TTL	Transistor-Transistor logic
GUI	Graphical User Interface
3D	Three Dimensional
DIO	Digital Input and Output
INPL	Integrated Neuro-Prosthesis Lab

TABLE OF CONTENTS

Page

LIST OF FIGURES

FIGURE Page

LIST OF TABLES

TABLE Page

1. INTRODUCTION AND PROBLEM STATEMENT

1.1 Prevalence of Dysphagia

One in twenty-five adult Americans suffer from swallowing disorders referred to as Dysphagia [4]. Dysphagia is regarded as a symptom prevalent among elderly individuals. Physiological decline by aging process contributes to the prevalence of dysphagia in elderly population, as swallowing is highly complicated neuromuscular process [5]. The prevalence of dysphagia is estimated as 8-22% for adults over the age of 50 [6] while 0.9% for the population between the ages of 3-17 [7]. Dysphagia is generally a symptom of a bigger underlying problem - most commonly: stroke, head and neck cancer, Traumatic Brain Injury, Parkinson disease or other degenerative neurological disorders like multiple sclerosis and Amyotrophic Lateral Sclerosis(ALS).

According to the Center for Disease Control and Prevention (CDC), stroke is the fifth leading cause of deaths in the United States. Stroke affects over 795,000 people in the United States every year and it is a major cause of long-term disability. Stroke results in between 37% to 78% of patients to suffer from mild to extreme Dysphagia [8]. The onset of Dysphagia coupled with the severity of existing problems makes undergoing treatment extremely important even though the treatment is difficult and time consuming. Dysphagia can lead to other severe problems like aspiration pneumonia, choking, chronic lung disease and weight loss [9].

Dysphagia is usually classified into three types depending on the location of the problem: oral, pharyngeal, and esophageal dysphagia [10]. While the problem can happen in all three regions, the problem at pharyngeal region is most critical. The pharyngeal phase of swallowing is an involuntary phase of swallowing in which food bolus is quickly moved from the pharynx to the esophagus. Precise coordination of several cranial nerves and muscles is necessary for the pharyngeal phase of swallowing [11, 12]. Because the airway and esophagus are very close to each other, it is important that the all the pharyngeal muscles work normally to prevent the food bolus from entering the airway. Any problem in the functioning of these muscles can lead to pharyngeal dysphagia. It

is difficult to treat because the pharyngeal region has a complex muscular structure and the time taken by the food bolus to pass this region is less than a second.

1.2 Current techniques for treatment of Dysphagia

Current techniques to treat pharyngeal dysphagia are swallowing exercises, dietary changes, surgery and neuromuscular stimulation [13]. Neuromuscular stimulation has huge potential because it opens the possibility of providing direct intervention to the nerves and muscles responsible for swallowing. One approach, which stimulates the intraoral sensory receptors, is referred to as thermal-tactile oral stimulation (TTOS) [14]. A cold laryngeal mirror or an iced lemon glycerin swab is used to stimulate areas around the oropharynx, such as the faucial arches, the soft palate, and the back of the tongue.

Another approach, which stimulates the pharyngeal muscles, is referred to as neuromuscular electrical stimulation (NMES) [15]. Surface electrodes are attached to the neck region and under the chin to stimulate the underlying muscles used for swallowing. Most of the NMES devices, currently available in the market, target a wide area of the mouth or neck for stimulation for stimulation because of the complexity of the muscular structure in the neck region. This broad targeting requires large electrodes for stimulation, thereby reducing the spatial resolution of the stimulation. Additionally, most of these devices don't track the swallowing activity of a patient and therefore don't target the stimulation with the swallowing phase. This leads to low temporal resolution of the device. The density of muscles in the neck region also increases the power required for stimulation leading to sharp pain being experienced by patients.

Several studies have been conducted to compare the effectiveness of NMES and TTOS in rehabilitation from Dysphagia. Even though, some studies conclude that NMES is significantly more effective than TTOS [15, 16], studies also show that NMES has no significant effect in treatment of swallowing dysfunction [17]. Studies also show that NMES is effective only in cases with mild or moderate dysphagia [18].

Note that, existing techniques such as TTOS and NMES, have a low spatio-temporal resolution. The low spatio-temporal resolution causes difference in effectiveness of the device on dif-

ferent patients [19] and makes it important to customize the device for every new patient, thereby requiring the need of a medical personnel for administering the therapy every time. Considering the short duration of pharyngeal phase of swallowing and complex recruitment pattern of pharyngeal muscles during pharyngeal phase of swallowing, the low spatio-temporal resolution of current neuromuscular stimulation techniques seriously limits the efficacy of modulation [20].

1.3 Hypothesis behind research

To address the unmet need, we propose a new neuromuscular stimulation approach using an intraoral device. The intraoral device monitors the beginning of pharyngeal swallowing phase and modulates the pharyngeal muscle activity by stimulating the associated nerves on the soft palate. As the intraoral device determines the timing of stimulation based on information of pharyngeal swallowing phase, it increases the temporal resolution of stimulation. The small size of the stimulation electrode and the accessibility to the dense nerve population inside the mouth increases the spatial resolution of the stimulation. Fig. 1.1 shows the exemplary swallowing problem and exemplary resulting change from the proposed closed-loop stimulation. In the figure on the left, the epiglottis does not close at the correct time leading to some part of the food bolus entering the trachea and in the figure on the right, the epiglottis closes at the right time with the intraoral stimulation and guides the entire food bolus to enter the esophagus.

We selected an intraoral device to modulate the activity of pharyngeal muscles during the pharyngeal phase of swallowing. The intraoral device will apply electrical stimulation to the proper intraoral sensory nerves at the right timing with high spatio-temporal resolution. The intraoral device, as located in the intraoral space, has an advantage in both determining the timing of stimulation by monitoring the beginning of the pharyngeal phase of swallowing (i.e., end of the oral phase of swallowing) and accessing proper intraoral sensory nerves modulating the activity of pharyngeal muscles for swallowing.

We hypothesize that the electrical stimulation applied onto the soft palatal area inside the 2^{nd} molar excites the lesser palatine nerve and augments sensory feedback triggering the pharyngeal phase of swallowing.

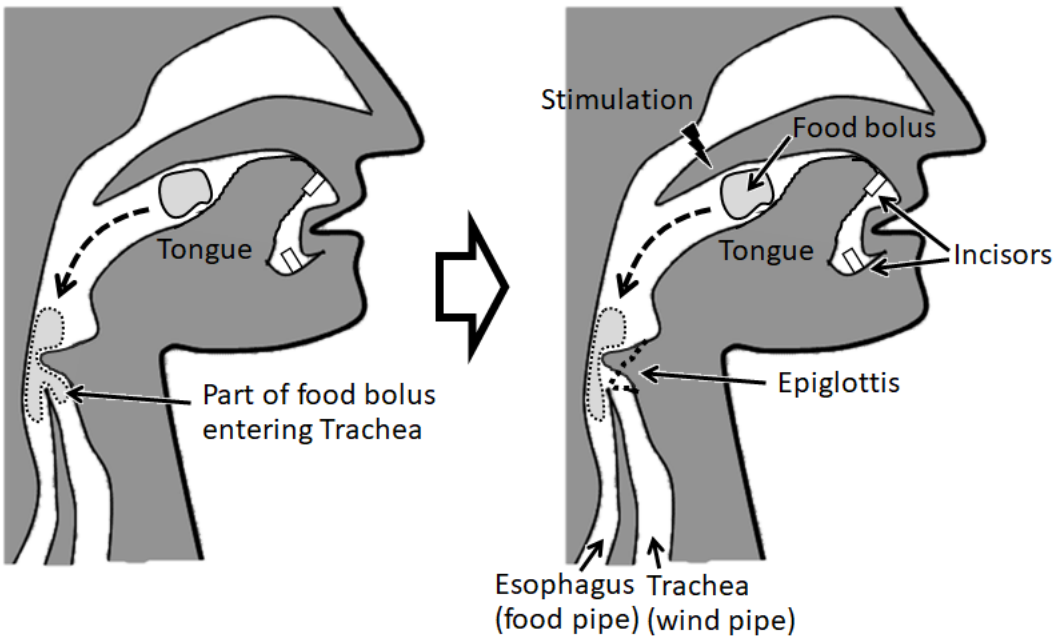

Figure 1.1: Research Hypothesis

2. PROTOTYPE DESIGN

2.1 Detecting pharyngeal phase of swallowing

Detection of the beginning of the pharyngeal phase of swallowing is important because we want to modulate the pharyngeal muscle activity during the pharyngeal phase of swallowing. We use the fact that tongue tip applies small pressure onto the upper incisors right before the pharyngeal phase of swallowing [21]. When the tongue-tip pressure increases over the predefined threshold, we recognize it as a the beginning of the pharyngeal phase of swallowing. As it is hard to anticipate the maximum pressure and the tongue tip is detached from the incisors right after the maximum pressure is applied, we triggered stimulation at the detachment of tongue tip from the incisors.

2.2 Modulating Swallowing Process

To modulate the swallowing process, we apply electrical stimulation to the soft palate area, inside the second molar, where the lesser palatine nerve resides, to excite and augment the sensory feedback which triggers the pharyngeal phase of swallowing. Note that, the lesser palatine nerve highly likely delivers the sensory feedback to modulate the pharyngeal muscle activity [22]

2.3 Prototype design

The intraoral device for the closed-loop monitoring and stimulation is built as a palatal retainer. The palatal retainer is custom made by pressing a dental thermoforming sheet onto a dental stone using a vacuum forming machine.

2.4 Pressure Sensor

2.4.1 Design Parameters

Various parameters had to be considered for selecting a pressure sensor :

- The pressure sensor should be small and thin in size so that it can accurately measure the tongue tip pressure and does not impede the swallowing process

- The pressure sensor should be made of bio-compatible material
- The performance of the pressure sensor should not vary haphazardly because of saliva in the mouth
- The pressure sensor should not deform because of pressure applied by the tongue-tip
- The pressure sensor should be easy to attach to the palatal retainer using bio-compatible glue

There were no pressure sensors commercially available which satisfied all the selection parameters. The pressure sensor used for this application was designed in the INPL lab at Texas A&M University.

2.4.2 Pressure Sensor Design

Because the pressure from the tongue tip is small and dispersed over the upper incisors, two separated ring electrodes were used instead of a typical pressure sensor. The electrodes need to be bio-compatible, so we used stainless steel as the material for electrodes. Two stainless-steel rings with 0.5-cm spacing work as a variable resistor and detect pressure by resistance change. One of the stainless-steel rings is connected to 3.3-V power supply via a fixed 20-k resistor while the other ring is connected to the ground. 20-k resistor is chosen because it is equivalent to the resistance of tongue and therefore gives maximum measurement sensitivity. The voltage at the lower side of 20-k resistor is measured by built-in analog-to-digital converter (ADC) of microcontroller.

A flexible 3 conductor 36 AWG shielded cable was used to connect the stainless steel rings to the microcontroller. It is difficult to solder copper wires on stainless steel, so arc welding was used to attach the wires to the electrodes. The electrodes were glued to the palatal retainer at the location of the middle two incisors on the upper jaw. The electrodes were glued using bio-compatible glue in such a way that the surface where the wires are welded is facing the palatal retainer, away from the tongue. Fig. 2.1 shows the pressure sensor glued to the palatal retainer.

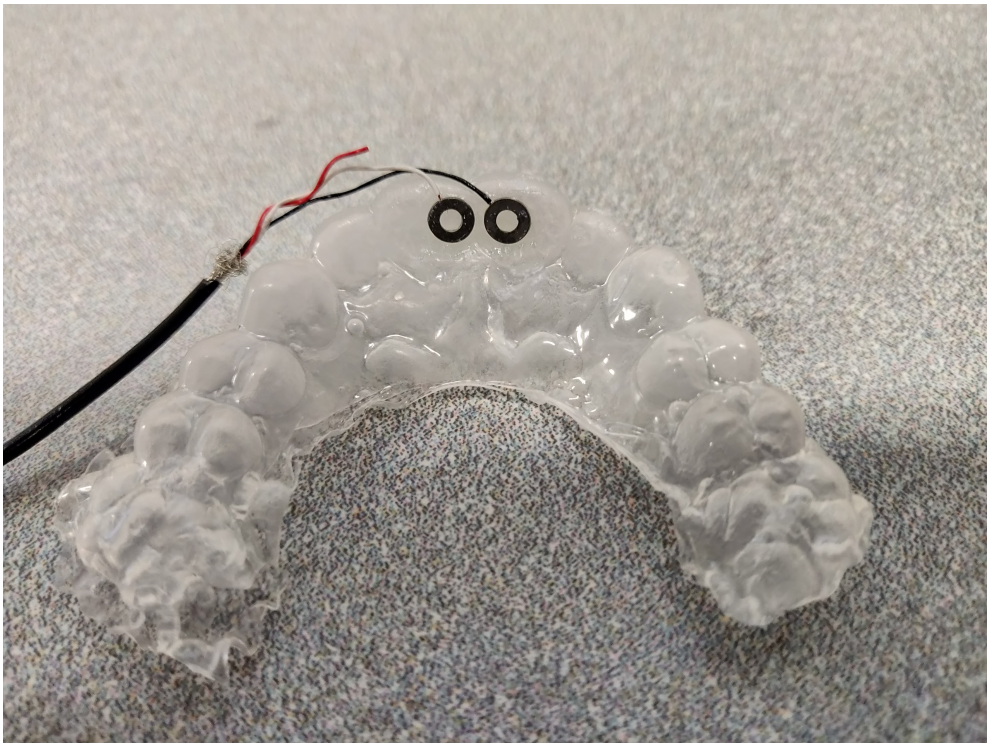

Figure 2.1: Pressure sensor design and integration with palatal retainer

2.4.3 Pressure Sensor Performance

The ADC voltage reads 3.3 V with no tongue contact, drops down to 1.65 V when the tongue slightly touches both rings, and increases again up to 2.1 V as tongue-tip pressure increases, as shown in Fig. 2.2 We expect that this increase of resistance is caused by the uneven surface of the tongue under the thin layer of saliva.

2.5 Stimulation system design

The stimulator system consists of two parts, the stimulator and the stimulation electrodes. The stimulator should be able to supply a minimum current to generate an action potential. This current varies between individuals. The stimulation electrodes need to be connected to the surface of the skin for generate the neural impulse.

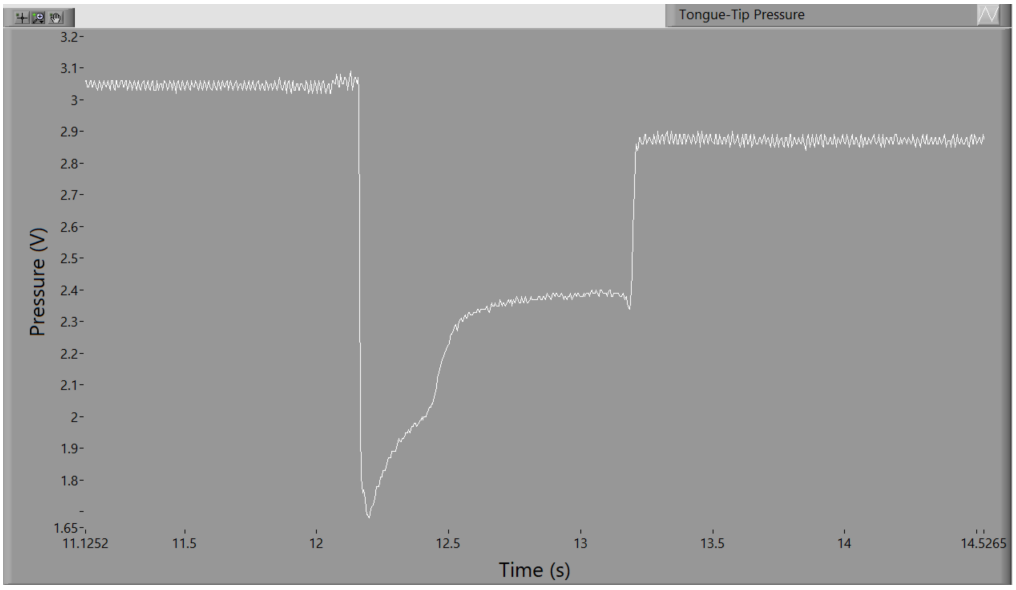

Figure 2.2: Pressure sensor performance

2.5.1 Stimulator

The stimulator is designed using CD4007UBE (Texas Instrument, TX, USA) and a potentiometer. Two NMOS and two PMOS transistors in the CD4007UBE are used to form a h-bridge (see Fig. 3.3) and the potentiometer is used to control the amount of current flowing through the stimulation electrodes.

2.5.2 Stimulation electrode

Various parameters had to be considered for selecting the stimulation electrode:

- The stimulation electrode should be small in size to target the intraoral sensory nerves and not impede in swallowing process
- The stimulation electrode should be made of bio-compatible material

There were no stimulation electrodes available commercially which satisfied both the selection parameters. The stimulation electrodes used for this application were designed in the INPL lab at Texas A&M University. Two stainless steel rings were used to form the stimulation electrode. A

flexible 3 stranded shielded cable was used to connect the stainless steel rings to the microcontroller. It is difficult to solder copper wires on stainless steel, so arc welding was used to attach the wires to the electrodes. One ring is connected to the positive end of h-bridge and the other ring is connected to the negative end of the h-bridge. The stainless steel electrodes are then covered with bio-compatible silicone to ensure that the surface of the electrode not attached to the surface of the skin remains insulated. The distance between the electrodes is around 1cm.

The saliva in the intraoral region makes it difficult to attach the stimulation electrodes to the skin surface. The silicone also assists in attaching the electrodes to the surface of the skin in the intraoral region. The cable connecting the electrodes to the stimulator circuit is stuck to the palatal retainer using bio-compatible glue, to ensure that the stimulation electrodes can remain in a fixed position for multiple trials.

2.6 Microcontroller board - Arduino DUE

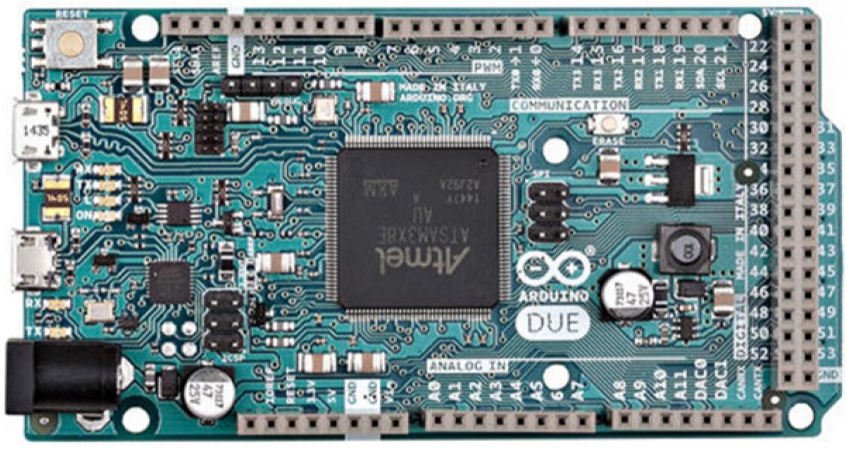

Figure 2.3: Arduino DUE board (Reprinted from [1])

2.6.1 Microcontroller

The Arduino DUE (see Fig. 2.3) is built on Atmel SAM3X8E ARM Cortex-M3 CPU. The SAM3XE has 2 blocks of 256KB (total of 512KB) of flash memory for storing the user programmed code. The program stored on this flash memory can be erased by pressing the on-board erase button. This button is connected to the RESET line of the microcontroller and when pressed, pulls the line low.

Atmel provides preburned bootloader in factory for the board, which is stored in a dedicated ROM memory. Two contiguous SRAM banks of 64KB and 32 KB are available for use. All available memory can be directly accessed as a flat addressing space.

2.6.2 Power Supply

The Arduino Due can be powered by a external battery or a USB connector, which it selects automatically based on the power supply connected. The external power can be supplied through the boards power jack or by connecting the leads of the battery to the Vin and Ground pins of the power connector of the Arduino DUE board. The operating supply voltage of the board is from 6V to 20V, though the recommended voltage is 7V to 12V. When supplied with a voltage under 7V, the Arduino Due cannot constantly give 5V at the 5V pin. When the supply voltage is over 12V, the board can be damaged because of overheating of the regulator

2.6.3 Input and Output

The Arduino DUE has 54 digital I/O pins. Each pin operates at 3.3V. The pins can act both as a current source or current sink. When operating as a current source, depending on the pin, they can source 3mA or 15mA of current. As a sink, the pins can sink 6mA or 9mA of current, depending on the pin. Every pin has an internal pull-up resistor of 100KOhm, which is disconnected by default. The pin direction (input or output) can be set using the pinMode() function. Based on the pin direction, the voltage on the pin can be set or read using the digitalWrite() and digitalRead() functions, respectively.

Some of the pins can also perform some specialized functions:

Serial : Pin 0 (RX) and Pin 1 (TX)

Serial 1 : Pin 19 (RX) and Pin 18 (TX)

Serial 2 : Pin 17 (RX) and Pin 16 (TX)

Serial 3 : Pin 15 (RX) and Pin 14 (TX)

These pins are used to send (TX) and receive (RX) TTL serial data with 3.3V level. Pins 0 and 1 are connected to the corresponding pins of the ATmega16U2 USB-to-TTL Serial chip.

PWM : Pins 2 to 13 - Provide 8-bit PWM output by default. The resolution of the PWM can be increased to 12-bit.

SPI : Through the SPI header

CAN : The CANRX and CANTX pins can be used for CAN communication

I2C : Pin 20 (SDA) and Pin 21 (SCL) can be used for I2C communication, along with the separate SDA1 and SCL1 pins.

The Arduino DUE has 12 Analog input pins (A0 to A11). The pins are connected to ADC which can be used to measure 0 to 3.3V with a maximum resolution of 12-bits. By default the resolution is set at 10-bits.

The board also has two DAC pins (DAC1 and DAC2) which can be used to provide true analog outputs with 12-bit resolution.

2.6.4 Communication

The Arduino DUE has various means available for communicating with a computer, another Arduino or a different microcontroller and other different devices. One hardware UART and three hardware USARTs are available for serial communication using TTL at 3.3V.

Two USB ports are available on the Arduino DUE, one called the programming port and the other called the native USB port. The native USB port is connected to the SAM3X and allows for serial communication over USB. This can be used to emulate a USB mouse or keyboard to an attached computer. The programming port, on the other hand, is connected to ATmega16U2 microcontroller, which provides a virtual COM port to software on a connected computer. This programming port can be used to program the board (upload sketches) using the Arduino IDE.

3. TESTING THE HYPOTHESIS AND PROTOTYPE

Two kinds of experiments were performed to test the operation of the proposed intraoral closed-loop monitoring and stimulation system. Experiments were designed to prove that the electrical stimulation applied to the lesser palatine nerve can change the pharyngeal muscle activity during the pharyngeal phase of swallowing. One male and one female subjects participated in the experiment according to the procedure described in the protocol approved by the Texas A&M Institutional Review Board. A total of 5 trials were conducted on each of two subjects.

3.1 Monitoring pharyngeal phase of swallowing

To monitor the resulting pharyngeal muscle activity, a 3D accelerometer was located on the thyroid cartilage using a sports cotton tape, as in Fig. 3.1 [23, 24]. The 3D accelerometer detects the laryngeal excursion during the overall phase of swallowing [22].

Figure 3.1: Placement of accelerometer

3.2 Accelerometer

The accelerometer used for measuring laryngeal excursion is a commercial-off-the-shelf 3-axis analog accelerometer, ADXL337 (Analog devices, MA, USA), shown in Fig. 3.2. This accelerometer has high sensitivity of 300 mV/g, to sufficiently measure the acceleration of laryngeal excursion ranging over 0.01-0.1 g [24]. The accelerometer is powered by supplying 3.3V and ground from the Arduino to the corresponding power pins of the breakout. The accelerometer has a bandwidth range of 0.5Hz to 1600Hz for x and y axes and 0.5Hz to 550Hz for the z axis. The x, y and z-axis output of the accelerometer are connected to three ADC pins on the microcontroller, respectively.

The accelerometer is oriented in such a way that the accelerometer movement in the anterior direction and posterior direction is recorded as acceleration along the +z axis and -z axis, respectively..

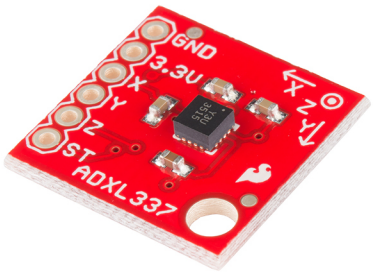

Figure 3.2: ADXL337 Breakout (Reprinted from [2])

3.3 Experimental Setup

The overall system block diagram is shown in Fig. 3.3. The pressure sensor output and the pins corresponding to the x-axis, y-axis and z-axis of the 3D accelerometer were connected to analog pins A0,A1,A2 and A3 of the Arduino DUE, respectively. The pressure sensor and stimulation

electrodes were stuck to the palatal retainer using bio-compatible glue. The thyroid cartilage for each subject was identified by placing a finger at a nearby approximate location and asking the subject to sip a spoonful of water to precisely detect the location of the thyroid cartilage.

The exact location of the stimulation was identified for each subject. The stimulating electrode was designed to be located onto the soft palatal area inside the second right molar, however the location was fine-tuned by bending wires. A continuous bi-phasic stimulation was provided at 5V, to determine the exact location. The wires were bent with hand to move the stimulation electrodes and identify the location where the subject had a sensory perception. The current delivered to the electrodes was then reduced by increasing the resistance using the variable resistor and the sensory perception of the user was found. By repeating the process of finding stimulation perception, we found the best stimulation location having the lowest stimulation threshold. Finally, the sensory threshold (T) based on each subject's subjective perception was established.

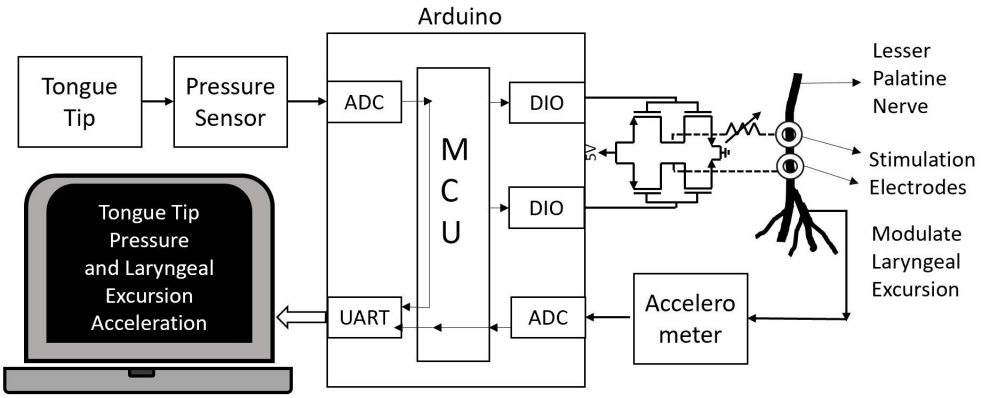

Figure 3.3: Block Diagram of Experimental Setup

3.3.1 Arduino Code

Both pressure sensor data from the palatal retainer and accelerometer data from the neck were delivered to the computer via Arduino DUE using UART interface. The Arduino was programmed to send the data at the rate of 57600 baud. Data from the pressure sensors was sent first, followed

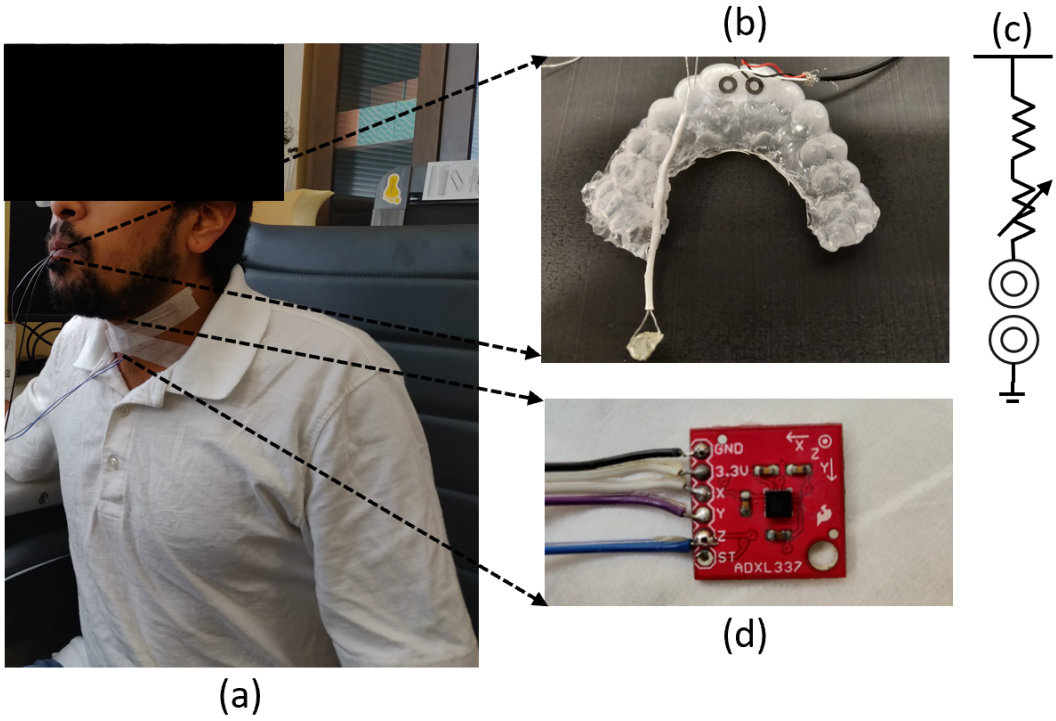

Figure 3.4: Image of Experimental Setup

by the ADC values measured by the accelerometer along the x-axis, y-axis and z-axis.

3.3.2 LabVIEW GUI

A LabVIEW GUI (called as a LabVIEW VI) records the sensor data received from the Arduino. Serial VISA Communication libraries available on LabVIEW IDE are used for communicating with the Arduino. On running the LabVIEW VI, a serial port corresponding to the serial port to which the arduino is connected, is opened using the Configure Serial Port SubVI. The Serial Port SubVI has various input options to configure the serial port. These include the VISA Resource name, baud rate, number of data bits, parity, flow control, error input, stop bits, Enable Termination Char, termination char and timeout. If the serial port is busy or already being used by another application, the LabVIEW code throws an error and stops automatically after it times out. The default timeout value is 10s and it can be made infinite by setting the timeout input to -1. Other inputs also have default values - baud rate (9600), data bits (8), parity (0:none), error input (no

error), number of stop bits (10: 1 bit), flow control (0: none), Enable Termination Char (True) and termination char (0xA = new line character). For the purpose of our application, we used the following values : timeout (1s), baud rate (19200), data bits (8), parity (0:none), error input (no error), stop bits (10: 1 bit), flow control (1: XON/XOFF), Enable Termination Char (True) and Termination Char (0XA = new line char).

Upon establishing serial communication, the LabVIEW VI first flushed the buffer using the VISA Flush IO Buffer SubVI. The VI then entered a continuous while loop until the cancel button (X button on the top right corner of the front panel) was clicked. During every iteration of the while loop, 8 bytes of data were read from the serial buffer. In the first iteration, pressure sensor value was read from the serial buffer and displayed on the graph corresponding to the pressure sensor (top-most graph on the front panel). In the second iteration, acceleration along x-axis was read from the serial buffer and displayed on the graph corresponding to the x-axis acceleration (second graph from top on the front panel). In the third iteration, acceleration along y-axis was read from the serial buffer and displayed on the graph corresponding to the y-axis acceleration (third graph from top on the front panel). In the fourth iteration, acceleration along z-axis was read from the serial buffer and displayed on the graph corresponding to the z-axis acceleration bottom-most on the front panel). This order was followed for all the following iterations. All the graph indicators were designed as flat controls in the lab.

At the start of the while loop, time was recorded using the High Resolution Relative Seconds SubVI in-built in LabVIEW. During every iteration, the time was recorded again using the same SubVI. The difference between the time recorded in every iteration and the initial recorded time was stored in an array for every iteration. Once the cancel button was pressed, the IO buffer was flushed and the Serial port was closed using the VISA Close button. All the sensor data and time data was stored in a .csv file which can be used for further processing. Fig. 3.5 shows the front panel and Fig. 3.6 shows the block diagram of the LabVIEW VI, respectively.

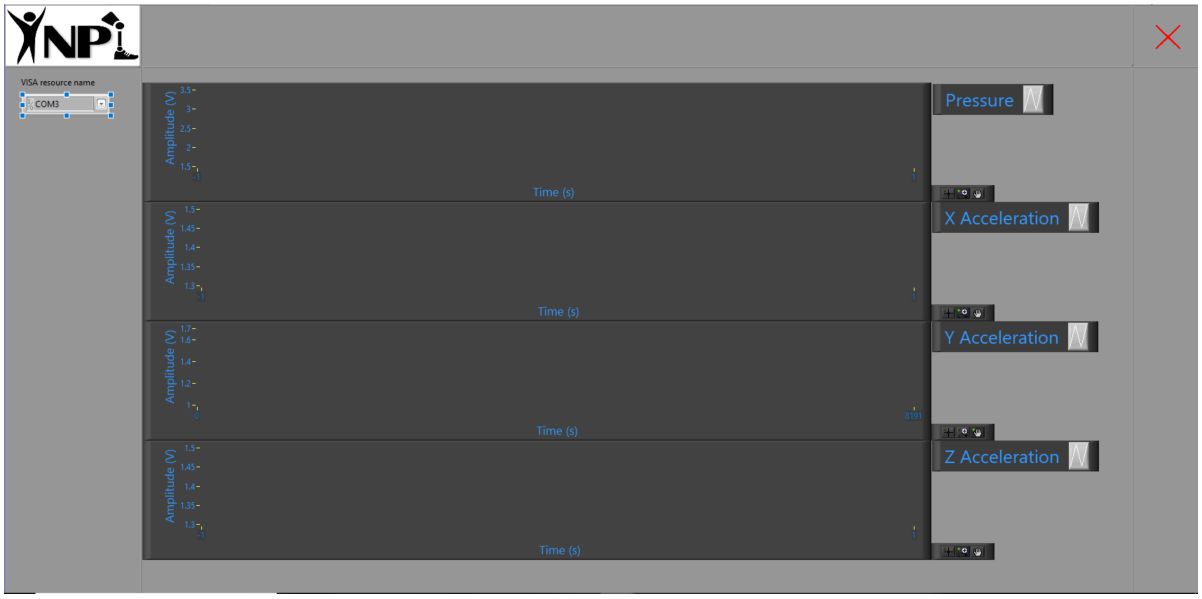

Figure 3.5: LabVIEW GUI for experiments

3.3.3 Data Processing

Data stored on the computer in the form of .csv file was used to evaluate the pharyngeal muscle activity by measuring timing and amplitude of the laryngeal excursion. The raw data from the accelerometer was noisy and it became difficult to identify the start and end of the laryngeal excursion from the raw data. So some form of filtering was required to accurately identify the timing and amplitude values of the laryngeal excursion.

To filter the data, it was important to first find the time difference between every two data points recorded for the z-axis acceleration data. The timing data recorded while running the experiment was used and the average of the time difference was first calculated. Using this time difference, a waveform was created. The amplitude of the waveform was the array of z-axis acceleration values. The initial time (t) was 0 and the time difference Δt was the average time difference calculated. LabVIEW created this waveform which could be used as an input for available filters on LabVIEW. To filter the waveform, the Filter Express VI was used. The Express VI is an in-built LabVIEW VI, the setting of which can be changed interactively through a dialog box. Low-pass filter was selected as the filter type. Because the pharyngeal transit time in adults is close to 0.8 seconds [25],

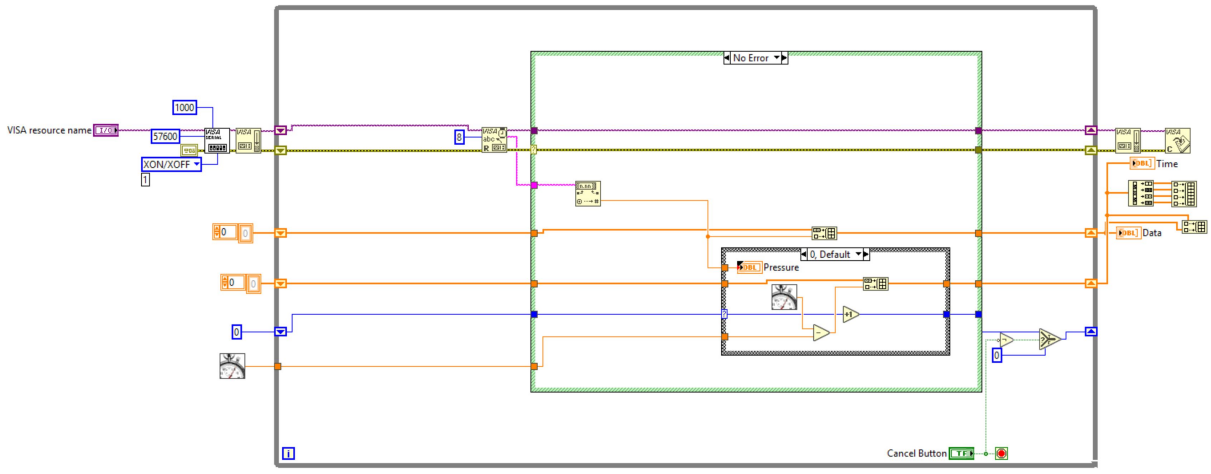

Figure 3.6: LabVIEW Block Diagram for collecting experimental data

the lower cut-off frequency of the filter was selected as 20 Hz. .

3.4 Experimental Design and Recorded Data

3.4.1 Experiment 1

The first experiment was designed to determine how consistent the timing and amplitude of the laryngeal excursion is, for normal swallowing. Subjects first wore the palatal retainer on their upper palate and the operator attached the accelerometer module on subject's neck, as in Fig. 3.4a. The subjects were then asked to put their empty fist between their chin and neck, to maintain the head posture relative to the pharyngeal region consistently for all trials. The head posture was later verified by the accelerometer output. The subjects were then asked to take a sip of water, hold it between the tongue and the hard palate for approximately 10 seconds to avoid the recording of unnecessary tongue movements, and swallow it at once. The sensor data corresponding to the tongue tip pressure and the acceleration of laryngeal excursion was recorded and saved to the computer. After each trial, the subjects were asked to take off the palatal retainer and the pressure sensor was cleaned with alcohol prep pads to remove any saliva and maintain the sensitivity.

The recorded data was filtered and timing and acceleration values were found for every trial. Every laryngeal excursion has two phases each starting with an acceleration minima along z-axis

and ending with an acceleration maxima along the z-axis. The laryngeal excursion starts at the minima of the first phase and ends at the maxima of the second phase as shown in Fig 3.7. The x-axis of the graph represents the recorded time. Along the y-axis, pressure sensor data is represented in terms of recorded voltage (V) and raw and filtered acceleration data is represented in (m/s2). Plot 0 (in white) represents pressure sensor data, Plot 1 (in blue) represents raw z-axis acceleration data (V) and Plot 2 represents (in green) filtered z-axis acceleration data (V). The high amplitude of digital noise in the raw z-axis acceleration data is because the accelerometer data is being acquired at a faster rate than its allowable bandwidth of 500Hz

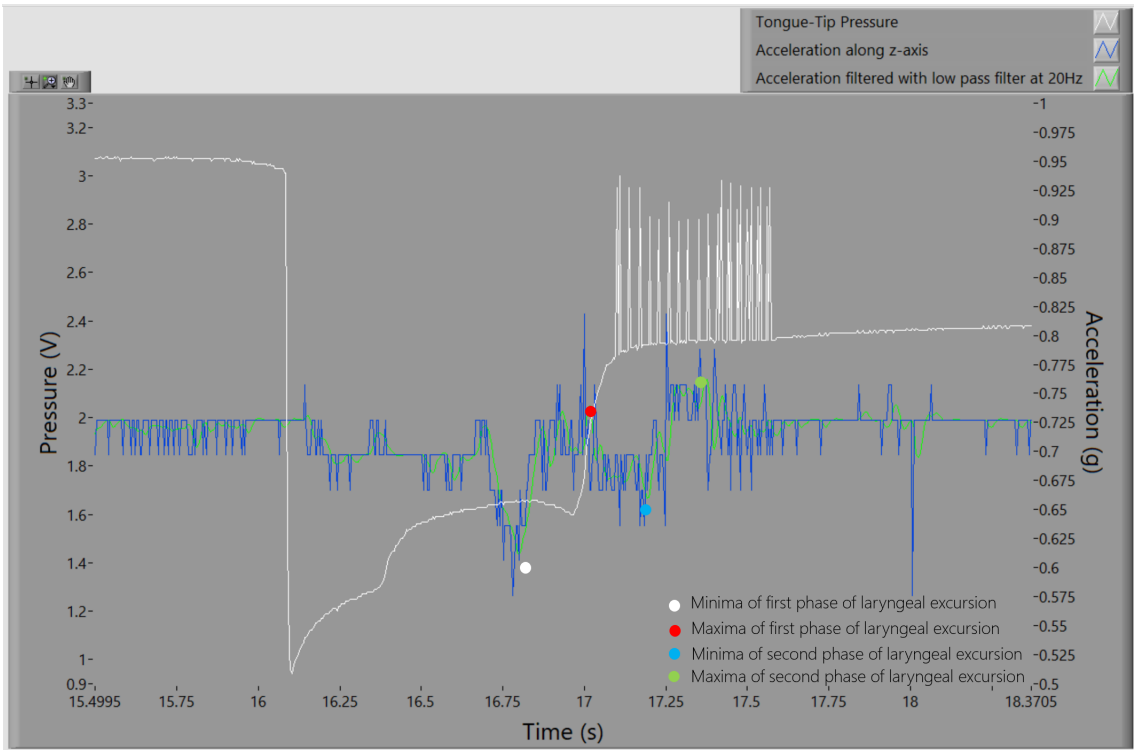

Figure 3.7: Important points during a Laryngeal Excursion

- Key timing values recorded
  - Trial number : Counter of trial conducted

  - Tongue Detach Time : Time after the beginning of the experiment when the tongue is detached from the pressure sensor
  - First Laryngeal Crest (FLC) : Time after the beginning of the experiment when the first laryngeal crest is observed during laryngeal excursion
  - First Laryngeal Crest (FLT) : Time after the beginning of the experiment when the first laryngeal trough is observed during laryngeal excursion
  - Second Laryngeal Crest (SLC) : Time after the beginning of the experiment when the second laryngeal crest is observed during laryngeal excursion
  - Second Laryngeal Crest (SLT) : Time after the beginning of the experiment when the second laryngeal trough is observed during laryngeal excursion

- Key acceleration values recorded
  - Trial number - Counter of trial conducted
  - First Laryngeal Crest (FLC) - Acceleration value at first laryngeal crest during laryngeal excursion
  - First Laryngeal Trough (FLT) - Acceleration value at first laryngeal trough during laryngeal excursion
  - Second Laryngeal Crest (SLC) - Acceleration value at second laryngeal crest during laryngeal excursion
  - Second Laryngeal Trough (SLT) - Acceleration value at second laryngeal trough during laryngeal excursion

Table 3.1 and Table 3.2 show the key timing values recorded for the first and second subject, respectively, during the first experiment. The tongue detach time is different between trials for a subject because of difference in time at which the data acquisition is started and slight variation in swallowing style of the subject in every trial. Table 3.3 and Table 3.4 show the key acceleration values recorded for the first and second subject, respectively, in the first experiment

Trial No.	Tongue Detach (s)	FLC (s)	FLT (s)	SLC (s)	SLT (s)
1	11.456	11.295	11.332	11.735	11.881
2	27.19	26.847	26.982	27.263	27.416
3	14.76	14.414	14.604	14.84	14.948
4	14.985	14.612	14.743	14.951	15.175
5	17.797	17.514	17.736	17.936	18.084

Table 3.1: Key timing values recorded for first subject in Experiment 1

Trial No.	Tongue Detach (s)	FLC (s)	FLT (s)	SLC (s)	SLT (s)
1	14.012	14.147	14.339	14.61	14.732
2	13.207	13.386	13.562	13.816	14.045
3	20.598	20.733	21.042	21.23	21.351
4	8.044	8.074	8.5	8.828	8.933
5	12.675	12.804	13.133	13.275	13.644

Table 3.2: Key timing values recorded for second subject in Experiment 1

Trial No.	FLC (g)	FLT (g)	SLC (g)	SLT (g)
1	0.368	0.484	0.38	0.49
2	0.351	0.447	0.363	0.444
3	0.387	0.453	0.4	0.485
4	0.355	0.436	0.4	0.467
5	0.384	0.482	0.398	0.506

Table 3.3: Key acceleration values recorded for first subject in Experiment 1

Trial No.	FLC (g)	FLT (g)	SLC (g)	SLT (g)
1	0.265	0.314	0.275	0.328
2	0.285	0.327	0.283	0.344
3	0.273	0.315	0.285	0.345
4	0.263	0.342	0.287	0.349
5	0.27	0.326	0.277	0.318

Table 3.4: Key acceleration values recorded for second subject in Experiment 1

3.4.2 Experiment 2

The second experiment was designed to determine if the closed-loop intraoral stimulation can modulate the timing and amplitude of the laryngeal excursion. The experimental procedure is same as exp. 1 except the electrical stimulation applied on the lesser palatine nerve. We stimulated the soft palatal area inside the 2^{nd} right molar, potentially lesser palatine nerve, when the tongue tip is removed from the pressure sensor. Note that, the food bolus touches the lesser palatine nerve at the beginning of the pharyngeal phase of swallowing, and we basically try to augment the sensory feedback delivered via the lesser palatine nerve.

The stimulation circuit was connected to a second Arduino DUE. The first Arduino DUE is programmed to detect the time when stimulation has to be started and send a digital signal (digital high) to the second Arduino DUE. The second Arduino DUE constantly polls its digital pin connected to the first Arduino for the digital signal (digital high) and starts the stimulation. To detect the start of stimulation, the pressure sensor value had to first cross a lower threshold which was found beforehand and varied for both subjects. Once it crosses the lower threshold, we look for the pressure sensor to reach an upper threshold which again varies from one subject to other and is found beforehand. As soon as the upper threshold is reached, we detect this as the start of the pharyngeal phase of swallowing and start the stimulation.

As stimulation parameters, we selected 100 Hz of carrier frequency that has been used to elicit tactile feedback in several previous works [26, 27], and 500 ms of stimulus train duration to stimulate over the entire pharyngeal phase of swallowing. The stimulation is bi-phasic and has a duty cycle of 10% for each phase, as shown in Fig 3.8. We also selected 5V of stimulation voltage. The same evaluation methods as Experiment 1 were used to determine the timing and amplitude of the laryngeal excursion. In addition to the parameters recorded during Experiment 1, the time of Start of Stimulation (SS) and time of End of Stimulation (ES) are also recorded. The Arduino DUE was programmed to send y-axis acceleration data as 1.0 at the start of stimulation. This data point was used to find the time of start of stimulation. The time of end of stimulation was computed to be 0.5s greater than the time of start of stimulation.

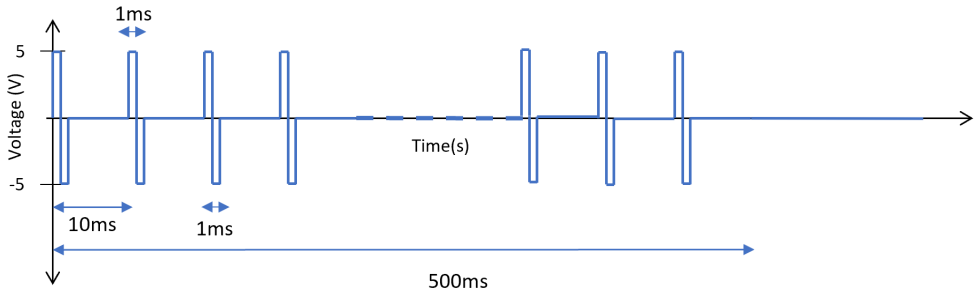

Figure 3.8: Bi-phasic signal waveform

Table 3.5 and Table 3.6 show the key timing values recorded for the first and second subject, respectively, during the second experiment. Table 3.7 and Table 3.8 show the key acceleration values recorded for the first and second subject, respectively, in the first experiment

Trial No.	**Tongue Detach (s)**	**FLC (s)**	**FLT (s)**	**SLC (s)**	**SLT (s)**	**SS (s)**	**SE (s)**
1	7.864	7.741	7.966	8.114	8.236	7.88	8.38
2	13.813	13.644	13.865	14.013	14.082	13.83	14.33
3	16.996	16.803	17.016	17.189	17.281	17.01	17.51
4	14.221	13.963	14.12	14.389	14.43	14.231	14.73
5	27.478	27.177	27.378	27.534	27.714	27.49	27.99

Table 3.5: Key timing values recorded for first subject in Experiment 2

Trial No.	**Tongue Detach (s)**	**FLC (s)**	**FLT (s)**	**SLC (s)**	**SLT (s)**	**SS (s)**	**SE (s)**
1	13.046	13.144	13.3	13.452	13.522	13.06	13.56
2	17.22	17.486	17.725	17.893	17.944	17.235	17.735
3	10.98	11.166	11.236	11.28	11.329	10.995	11.495
4	14.733	14.876	15.105	15.309	15.375	14.75	15.25
5	15.573	15.737	15.806	15.851	15.926	15.585	16.085

Table 3.6: Key timing values recorded for second subject in Experiment 2

Trial No.	FLC (g)	FLT (g)	SLC (g)	SLT (g)
1	0.346	0.424	0.371	0.447
2	0.353	0.419	0.353	0.445
3	0.368	0.442	0.396	0.454
4	0.348	0.414	0.339	0.445
5	0.336	0.427	0.352	0.427

Table 3.7: Key acceleration values recorded for first subject in Experiment 2

Trial No.	FLC (g)	FLT (g)	SLC (g)	SLT (g)
1	0.35	0.4	0.365	0.41
2	0.323	0.363	0.344	0.372
3	0.318	0.353	0.309	0.378
4	0.304	0.359	0.315	0.345
5	0.3	0.335	0.31	0.359

Table 3.8: Key acceleration values recorded for second subject in Experiment 2

3.5 Data Analysis and Interpretation

Based on the data recorded for both subjects in both the experiments, we tried to characterize the laryngeal excursion by both peak-to-peak duration and peak-to-peak amplitude between the minimum and maximum peaks. The minimum peak was always detected at the earlier phase and the maximum peak was always detected at the later phase of pharyngeal swallowing. We used the recorded data to compute the following parameters :

- Time (FLT-TD) : The time difference between Tongue Detach and First Laryngeal Trough
- Time (SLC-FLT) : The time difference between First Laryngeal Trough and Second Laryngeal Crest
- Acc (FLT-SLC) : Change in acceleration between First Laryngeal Trough and Second Laryngeal Crest

The computed data for one trial was plotted on a graph with two y-axes, one each for tongue-tip pressure in percentage and acceleration along z-axis (AP direction). The x-axis shows adjusted

time. The adjusted time was considered 0s at the time when pressure sensor value recorded is minimum. The pressure at this instant was considered 0%. The maximum value of pressure sensor was recorded before the experimental trials began by asking the subject to press continuously on the pressure sensor. The variation in pressure sensor value is linear with the recorded voltage. So, considering the maximum pressure recorded as 100% and minimum pressure recorded as 0%, the data recorded by the pressure sensor through the swallowing process was represented in terms of percentage.

3.5.1 Experiment 1

In the first experiment, we use the recorded experimental data to characterize the laryngeal excursion of both subjects without any applied electrical stimulation. Table 3.9 and Table 3.10 show the computed values for characterizing laryngeal excursion for subject 1 and subject 2, respectively.

Trial No.	**Time (FLT-TD) (s)**	**Time (SLC-FLT) (s)**	**Acc (FLT-SLC) (g)**
1	-0.161	0.586	0.122
2	-0.343	0.569	0.093
3	-0.346	0.534	0.098
4	-0.373	0.563	0.112
5	-0.283	0.57	0.122
Average	-0.301	0.564	0.109
Standard Deviation	0.076	0.017	0.012

Table 3.9: Computed time and acceleration values for first subject in Experiment 1

Fig. 3.9 shows the exemplary laryngeal excursion without stimulation, for both subjects. One of the first observation in the trials was the difference in the start of swallowing for each subject. The second subject starts swallowing before the tongue is detached from the incisors, while the first subject starts swallowing after the tongue is detached from the incisors.

Filled dots in Fig. 3.11 show how consistent peak-to-peak duration and amplitude for each subject is, by representing average and standard deviation. For the first subject, the average laryn-

Trial No.	Time (FLT-TD) (s)	Time (SLC-FLT) (s)	Acc (FLT-SLC) (g)
1	0.135	0.585	0.063
2	0.179	0.659	0.059
3	0.135	0.618	0.072
4	0.03	0.859	0.086
5	0.129	0.84	0.048
Average	0.122	0.712	0.066
Standard Deviation	0.049	0.115	0.013

Table 3.10: Computed time and acceleration values for second subject in Experiment 1

geal excursion time was 0.564 s with a standard deviation of 0.017 s. For the second subject, the average laryngeal excursion time was 0.712 s, with a standard deviation of 0.115 s. We consider the values as consistent enough to test the effect of stimulation between trials.

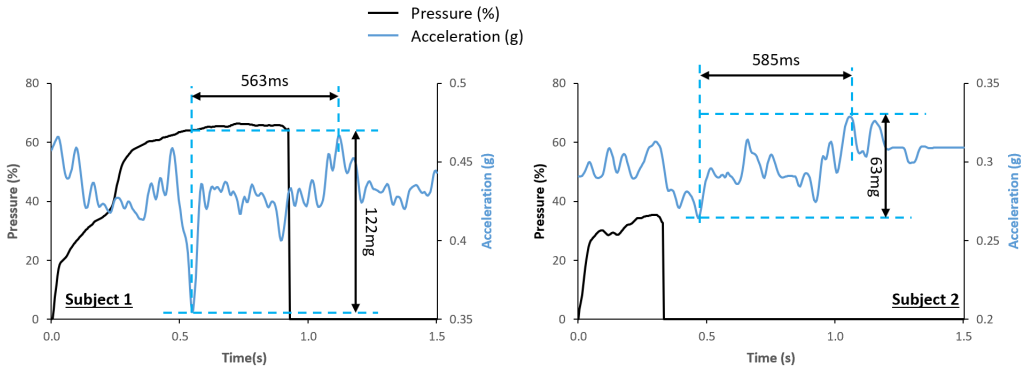

Figure 3.9: Laryngeal excursion measurements for Experiment 1

3.5.2 Experiment 2

Electrical stimulation was applied for 500 ms, starting right after subjects detached their tongue from the incisors. Table 3.11 and Table 3.12 show the computed values for laryngeal excursion, with stimulation, for subject 1 and subject 2, respectively. As shown in Fig. 3.10, peak-to-peak duration was decreased by 14.4% on average and 52.6% on average, for the first and the second subjects, respectively. By one-tailed t-test with 95% confidence interval, with hypothesis of

duration being decreased by stimulation, we could get statistically meaningful reduction of peak-to-peak duration caused by stimulation, for both subjects. However, by two-tailed t-test with 95% confidence interval, with hypothesis of amplitude being changed by stimulation, statistical test result shows that the peak-to-peak amplitude was not changed by stimulation, for both subjects.

Trial No.	**Time (FLT-TD) (s)**	**Time (SLC-FLT) (s)**	**Acc (FLT-SLC) (g)**
1	-0.123	0.495	0.101
2	-0.169	0.438	0.092
3	-0.193	0.478	0.086
4	-0.258	0.467	0.097
5	-0.301	0.537	0.091
Average	-0.209	0.483	0.093
Standard Deviation	0.063	0.033	0.005

Table 3.11: Computed time and acceleration values for first subject in Experiment 2

Trial No.	**Time (FLT-TD) (s)**	**Time (SLC-FLT) (s)**	**Acc (FLT-SLC) (g)**
1	0.098	0.378	0.06
2	0.266	0.458	0.049
3	0.186	0.163	0.06
4	0.143	0.499	0.041
5	0.164	0.189	0.059
Average	0.171	0.337	0.054
Standard Deviation	0.056	0.138	0.008

Table 3.12: Computed time and acceleration values for second subject in Experiment 2

Experimental results show that the peak-to-peak duration is reduced by the closed-loop stimulation, which means that the pharyngeal phase of swallowing can start earlier by the electrical stimulation. Experimental results also show that second subject showed much bigger reduction of peak-to-peak duration than the first subject. We expect that it is because the stimulation was applied earlier for the second subject. As in Fig. 3.10, stimulation was applied in the middle of

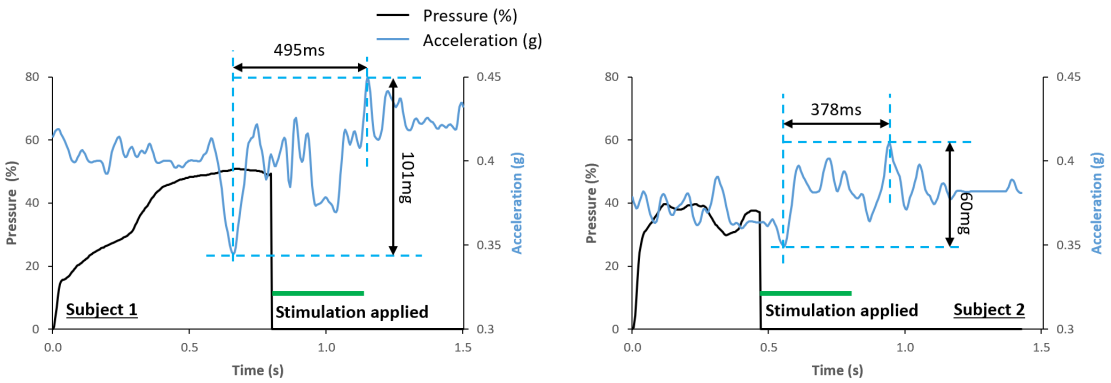

Figure 3.10: Laryngeal excursion measurements for Experiment 2

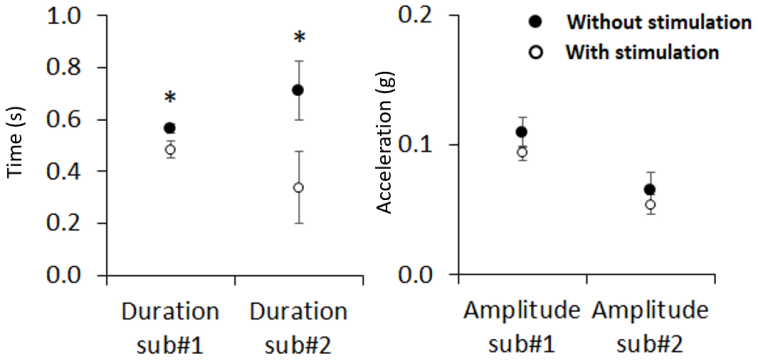

Figure 3.11: Comparison of peak-to-peak amplitude and peak-to-peak time of laryngeal excursion with and without stimulation

the laryngeal excursion for first subject, but stimulation was applied at the beginning of the laryngeal excursion for the second subject. Much larger reduction in peak-to-peak duration in the second subject rather supports our hypothesis that the electrical stimulation augments the sensory feedback triggering the pharyngeal phase of swallowing.

4. MARKET VALIDATION

4.1 Market Research - NSF I Corps - Site

The proposed medical device is a first of its kind research idea for treatment of Dysphagia. While the proof-of-concept showed promising results on the first two subjects, the working of the device had to be tested on more subjects, including patients who suffer from Dysphagia. At the beginning of this research, we wanted to build a product which can be used in the market. So, we wanted to build the next version of the prototype taking into mind, the needs of the market and try to incorporate the suggestions of various stakeholders that are involved in the treatment of Dysphagia. As part of the NSF I Corps - Site program organized at Texas A&M University, we tried to validate the hypothesis, improve design and find the market potential of this device, under the name of Gulp.

USP of Gulp : Gulp tracks the swallowing activity of patients and uses electric stimulation to modulate the swallowing activity. The high spatio-temporal resolution of the stimulation increases the efficacy of the stimulation. Unlike other NMES devices, Gulp does not require continuous stimulation thereby reducing the current required and pain caused by subjecting the patients to electric stimulation for longer times.

During the 8 weeks spent in Fall 2018, various stakeholders, involved in the treatment of Dysphagia, were targeted. These include patients, their caretakers, speech and language therapists (SLT), neurologists, university researchers and nurses. A total of 28 interviews were conducted by the team with at least one interview from the above mentioned stakeholder. Interviews were conducted by not giving the customers a complete idea of the proposed device, so as to not bias the answers for questions asked during the interview. We initially conducted the interviews to validate certain hypotheses that we had. These include :

- Stimulating the lesser palatine nerve can help in modulating the swallowing process
- A dental palatal retainer does not hinder swallowing activity in mouth

- Patients suffering from stroke are the most common who undergo dysphagia treatment
- Current techniques target stimulation at the neck region and dont time with the swallowing phase

The customer interviews validated all the hypotheses we had, but also gave us additional insights about customer requirements, existing treatments and other possible markets which could be targeted.

Some of the key learnings from this program are as follows:

- Stimulation on soft palate can help in treating migraine
- Electrical stimulation cannot be an exclusive therapy for Dysphagia
- No FDA recalls for E-Stim devices like VitalStim in last 5 years
- Most patients who suffer from Dysphagia stop therapy because of lack of insurance coverage
- Treatment can take months depending on how early it is started, after the stroke
- Lot of patients undergo home health therapy

The Total Market Size (TMS) is approximated to be over 800,000 patients every year and a market revenue of 130 million USD. The interviews gave us a good idea about the size of the market which could be targeted for introducing the device. The total number of patients which could be targeted initially is the number of stroke patients suffering from Dysphagia, which is over 520,000. 30% of interviewers were willing to use this device. So, taking this into account, the Serviceable Market Size (SMS) reduces to 156,000 patients and a market revenue of over 40 million USD. The final decision for the project was a "Go" with modifications in the idea to build an intraoral platform which can be used to treat multiple disorders which can be treated with stimulation on the soft palate, along with Dysphagia.

4.2 Wireless Prototype

Next, I am currently working on building a wireless prototype for the medical device which can transmit sensory data to an external display device, either for display or decision making for the start of electrical stimulation. The wireless prototype should have the following features:

- Ability to communicate to an external device to a distance of 5-10m
- Should consume very low energy
- Provide interface to communicate with external sensors and actuators
- Support for the components of the prototype should be available from the manufacturer for at least 5 years

With the following features in mind, we decided on using CC2640R2F, a BLE microcontroller manufactured by Texas Instruments, as the microcontroller for the wireless prototype.

A proof-of-concept of the device was then built using a CC2640R2F Launchpad, shown in Fig. 4.1. The CC2640R2F is built on SimpleLink ^{TM}microcontroller platform. The device supports Bluetooth 5 high speed mode along with 4.2 certified software stacks. The device runs on a 32-bit ARM Cortex-M3 microcontroller, which runs at 48MHz. The peripherals available on the device allow for communication with various kind of I/O devices.

The software for the device was developed using existing projects provided by Texas Instruments on Code Composer Studio. Two CC2640R2F launchpads were used to test the working of the prototype, one acting as a master and the other acting as the slave. The master initiates the communication with the slave device and controls the communication parameters.

The first launchpad is connected to the pressure sensor and accelerometer using on-board ADC pins. Two DIO pins were used to control the stimulator. Because every act of initiating communication consumes current, this launchpad is made the slave device, to reduce the amount of current it consumes. Upon establishing connection with the master, the device captures the sensory information, processes data to make decision on stimulation, packs the data to be transmitted according

Figure 4.1: CC2640R2F Launchpad-XL (Reprinted from [3])

to the protocol and places it in the BLE buffer. Once the master requests for data transmission, the latest data in the BLE buffer is sent to the master.

The second launchpad acts as the master and constantly pings the first launchpad to send the data it requires. The data is then relayed to a laptop computer using UART and displayed on a built LabVIEW GUI to validate the received data. Upon power-up, the launchpad enters Discovery state and constantly discovers new Bluetooth devices till it finds 8 devices. Once it discovers 8 devices, it leaves the discovery state and tries to find the MAC Address of the first launchpad. If it does not find the first launchpad in the 8 devices, it re-enters the discovery state. If the MAC address for the first launchpad is found, it enters the Communication Initiate state, where it tries to establish communication with the first launchpad. Once communication is established, it constantly polls the first device for transmission of required data, which is sent as a single message. Once, the data is received, it sorts the data according to the decided protocol and prints it using serial communication protocol, which is then displayed on the designed GUI.

5. CONCLUSIONS AND FUTURE WORK

Based on the initial prototype and the experimental results, we were able to verify the hypothesis behind the research and conclude that stimulation to the soft palatal area inside the 2^{nd} right molar, potentially lesser palatine nerve, can reduce the duration of the pharyngeal phase of swallowing. When the stimulation was better synced with the onset of pharyngeal swallowing, the result was better observed. This result suggests that the closed-loop intraoral stimulation on the soft palatal area inside the 2^{nd} molar can be used to treat swallowing problems. By activating the pharyngeal muscle quicker, we can help people with swallowing problems to close their airway better and have less problem in swallowing. The experimental results also show that the acceleration of laryngeal excursion does not change by electrical stimulation.

For future studies, we need to try different stimulation patterns and timings. Also, more subjects need be recruited to increase the statistical power. Also, an accurate nerve map will have to be built onto the soft palatal area inside the molar using imaging techniques, to identify the nerve to be stimulated.

The NSF I-Site study validated the need for this device in the market while also opening up avenues for building this device as a platform for soft palatal stimulation to treat other neurological disorders like migraine and obstructive sleep apnea(OSA).

The next step will be to enter Gulp in the NSF I-Site national program, which can give the opportunity to conduct 150 customer interviews and build a working wireless prototype for next phase of subject trials. First, proof-of-concept wireless prototype of the device will have to be built to establish the ability to communicate the sensory data captured by the device to another external device, using Bluetooth. This will be followed by designing a PCB which houses the microcontroller along with the sensor peripherals, stimulator and battery charger, and validating the working of this PCB and using it in patient trials

REFERENCES

[1] Arduino, "DUE." https://store.arduino.cc/usa/arduino-due.

[2] SparkFun, "SparkFun Triple Axis Accelerometer Breakout - ADXL337." https://www.sparkfun.com/products/12786.

[3] Texas Instruments, "CC2640R2F." https://www.ti.com/tool/LAUNCHXL-CC2640R2.

[4] Bhattacharyya N, "The prevalence of dysphagia among adults in the united states," *Otolaryngology-Head and Neck Surgery*, vol. 151, no. 5, pp. 765–769, 2014.

[5] Sura L, Madhavan A, Carnaby G, Crary MA, "Dysphagia in the elderly: management and nutritional considerations," *Clinical interventions in aging*, vol. 7, pp. 287–298, 2012.

[6] Sven Lindgren, Lars Janzon, "Communication disorders and use of intervention services among children aged 3-17 years," *NCHS Data Brief*, no. 205, pp. 1–8, 2015.

[7] Lindsey Black, Anjel Vahratian and Howard Hoffman, "Prevalence of swallowing complaints and clinical findings among 50-79-year-old men and women in an urban population," *Dysphagia*, vol. 6, no. 4, pp. 187–192, 1991.

[8] Rosemary M, Norine F, Sanjit B, Nicholas D, Mark S, and Robert T, "Dysphagia after stroke," *Stroke*, vol. 36, no. 12, pp. 2756–2763, 205.

[9] Castell DO, Donner MW, "Evaluation of dysphagia: A careful history is crucial," *Dysphagia*, vol. 2, no. 2, pp. 65–71, 1987.

[10] Cook IJ, Dodds WJ, Dantas RO, Kern MK, Massey BT, Shaker R, Hogan WJ, "Timing of videofluoroscopic, manometric events, and bolus transit during the oral and pharyngeal phases of swallowing," *Dysphagia*, vol. 4, no. 1, pp. 8–15, 1989.

[11] Dodds WJ, Stewart ET, Logemann JA, "Physiology and radiology of the normal oral and pharyngeal phases of swallowing," *AJR. American journal of roentgenology*, vol. 154, no. 5, pp. 953–963, 1990.

[12] Steele CM, Miller AJ, "Sensory input pathways and mechanisms in swallowing: a review," *Dysphagia*, vol. 25, no. 4, pp. 323–333, 2010.

[13] Logemann JA, "Medical and rehabilitative therapy of oral, pharyngeal motor disorders," *GI Motility online*, 2006.

[14] Teismann IK, Steinsträter O, Warnecke T, Suntrup S, Ringelstein EB, Pantev C, Dziewas R, "Tactile thermal oral stimulation increases the cortical representation of swallowing," *BMC neuroscience*, vol. 10, no. 1, p. 71, 2009.

[15] Bülow M, Speyer R, Baijens L, Woisard V, Ekberg O, "Neuromuscular electrical stimulation (nmes) in stroke patients with oral and pharyngeal dysfunction," *Dysphagia*, vol. 23, no. 3, pp. 302–309, 2008.

[16] Freed ML, Freed L, Chatburn RL, et al., "Electrical stimulation for swallowing disorders caused by stroke," *Respir Care*, vol. 46, no. 5, pp. 466–474, 2001.

[17] Kiger M, Brown CS, Watkins L, "Dysphagia management: an analysis of patient outcomes using vitalstim therapy compared to traditional swallow therapy," *Dysphagia*, vol. 21, no. 4, pp. 243–253, 2006.

[18] Shaw GY, Sechtem PR, Searl J, et al., "Transcutaneous neuromuscular electrical stimulation (vitalstim) curative therapy for severe dysphagia: myth or reality?," *Annals of Otology, Rhinology Laryngology*, vol. 116, no. 1, pp. 36–44, 2007.

[19] Humbert IA, Michou E, MacRae PR, Crujido L, "Electrical stimulation and swallowing: How much do we know? in seminars in speech and language," *Thieme Medical Publishers*, vol. 33, no. 3, pp. 203–216, 2012.

[20] Mu L, Chen J, Li J, Arnold M, Sobotka S, Nyirenda T, Fowkes M, Christopherson M, Sanders I, "Sensory innervation of the human soft palate," *The Anatomical Record*, vol. 301, no. 11, pp. 1861–1870, 2018.

[21] Hori K, Taniguchi H, Hayashi H, Magara J, Minagi Y, Li Q, Ono T, Inoue M, "Role of tongue pressure production in oropharyngeal swallow biomechanics," *Physiological reports*, vol. 1, no. 6, p. e00167, 2013.

[22] Zoratto DC, Chau T, Steele CM, "Hyolaryngeal excursion as the physiological source of swallowing accelerometry signals," *Physiological measurement*, vol. 31, no. 6, p. 843, 2010.

[23] Reddy NP, Katakam A, Gupta V, Unnikrishnan R, Narayanan J, Canilang EP, "Measurements of acceleration during videofluorographic evaluation of dysphagic patients," *Medical engineering physics*, vol. 22, no. 6, pp. 405–412, 2000.

[24] Wang CM, Chuang CC, Chen CP, Tseng WC, Chen JY, "Non-invasive swallowing test for young healthy adults: Finding the best location to monitor thyroid cartilage movements," *Journal of Medical and Biological Engineering*, vol. 34, no. 4, pp. 393–398, 2014.

[25] Nikhil Naidu, Rahul Krishnan, Gayathri Manjula, "Oral and pharyngeal transit time as a factor of age, gender and consistency of liquid bolus," *Journal of Laryngology and Voice*, vol. 4, no. 2, pp. 45–52, 2014.

[26] Park H, Oh K, Prilutsky BI, DeWeerth SP, "A real-time closed-loop control system for modulating gait characteristics via electrical stimulation of peripheral nerves," *In IEEE Biomedical Circuits and Systems Conference (BioCAS)*, 2016.

[27] Tan DW, Schiefer MA, Keith MW, Anderson JR, Tyler J, Tyler DJ, "A neural interface provides long-term stable natural touch perception," *Science Translational Medicine*, vol. 6, no. 257, p. 257ra138, 2014.

APPENDIX A

ARDUINO CODES FOR EXPERIMENT 1 AND EXPERIMENT 2

A.1 Arduino code for capturing pressure sensor data and serial communication

```
float val = 0.0;
float xacc = 0.0;
float yacc = 0.0;
float zacc = 0.0;
int data = 0;
int state = 0;
int count = 0;
float val1,val2,val3,val4,avg = 0.0;
void setup()
Serial.begin(57600);
analogReadResolution(12);
pinMode(2,OUTPUT);
pinMode(3,OUTPUT);
digitalWrite(2,LOW);
digitalWrite(3,LOW);
void loop()
Serial.flush();
val4 = val3;
val3 = val2;
val2 = val1;
val1 = val;
val = analogRead(A0)*3.3/4095;
```

```
xacc = analogRead(A1)*3.3/4095;
yacc = analogRead(A2)*3.3/4095;
zacc = analogRead(A3)*3.3/4095;
avg = (val + val1 + val2+ val3+ val4)/5;
if(state == 0 && avg <= 1.9)
state = 1;
if(state == 1 && avg >= 2.2)
digitalWrite(3,HIGH);
delay(5);
state = 0;
yacc = 1;
digitalWrite(3,LOW);
Serial.println(val);
Serial.println(xacc);
Serial.println(yacc);
Serial.println(zacc);
```

A.2 Arduino code for stimulation

```
int state = 0;
int val = 0;
int count = 0;
void setup()
pinMode(2,OUTPUT);
pinMode(3,OUTPUT);
pinMode(7,INPUT);
void loop()
if(state == 0)
val = digitalRead(7);
```

```
if (val == 1)
state = 1;
if(state == 1 && count <= 50)
digitalWrite(3,HIGH);
digitalWrite(2,LOW);
delay(1);
digitalWrite(3,LOW);
digitalWrite(2,HIGH);
delay(1);
digitalWrite(2,HIGH);
digitalWrite(3,HIGH);
delay(8);
count++;
if(count > 50)
state = 0;
count = 0;
```