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Design of a portable device: Toward assisting in tongue-strengthening exercises and dysphagia management

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ABSTRACT A Tongue-Machine Interaction System (TMIS) can assist in tongue-motor training and would consequently help in mending the oropharyngeal pattern of swallowing. Requiring movement of tongue musculature, TMIS's would increase saliva production in the mouth to lubricate mastication and help dysphagia patients in swallowing and digesting food. Using a TMIS for interacting with computers, a variety of communication devices and mobility support systems, would be tantamount to performing indirect tongue muscle strengthening exercises. Such exercises can help cancer and stroke patients who suffer from dysphagia, and people who receive injuries above C7 on spinal vertebrae. Such facilitation may also improve the swallowing physiology in applying force and maintaining speed. TMIS's features would allow using them for supervised and structured tongue muscle exercises as well. The real-life adoption of TMIS's is impeded by the fact that many of them require undergoing a procedure for mounting a palatal plate or some component of interactivity in mouth and/or on the tongue. We report the design and implementation of a portable, low-cost, minimally invasive and, easy to learn and use TMIS for direct and indirect non-swallowing training of tongue muscles. We highlight selection and incorporation of design features important to the target patient demography.

INDEX TERMS Non-swallowing rehabilitative exercise, direct and indirect dysphagia therapy, tongue motor training, human-computer interaction

I. INTRODUCTION

Tongue-Machine Interaction Systems (TMIS's) have been used in lab settings for helping patients to communicate with computers, controlling domestic appliances and equipment and, navigating mobility support systems like wheelchairs. TMIS's could also assist vision-impaired people through tactile vision as they could substitute form-perception [1-8]. TMIS's were also employed for improving human balance and preventing people from non-voluntary fall using tongue as part of the biofeedback system [9].

As TMIS's require movement of the tongue musculature, their (aforementioned) applications would indirectly help

in non-swallowing rehabilitative exercises. TMIS's can facilitate indirect dysphagia therapy for patients who find it difficult to comply with the requirements of swallowing exercises [10]. This becomes possible as patients would carry out several tongue strengthening exercises while using a TMIS (without swallowing food). Hence, TMIS's have the potential to be used for both indirect and direct non-swallowing exercises. Recent literature suggests that non-swallowing exercises have a high degree of efficacy in strengthening oropharyngeal muscles like suprahyoids [11]. Benefits of non-swallowing exercises are gradually transferred to the practice of swallowing food [12, 13]. As skeletal muscles benefit from endurance exercises, it is safe

to assume that oropharyngeal muscles would benefit from non-swallowing exercises [13]. Furthermore, it is believed that non-swallowing exercises can work as behavior change techniques for improving dysphagia patients' adherence to rehabilitative regimen. Note that patient's adherence is often used as a measure of compliance with health practitioner's requirements [11, 14]. Thus, it is safe to posit that TMIS-facilitated non-swallowing rehabilitative exercises can indirectly improve the swallowing physiology in force and speed as they help in retraining the neuromuscular systems. In some previous works, TMIS's could also improve neuroplasticity in oropharyngeal muscles as they were able to help in pushing the musculature in an intense and persistent way [13, 15-17]. Despite their utility and potential, clinicians and therapists have not adopted TMIS's and they received less attention compared to other non-traditional human-computer interaction (HCI) systems, like the ones that utilize voice commands, brain signals, eye tracking and body or head movements. So far, TMIS's look far from being commercially available to patients [2, 9, 18-20]. This paper begins by discussing design and functionality related problems of TMIS's. We discuss how selection and incorporation of appropriate design features would help the target patient demography. We follow by describing a better TMIS design and finally report design and implementation of a low-cost, portable, minimally invasive and, easy to use TMIS. implementation of a low-cost, portable, minimally invasive and, easy to use TMIS.

II. WHAT ENCUMBERS ACCEPTANCE OF TMIS'S?

The tongue-computer interface design of TMIS's is the most important factor among the many factors that hinder the wider acceptance of TMIS's. The following paragraphs present a review of important issues pertaining to design of TMIS' interfaces.

A. INABILITY TO EXPLOIT TONGUE MUSCLES' CHARACTERISTICS

Even the best available sensing modalities such as surface electromyography (sEMG) are only partially effective in monitoring and analyzing the mechanical characteristics of the tongue muscles. The signals generated on the surface of the involved muscles viz., suprahyoid, digastric, stylohyoid, mylohyoid and geniohyoid, are difficult to sense, separate and classify. Thus, understanding the tongue-muscle movement patterns is problematic and remains incomplete. This prohibits exploiting the tongue muscle features for designing a reliable, acceptable and effective tongue-computer interface system. Furthermore, dexterousness of the tongue in a particular patient demography may differ from that of another patient demography. So, it is difficult to establish generic characteristics of tongue muscles and incorporate them in a TMIS interface design. In a recent attempt to acquire and classify signals measured on various muscles of the tongue, surface electrodes (part of a 22-channel active electrode

mount) were attached to the underside of the jaw for capturing the tongue movement patterns [20-22]. The signal acquisition approach used in this study was extended to classify tongue position for indirect training of swallowing in elderly subjects [22]. Further details of this investigation are awaited.

B. INABILITY TO TRACK AND LOCALIZE THE TONGUE MOVEMENT

Real time, continuous monitoring of tongue movement and determining its position inside the mouth are challenging tasks. In a tongue-computer interface mechanism, the tongue position and direction must be dynamically determined with a high degree of accuracy. A large majority of existing TMIS's relies on variations in either electromagnetic fields or inductance levels for monitoring the tongue movement and determining its position. Either magnetic or inductive field generating components are permanently attached to the tongue and the mouth surface for generating either electromagnetic or inductive field and determining the tongue position. Patients and carers find it difficult to keep these additional, usually metallic, components inside the mouth. Mounting such components inside the mouth would usually require patients to go through a procedure [5, 6, 8, 23-26]. This deters use of TMIS's in practice and makes it difficult to use them for patients who already suffer from disabilities and impairments [5].

C. OPERATIONAL AND FUNCTIONAL LIMITATIONS

Other pertinent factors contributing to the limited success of the existing TMIS's include cost, operational and functional complexities, difficulties in learning and adopting, dependability in a variety of real-life situations, portability, size, volume and mass.

Many recent works focused on overcoming these limitations. For example, attempts are being made to design minimally invasive tongue-computer interface mechanisms and classify tongue position using machine learning techniques. Attention was also paid to the cost and operational difficulty related issues of the TSIS's [7, 22, 27, 28].

III. AN OVERVIEW OF EXISTING TMIS'S

Several highly sophisticated tongue-computer interfaces and mechanisms have been developed and employed in the TMIS's. Some of these interfaces can determine the tongue movement patterns for estimating the tongue position. As such they enable tongue's use as an input medium. A variety of transducers and sensors like piezoelectric sensors, contact sensors, pressure sensors, Hall-Effect sensors and certain types of proximity sensors have been used in these TMIS's. As obvious in the two patents [6, 29], the employed sensing modality would determine the nature of the interaction mechanism in a TMIS. Table I presents a representative list of TMIS's. Brief details of the employed tongue-computer interaction approach are also presented in Table I.

The technology and accuracies of TMIS's reported in Table I have evolved during the last two decades or so. With the

TABLE I
TONGUE-COMPUTER INTERFACE DESIGN IN EXISTING TMIS'S

Author/(s)	System/ application	Tongue-computer interface design
<i>Sheriff and York 1988[29]</i>	Oral machine controller	Two tooth-shaped dentition grips are attached to the teeth and a tongue -actuated micro-switch controls the machine operation. Obtrusive.
<i>Buchhold 1995 [6]</i>	Peripheral device controller	Tongue receptacle attached to the tongue and a mouthpiece is disposed into oral cavity. Obtrusive.
<i>Strujik. 2006[5]</i>	Inductive tongue computer interface	An activation unit glued to the tongue. A palatal plate attached to the mouth top. Obtrusive.
<i>Krishnamorthy, and Ghovanloo, 2006 [30]</i>	Tongue Drive	Permanent magnet pierced on the tongue. Sensors mounted on a dental retainer attached to the teeth. Obtrusive
<i>Huo et. al. 2008 [23]</i>	Magneto-inductive sensor based wireless tongue-computer interface	A small permanent magnet placed inside a fixture is pierced on the tongue. Two 3-axial magneto-inductive sensor modules are placed near the cheeks. A controller is placed on the headset. Minimally Invasive.
<i>Caltenco et. al., 2008 [4]</i>	Tongue-computer interface	Similar to Strujik, L.N.S.A. (2006). Activation unit glued to the tongue and a palatal plate placed inside the mouth. Obtrusive.
<i>Vuillermé, N., et. al. 2009 [9]</i>	Tongue tactile biofeedback system	A wireless radio-controlled tactile output device placed on the tongue and worn as a dental retainer. Obtrusive.
<i>Huo et al. 2009 [24]</i>	Tongue motion based wheeled body control	Extension of [22]. Minimally invasive.
<i>Park et al. 2012 [28]</i>	Wireless magnetoresistive sensing in intraoral tongue-computer interface	Small footprint components placed on a printed circuit board, are contained inside a dental retainer. A system-on-a-chip placed inside the mouth. Obtrusive.
<i>Sandy and Khan 2012 [27]</i>	Tongue-Activated Emergency Alarm System	Entire system is enclosed in a lightweight, chemical resistant plastic casing that is mounted in a common oxygen mask attached to the face. Unobtrusive.
<i>Draghici, et. al. 2013 [31]</i>	A tongue-computer interface	An intraoral touchpad requires touch of the tongue for input. Obtrusive.
<i>Quain and Khan 2014 [18]</i>	Portable Tongue-Supported Human Computer Interaction System	Provisions to activate an emergency alarm; provide input to a computer to use appliances and control wheelchairs. Reflective tape is attached to a sleep apnea silicone device, which is mounted on the tongue. Minimally invasive.
<i>Sasaki, M. 2014 [20]</i>	Tongue motor training support system	Surface electromyographic (sEMG) signals acquired using electrodes. Intraoral arrangement.
<i>Sasaki, M. 2020 [22]</i>	Oral motion classification	Surface electromyographic (EMG) signals acquired using electrodes and classified using a support vector machine.
<i>S. Niu, L. Liu, and D. S. McCrickard [32]</i>	Camera-based tongue-computer interface	Camera-supported determination of tongue position.
<i>M. Mohammadi et al. [33]</i>	I. TONGUE-BASED JOYSTICK TO CONTROL A ROBOT	
<i>K. Gorur et al., 2019 [34]</i>	<i>Glossokinetic potentials supported tongue-computer interaction</i>	Glossokinetic potentials signal processing using deep Convolutional Neural Network and Support Vector Machine for tongue-machine interface

emergence of better digital and analog design capabilities, TMIS's kept improving in terms of architecture, usability, functionality, volume and size. However, TMIS's are

generally obtrusive and physically demanding for the users and their efficacies in direct, indirect, non-swallowing and swallowing exercises have not been fully explored yet. Incorporating a user-friendly and more effective human-computer interaction design would encourage patients to use these TMIS's and interact with the world around. It can be anticipated that being more user-friendly than the prevailing MTIS's, the new breed of TMIS's would be more acceptable to the community for real-life adoption.

IV. TOWARD BUILDING A BETTER TMIS

Based on previous attempts of overcoming the aforementioned limitations in TMIS's, we developed a novel set of features that would help in designing the tongue-machine interface. These features were reported in the wider literature on designing medical devices and their evaluation [35-39]. The design features considered essential for developing a minimally invasive and more acceptable TMIS are listed in column 1 of Table II. Relevance of the proposed features to the potential user demography is elaborated in column 2 of the table.

The TMIS features included in our reported design were discussed with the Royal Perth Hospital staff whose expertise helped in enhancing the proposed criteria. These design features were incorporated in a minimally invasive tongue-supported interaction system (TMIS), which uses a novel tongue position and movement monitoring method and could be mounted without a procedure [7, 27]. Thus, the demanding and expensive procedure that discourages TMIS's application in real-life situations was avoided.

The process of designing the proposed TMIS is presented in section 5 and its implementation details are presented in section 6. TMIS's performance results are reported in section 7. The design, implementation and tests are discussed in section 8 and section 9 concludes this work.

V. FEATURES OF TONGUE FOR INDIRECT NON-SWALLOWING EXERCISES

A. Tongue-computer interaction modalities

In order to select the most effective tongue-computer interaction modality, six possibilities were considered. These evaluated modalities included: keypad, touch screen, infrared proximity sensors, tongue magnet tracking, push-button switching and isometric joystick. These considered modalities were evaluated for designing a comfortable, portable, easy to learn and use TMIS. Dominic analysis method, a method of iterative redesign used in many engineering studies [40] was invoked to compare these modalities and establish their relative suitability for a TMIS. The evaluation criteria for comparing these modalities were based on the design feature requirement analysis listed in Table II. Table III reports the employed assessment features and the evaluation schema. Table IV shows the outcome of the Dominic analysis.

The analysis, shown in Tables III and IV, suggested that the touch screen was a highly appropriate choice for implementing the tongue-computer interaction mechanism. This analysis was further evaluated by real life testing of the touch screen option.

B. Initial assessment of tongue as an interaction medium

Since the touch screen modality stood first during the analysis, it was vital to examine if the normal speed of the tongue movement would allow for an effective interaction with computers and machines. The speed of the tongue for selecting a target and the tracking accuracy of the tongue while interacting with different interface layouts has been investigated in the literature [19, 41-43].

Studies suggest that positional accuracy and speed of the tongue movement increase after a few practice sessions. The possibility of swiftly achieving accuracy highlights motor learning abilities of the tongue. In a previous investigation, performance of tongue was compared with that of a finger using an IBM Trackpoint IIITM. The study concluded that the tongue remained 5 to 50% slower than a finger-supported pointing device [44, 45]. These results suggest that tongue's

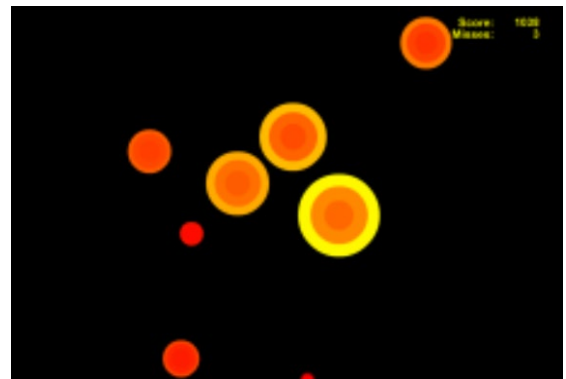


Figure 1. Disc Dash screen shot.



Figure 2. Mobile phone screen displaying the Remote Droid.

overall performance is lower than that of the finger but the tongue can still be effectively used in human-computer interaction. Despite a slow speed and lower accuracy, tongue could be used as an input medium for indirect dysphagia therapy.

Having established that the tongue could move at a reasonable speed, its use with a capacitive screen was explored. An android phone was connected to a laptop through WiFi and an application software called Remote Droid [45, 46] was run. This application allows the phone to be used as a mouse for tracking and clicking on the screen in left-click/ right-click modes.

The capability of the tongue was compared against the human thumb using an online game called Disc Dash [47]. The game tests user's mouse movement skills, speed and accuracy. The aim of the game is to click upon the rings as they appear, as fast and as close to the center as possible. Points are awarded depending upon how close the click is made to the center of the circle and the time taken in clicking. Figure 1 shows an example screen of the game play. The test was repeated 5 times. The Remote Droid application [45, 46] was configured on the android phone such as it was automatically clicked when the screen was touched, in the same way that a person would touch a touch screen to activate a command. The available screen size for the input was 7.5cm x 5.5cm, with a

TABLE II
PROPOSED TMIS DESIGN FEATURES

Feature	Significance and relevance
<i>Affordability</i>	<ul style="list-style-type: none"> Should be affordable (for the patients and/or carers) Should cost less than \$ 300.00
<i>Compatibility</i>	<ul style="list-style-type: none"> Should have low power consumption and have a long battery life Should require minimal maintenance and part replacements
<i>Effectiveness</i>	Should be compatible with support devices, such as; wheelchairs, computers (substituting the mouse, allowing input and typing), joysticks and similar peripherals, domestic devices (rolling curtains up and down, turning lights on and off)
<i>Dependability</i>	<ul style="list-style-type: none"> Should be unobtrusive Should be easy to mount and dismount Should help in confidently using the device Should allow fool proof operation (minimal probability of making mistakes) Should not interfere with the neighboring communication or medical equipment Should be resilient to vibration and noise emanating from other equipment Should avoid accidental triggering of the emergency alarm Should be reliable in various domestic and clinical conditions (withstand humidity, temperature, illumination condition) Should have an expected life of 3-5 years (normal conditions) Should have a battery life of 1000 hours Should sustain movements when patients change rooms Should sustain fall from the height of the bed (1.0 ~ 2.0 m)
<i>Learnability</i>	<ul style="list-style-type: none"> Should have an easy to comprehend user interface and be simple for a patient and carers to understand Should take a user only a few minutes to become proficient so a legible and easy to read display is required Should be able to display the current needs of the patient to the carer/s (e.g., on a screen) Should be able to use different types of alarm signals for conveying a variety of conditions/ situations to the carer/s
<i>Storability</i>	<ul style="list-style-type: none"> Should not require any surgical or medical procedure for mounting, dismounting and application Should be unobtrusive, comfortable and small
<i>Accessibility</i>	The system volume should be as minimum as possible. The system should weigh less than 500 grams
<i>Repeatability</i>	The system should be able to produce the same output given the same input
<i>Accuracy</i>	The system should be able to achieve a high level of accuracy and should provide very low levels of tolerance

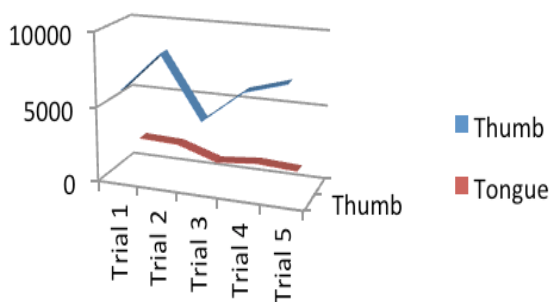


FIGURE 3. Comparison of points scored (along the y-axis) using thumb and tongue while playing an online game Disc Dash. Results were gathered by touching the rings 7.5cm x 5.5cm screen.

total area of 41.25 cm² was used for the system. Figure 2 shows the screen used for the testing. The results (in terms of points scored while playing the game using the thumb and the tongue) were then graphed as shown in Figure 3. points scored while playing the game using the thumb and the tongue) were then graphed as shown in Figure 3.

VI. DESIGN OF TMIS

In order to incorporate a higher level of usability, the proposed TMIS design criteria were transformed into a set of desired features (Table II). The system was required to be unobtrusive, easy to mount and dismount, able to translate patient's inputs into appropriate outputs and be usable under no or minimal supervision. These features were required to be incorporated in the tongue-computer interaction

mechanism (TCIM) without much reliance on mechanical features of the tongue muscles. As a patient would use the mechanism for reasonably long durations, the system needed to be usable for longer periods of time even if the tongue was required to protrude outside of the mouth for using the system.

Keeping these factors in view, the TMIS was designed with the help of rehabilitation engineering team of the Royal Perth Hospital (RPH) Western Australia. The RPH engineers had used a tongue joystick on high-level spinal injury patients requiring the tongue extended outside of the mouth [18]. The RPH team assessed the system design and determined that it would be acceptable to keep the tongue extended outside the mouth for interacting with supporting devices. The TMIS tests at the RPH were carried out under the supervision of a team of Physiotherapists and Occupational therapists. The RPH patients who used the TMIS provided positive feedback on its performance suggesting that they could comfortably extend the tongue outside the mouth for more than an hour in a single go (a reasonably long period of time). During the tests, the patients at RPH were able to use the tongue-device as a primary method of communication (hinting its use as an indirect, non-swallowing therapy device).

Based on the RPH experience, a similar design approach was adopted for developing a less obtrusive TMIS. We employed an array of InfraRed (IR) Light Emitting Diodes (IRLED's)

with reflective tape to enable tracking an object in a 2-dimensional (2D) space with the help of an IR camera and a Wii remote. A similar approach was employed in a previous system [48] that enabled users' interaction with a computer through movement of human body parts, e.g., moving fingers in air. Exploiting this tracking approach, a design concept was developed for tracking the tongue position and conveying the same to a computer. We progressively tried three different configurations of this arrangement. These configurations had different positions and arrangements for the IR transmitter-receiver. Each configuration was evaluated and conclusions were drawn in relation to the TMIS's performance against the design criteria. Through Dominic analysis, best of the three configurations in terms of usability, functionality, affordability and physical attributes was discovered. Table III reports features that were considered, assessed and used in designing the TMIS.

Table IV presents analyses of various design configurations and their results. After a number of assessments, it was decided to keep a reflective surface on the tongue (signal transmitter) and an IRLED array on the receiving end. This was the most plausible method for implementing a wireless, low-cost, portable and energy-efficient tongue-computer interaction mechanism.

TABLE III
TONGUE-COMPUTER INTERFACE MODALITY ASSESSMENT

Assessment features	Priority for the feature	Design Concept					
		Keypad (A)	Touch screen (B)	Infrared proximity sensors (C)	Tongue magnet tracking (D)	Push button switch (E)	Iso-metric joystick (F)
Unobtrusive	H	F	G	G	F	E	G
Cost	H	F	G	P	P	E	G
Functionality of Output signal	H	G	E	G	E	P	E
Customizability Required	M	P	G	P	P	E	E
Tongue Strength	M	G	G	E	E	G	G
Tongue Endurance	M	F	G	E	E	P	G
Continuous Direct Input	L	G	E	G	E	P	E
Easy to use	L	G	E	F	G	E	E
Repeatability	H	H	H	H	H	H	H
Accuracy	H	H	G	G	G	G	G

Legend: E-Excellent; G-Good; F-Fair; P-Poor; U-Unacceptable

TABLE IV
DOMINIC ANALYSIS OF VARIOUS TONGUE-COMPUTER INTERFACE MODALITIES AND ASSESSMENT OUTCOMES

Rank	Very Important (H)	Important (Moderate)	Desirable (Low)
Excellent (E)	DEEFB	CCDDEF	DEFFBB
Good (G)	ACCFBB	AEFFBBB	AACD
Fair (F)	AAD	A	C
Poor (P)	CDE	ACDE	E
Unacceptable (U)			

Overall Evaluation is Excellent

Overall Evaluation is Good

Overall Evaluation is Fair

Overall Evaluation is Poor

A = Poor

B = Good

C = Poor

D = Poor

E = Poor

F = Good

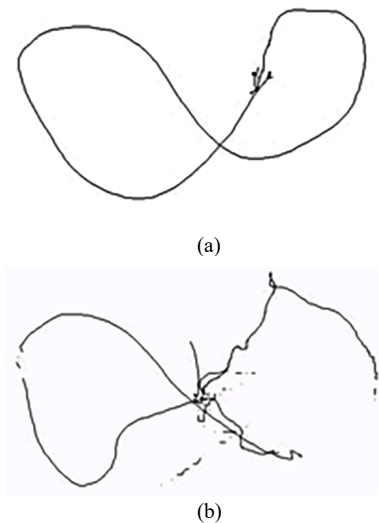


FIGURE 4. Examples of drawing numeral 8 using (a) Reflective Tape and (b) Alfoil – notice broken lines visible in (b).

Having determined the best possible TMIS design, the next step was to use tongue as a pointer. We needed to achieve reasonable levels of pointing accuracy, control over the tongue movement and a suitable operational range (user-to-system distance). As a reflective surface was needed to reflect the IR light on the IR camera, two types of reflective surfaces (regular alfoil and reflective tape) were tested with the Wiimote

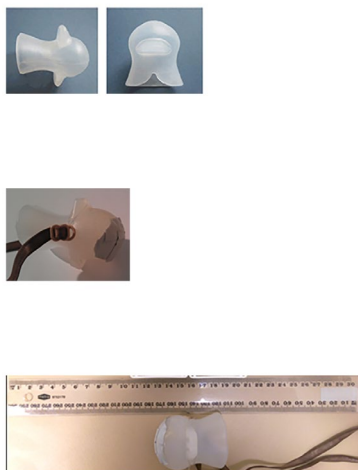


FIGURE 5. Silicone Tongue Device (Top) Two views of the device (*Snoring Cessation*); (Middle) Reflective tape attached to the device; and (Bottom) Physical dimensions of the tongue device: L=65 mm, W=55mm.



FIGURE 6. Final Infrared array system and its dimensions: A close-up of the mounted system (above) and actual dimensions of the Infrared array; W=100mm; H=85mm, (below).

Whiteboard V0.3 software. The effective range of the alfoil was found to be 35 cm and that of the white reflective tape was 150 cm. A simple tongue-supported drawing test was carried out to assess the usability of the two media. Users were required to draw the numeral ‘8’ in Microsoft’s utility program Paint; first using the tape and then using alfoil mounted on the tongue. Drawing the numeral ‘8’ would involve precise pointing, continuous movement and accurate control. The two drawings of numeral 8 (Figure 4) suggested that the user performance was far superior with reflective tape compared to the piece of alfoil. Possibly for alfoil had a rough surface so light could be scattered and not reflected back to the target. The smoothing capabilities of the Wiimote Whiteboard V0.3 software (averaging out the spread of IR light) were exploited in order to reduce the light scatter and overcome this problem. Repeated tests suggested the reflective tape would be a more plausible medium to reflect light back to the Wii remote. In order to fulfill the design criteria, the reflective tape needed to be attached to the tongue tip in a less invasive, easy to mount/dismount and economical manner. Such an arrangement would bring four features: unobtrusiveness, low-cost, long-hour usage and ease of cleaning needed to the TMIS. A silicon tongue device, usually worn by sleep apnea patients (Figure 5) was used for attaching the tape to the tongue. The device opens up the airways and improves patients’ quality of sleep. A patient could remove the device simply by bringing the teeth together to break the air seal. The device can be comfortably worn for long periods of time as demonstrated through its use as a sleep apnea device. As the device is made of a medical grade silicone, sterilization is easy. Alternately, the device could be cleaned with a handheld Ultraviolet light cleaner. Non-toxic silicone glue was used to attach the reflective tape to the silicon tongue device. Hence, no direct contact between the reflective tape and the patient’s

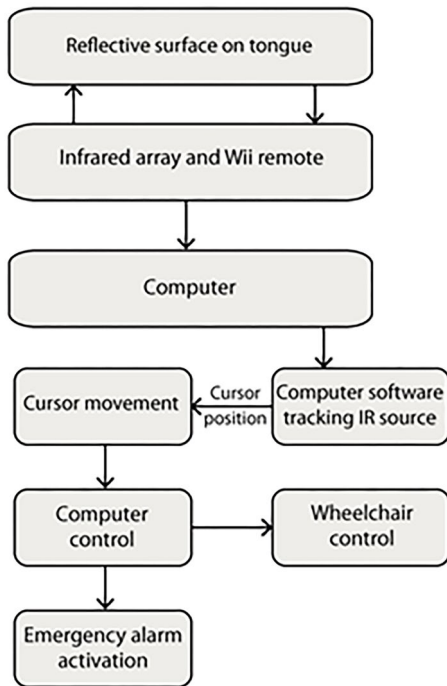


FIGURE 7. Architectural and functional details of the IRTCIS.

tongue was required. The snoring device, its tape-mounted version, and its physical dimensions are shown in Figure 5.

A. INFRARED LIGHT SOURCE DETECTION

For the system to sense the tongue position and enable execution of any commands, an appropriate IR light source detection mechanism was required. An IR light array was employed for this purpose. As the IR light array was likely to be used by the impaired patients, it was expected to be less than 1.5 m away from the users. As shown in Figure 6, an array of 4 x 7 TSHA6202 model IRLed with a peak wavelength of 875 nm was used. It was a cheaper option and had an appropriate wavelength range for the Wii's IR camera. The angle of half intensity of the LED was $\pm 12^\circ$ making the IR array powerful enough to work in an adequate range at wider viewing angles. The forward current of the LED was 100 mA. There were four parallel strings per array so eight strings, each requiring 100 mA, were used. A 13.5V DC supply source outputting a total of 800 mA would adequately power the array. A simple bi-directional switch would turn the connection to the supply on/off. The final product and its dimensions are obvious in Figure 8.

B. SIGNAL COMMUNICATION AND COMMAND EXECUTION

The signal communication and command execution functionalities were implemented by connecting the Wii remote, a Human Interface Device (HID)-class peripheral, and the computer via Bluetooth communication protocols. The raw IR data from the Wii remote, was translated into usable signals for being used in software. Following the design

criteria, an easy-to-use software that would process the input of the Wii remote's IR camera and translate the incoming data into both cursor movements and commands was needed. A multi-purpose optical motion tracking software called FreeTrack was employed for the task. It would track the source of the IR light being attached to the tongue tip. Hence, the tongue tip will relay the tongue movements and would control the mouse cursor. FreeTrack version 2.2, primarily used for head tracking in video games and hands-free computing, is capable of tracking markers for monitoring the position of an object in space [49]. To incorporate the tongue tip tracking ability, a dwell-clicking program was used with the FreeTrack software. This dwell-clicking program provided a mouse clicking functionality without requiring a physical button and reducing the potential obtrusiveness to meet the design criteria. For achieving the mouse control, a profile generation facility was added to the FreeTrack software. The profiles were generated and stored within FreeTrack to let a user select any pre-registered patient. Therefore, carers would not need to create a profile each time a patient uses the system.

In order to determine the FreeTrack settings for correct execution of the mouse control, a threshold control was incorporated. This would eliminate any unwanted sources of light interference prevailing in the system. The threshold level could be adjusted through a control bar. Once the center icon is pressed FreeTrack would record the current position of the tongue as the center position for all future positions and related outputs. The auto pan function allows the mouse cursor to

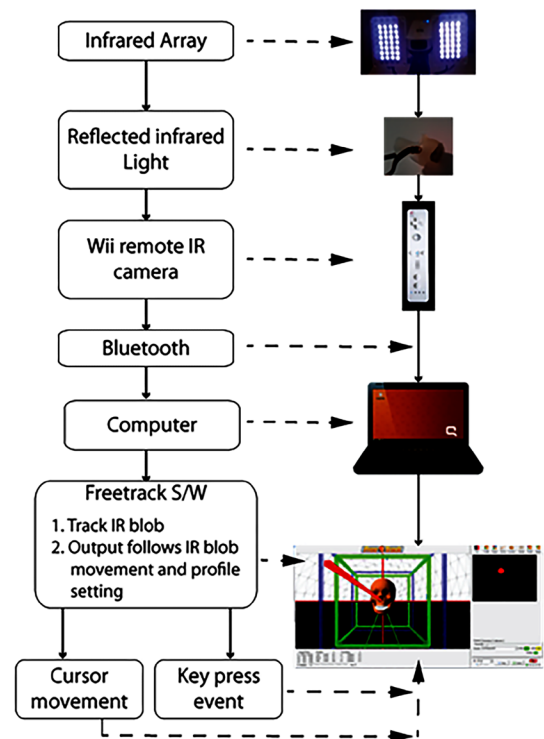


FIGURE 8. Flow of information through various components of the TMIS.

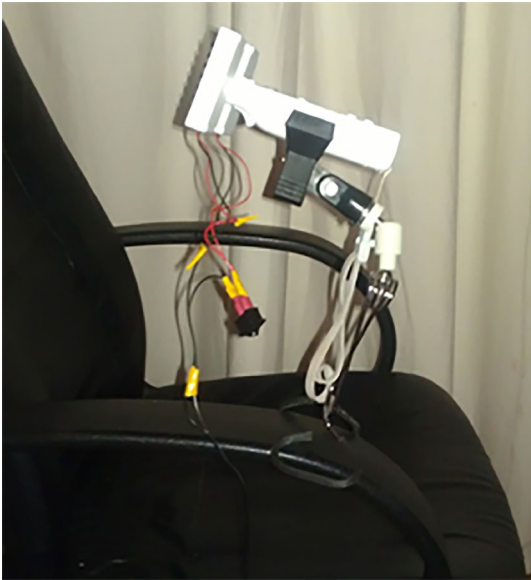


FIGURE 9. The complete IRTCIS shown as mounted to the chair handles with a clamp.

move across the entirety of the screen. It works by initially detecting the tongue location relative to the center point. The mouse cursor continues to auto pan in the direction of the tongue from the center point. When the tongue is brought back to the center point the cursor stops and after 200-250 ms Dwell Clicker 2 initiates a regular mouse click. Dwell clicking programs are commonly used by dexterity impaired people with repetitive strain injuries. They allow left-click, right-click, double-click and drag without physically pressing a button [50].

VII. IMPLEMENTATION DETAILS

Effectively incorporating the design criteria in the IRTCIS would require the flow of information within the system to be compliant with the design goals. The information flow scheme of the TMIS is shown in Figure 10. It should be noted that for keeping the system lightweight, portable and compatible with other devices, the computer used in the prototype TMIS can be replaced with a LCD display equipped microcontroller. Such a modification can allow easy mounting of the system on

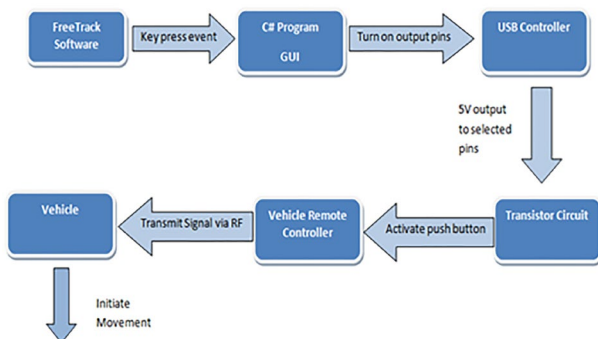


FIGURE 10. The Proposed Vehicle (wheelchair) Navigation Scheme



FIGURE 11. Measured horizontal and vertical usable distance ranges of the IRTCIS.

a wheelchair. It would also facilitate an adequate execution schema for the TMIS. Figure 7 shows the system implementation and Figure 8 exhibits the architectural details of the TMIS.

The target demography (impaired patients) would primarily spend time either in a bed or sitting on a wheelchair. In order to properly mount the system and ensure its effectiveness, the TMIS was made to easily transition between these two

TABLE V. IRTCIS-DISC DASH TEST RESULTS

Trial	Thumb	IRTMIS	Tongue- Capacitive
<i>Trial 1</i>	5613	1906	1146
<i>Trial 2</i>	5859	2121	1494
<i>Trial 3</i>	5076	1839	1635
<i>Trial 4</i>	6813	2730	1125
<i>Trial 5</i>	5559	1968	1659
<i>Mean</i>	5784	2112.8	1411.8

positions with the help of a flexible mounting mechanism. Factors such as patients' room size, bed size and wheelchair models were considered while designing the mounting mechanism. Also, the system was meant to be easily adjusted for operating an electric wheelchair. It was ensured that a carer was able to make the necessary adaptations in 2-3 minutes. For the wheelchair use, the mounting base plate can be disconnected and replaced with a clamp screwed into the main shaft. A 12V DC IRLED array can be connected directly to the output terminals of a standard battery generally used with electric wheelchairs. A microcontroller-LCD display set or a small tablet running the FreeTrack program can be attached to the wheelchair. The Wii remote would remain connected to any computing element using Bluetooth. Use of a simple clamp for mounting the TMIS to a wheelchair is demonstrated in Figure 9. Its navigation control scheme is shown in Figure 10.

VIII. PERFORMANCE EVALUATION AND RESULTS

The relevant tests were carried out to test the functionality of each sub-system and finally the overall system performance was assessed. The system was assessed in terms of three key factors: operation range, communication ability, and

functional performance. These key-factors directly reflected on the design criteria and addressed the interaction and communication needs of the patients.

A. TEST PARTICIPANTS

The TMIS was tested in two stages, first on-campus and then off-campus. Three male Caucasian students volunteered for the on-campus tests and eight international students of Central Asian and Indian origins, three female and five male students volunteered for the off-campus tests. All volunteers were able-bodied and young students whose ages varied between 17½ - 23 years.

B. RANGE OF OPERATION

For effectively using the TMIS, its horizontal and vertical sensing ranges were tested and measurements, shown in Figure 11, were taken at various distances from the Wii Remote's IR camera. The average field of view was found to be 42° horizontally and 33° vertically. These measurements were compatible with those observed in earlier studies. In previous works, the average field of view of the Wii Remote was reported to be 41° horizontally and 31° vertically [51]. The minimum operating distance of the IRTCIS was 8 cm. Some distortion of the IR light takes place in the Wii camera at a distance less than 8 cm. The maximum reliable operation of the IRTCIS was found to be within the 5 m range. Though the system could detect the light reflected from the tape placed as far as 8 m. However, the cursor movement won't be smooth at such distances. Figure 11 also shows variations in the communication range as a user controls a path-following robotic-car with the TMIS.

C. ABILITY TO INTERACT AND COMMUNICATE

The TMIS's ability to interact and communicate with computers and other devices and its performance as an input medium were rigorously assessed. The aim was to determine how well the tongue could replace a traditional input device for interacting with computers. The mouse movement accuracy and typing speed in words per minute (wpm) were used as measures of the system's ability to communicate and interact.

The effectiveness of the TMIS was tested using Disc Dash, a software program that is used to evaluate the mouse accuracy and speed. Tests were carried out by letting the participants play Disc Dash using the TMIS. After an initial practice period of ten minutes, five consecutive tests were performed, and results (shown in Table V) were recorded. As shown in Table V the system performance was compared against two other system; one of them uses the human fingers on a capacitive screen (MTS, 2014) and the other system uses the tongue on a capacitive screen [52]. As shown in Table V, the TMIS consistently performed better than the tongue-capacitive screen systems. However, the finger-capacitive screen system performed better than the TMIS.

As shown in Table V, the TMIS was only 36.5% as effective as the finger-capacitive touch screen in controlling a computer cursor (in terms of speed and accuracy). However, it was

33.2% more effective than the tongue-capacitive screen touch system. Thus, TMIS demonstrated an acceptable level of ability to control a computer cursor.

The typing speed in the range of 25-30 words per minute (wpm) is considered apt for extensive personal needs (Yulian Electronic Technology Co. <http://gzyluan.com/en/home/>, Shenzhen Hua Shun Tong Technology Co., Ltd. <http://www.hsttp.com/en/?index.html>,). Therefore, we set 25 wpm productivity benchmark for the TMIS. The 25 wpm typing speed was to be accomplished using an on-screen keyboard and a dwell clicking program [53, 54]. The keystrokes were generated using Dwell Clicker 2, which was set to have a dwell period of one second. An onscreen keyboard was used on the Speed Test website for the typing test [55]. The online speed test application was able to monitor the word per minute typing performance. Each trial was performed for a duration of 2 minutes with the help of Virtual Keyboard's word prediction feature.

The average typing speed achieved by the TMIS was 5.6 words per minute while the average word length was 5.4 characters. A maximum speed of 7.2 words per minute was achieved. In comparison, the average computer user transcribes at a speed of 33 words per minute. This suggested that typing with the TMIS, on average, is only 17% as fast as that with a traditional keyboard. This typing speed might improve with the patient's regular use of the system and development of the necessary motor skills needed for using the device.

Historically speaking, typing productivity through the use of an onscreen keyboard has been relatively low – up to one word per minute typing speeds were achieved in the past when patients were asked to enter their names and addresses using an eye tracker. Studies into various modalities of typing systems [56-58] showed that people could type 25 wpm with a touch screen keyboard and 17 wpm with a mouse and an on-screen keyboard. In a previous study, the SmartNAV system (which operates in a manner similar to the TMIS) was tested on 12 able bodied students using a Danish on-screen keyboard. The system was capable of producing 6.1 word per minute, close to the TMIS's 6.2 wpm typing speed. Therefore, the TMIS's typing speed could be considered comparable with the existing systems. Though the TMIS was unable to outperform some of the existing systems, it was still successful in terms of the typing speed and its ability to provide a less invasive way of typing and interacting with several devices.

D. PORTABILITY TESTS

The TMIS was tested for portability using a set of target parameters and their associated values. These parameters included: range of operation, use of games software, activation of alarm systems, use of a word processor, and a wheelchair navigation system. These assessment features, their target values and the test results are summarized in Table VII. The TMIS was successfully used for all the features. It was tested on a local alarm buzzer and on an internal hospital alarm system. During the game playing and word processing tests,

TABLE VII
TMIS PERFORMANCE EVALUATION

TESTING CRITERIA	TARGET	TMIS
<i>System Operation</i>		
<i>Minimum Range of Operation (meters)</i>	0.5m	0.08m
<i>Maximum Range of Operation (meters)</i>	3.6m	5m
<i>Effectiveness</i>		
<i>Typing (wpm)</i>	25 wpm	6.2 wpm
<i>Mouse control score</i>	>1411.8 average point score in Disc Dash	2112.8 average point score 33.2% improvement
<i>Playing games</i>	Yes	Yes
<i>Functionality</i>		
<i>Activate Emergency alarm</i>	Hospital Alarm System	Hospital Alarm System Local Alarm Buzzer
<i>Using Computer</i>	Yes	Yes
- Start programs through icons	Yes	Yes, as displayed by ability to activate emergency alarm button
- Cursor control	Yes	Yes, can perform fast and accurate movements as shown by Disc Dash
<i>Potential control of an electric Wheelchair</i>	Yes	Yes Navigated a remote controlled car Controlled a Smart line following robot

the test participants were able to accurately click 70% of the times on average. A set of accompanying video clips show the system being used for playing games and navigating a toy car.

E. THE ITR TEST

TABLE VIII
THE ITR-BASED PERFORMANCE OF TMIS AND SOME PREVIOUSLY IMPLEMENTED SYSTEMS

System	Description	ITR
<i>TMIS</i>	This system	~37.36
<i>Huo, Wang & Ghovanloo, 2008 [60]</i>	<i>Tongue-computer interface</i>	~130
<i>Lao & O'Leary, 1993 [58]</i>	Head-operated computer-mouse interface	120
<i>Huo, Wang & Ghovanloo, 2007</i>	Tongue-computer interface	97
<i>Sera, 2014</i>	Tongue-computer interface	87

The performance of many compatible interaction systems was measured using a well-known parameter called the information transfer rate (ITR). The ITR scores have been used to assess several interaction modalities such as the tongue, brain signals, eye gaze, and head movement [58-60]. The ITR is calculated as:

$$ITR = \frac{1}{T} \left[\log_2 N + P \log_2 P + (1 - P) \log_2 \frac{(1-P)}{N-1} \right], \quad (1)$$

where T is the system response time, P is the number of correctly completed commands and N is the total number of commands a system can handle.

The ITR score of the TMIS was compared with ITR scores of other systems in Table VIII using the previously published data. As reported in Table VIII, the TMIS in [23] was able to achieve around 130 ITR when tested on a set of 6 commands. The TMIS, tested on a set of 58 commands, was able to achieve approximately 37.36 ITR. Given that it was tested on an almost 10 times larger set of commands, the ITRCIS's performance could be considered acceptable.

F. SYSTEM COST

Since affordability was an important design criterion, efforts were made to keep the system cost as low as possible. The total system cost given in Table IX was under Australian \$500.00 (under US\$ 400). This total cost was based on the costs of commercially available components and off the shelf products used in the system. The cost of a computer (a computing device) could be further reduced by replacing the computer with a smaller computing device (available at a cost of less than US\$ 250.00). Hence, the overall cost of the ITRCIS, though affordable, can be reduced.

G. LIMITATIONS

The physical size of the silicone tongue mounting could be further reduced. It would be more convenient for a patient to wear a smaller object for mounting the reflective medium. However excessive customization may increase the system cost.

The overall volume and the weight of the TMIS are much smaller than those of many comparable systems. For its less invasive design, it is an easy to use and easy to mount/dismount system. Mounting a computer on a wheelchair in certain conditions might pose some challenges for the users but one should not forget that the prevailing wheelchairs navigation systems have dimensions similar to a laptop. As these navigation systems can be mounted on wheelchairs, mounting the TMIS on a wheelchair should not cause a major problem. Yet, a future implementation of the TMIS would focus on using an alternate computing device, e.g., a microcontroller-and-display-unit for overcoming this limitation.

The TMIS was tested on young and able-bodied volunteers; mainly for not being able to find volunteers with mobility and/or dexterity impairment. Several biomedical device design and development related investigations use data collected from young and able-bodied volunteers during initial studies and pre-clinical trials. In particular, when volunteers with target levels of mobility and/or dexterity impairment are not available, data collected on young and able-bodied subjects are employed for testing the prototype systems. Hence, use of data collected from young and able-bodied people is common in the realms of biomedical engineering and HCI systems [61]. However, as the initial test results are available now, the real-life performance of the system can be determined by engaging the real patients. Such real-life tests would require additional resources, time and funds. Nonetheless, the reported results demonstrate the potential of TMIS's application in real life situations.

IX. CONCLUSION AND DISCUSSION

This work demonstrates the design and implementation of a less invasive tongue-computer interaction device. The proposed TMIS can facilitate tongue-motor training and can consequently help in mending the oropharyngeal pattern of swallowing. Patients can use the TMIS for interacting with computers, communication devices and mobility support systems vis-à-vis going through indirect tongue muscle strengthening exercises. This system can be beneficial

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TABLE IX OVERALL COST OF IRTCS (IN AUSTRALIAN DOLLARS)*	
Item	Cost
Nintendo Wii Remote	\$17
Wii Remote Mount	\$25
2- 4x7 Infrared Array	\$44
13.5V DC Supply	\$10
Bluetooth dongle	\$3
Silicone tongue attachment V	\$28
Laptop V	\$350.00
Total Cost	\$477.00

* Costs are based on quotes received from the local vendors.

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