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RESEARCH ARTICLE

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 serve as a valuable tool for tongue strengthening training which could contribute to rehabilitation of patients with dysphagia and eventually help in mending the oropharyngeal pattern of swallowing. The TMIS can also facilitate research into dysphagia, as tongue positioning and Range-of-Motion are commonly used outcome parameters in dysphagia research. Using a TMIS (for interacting with computers, a variety of communication devices and mobility support systems) would be tantamount to performing tongue muscle strengthening exercises. Such exercises can help patients with dysphagia in improving strength of the oral musculature. TMIS's features can also provide valuable biofeedback during the tongue muscle exercises. The adoption of TMIS's in clinical practice has been limited in the past since many of them require patients to have a palatal plate or some component of interactivity mounted in the mouth and/or on the tongue. This paper reports the design and implementation of a portable, low-cost, minimally invasive and, easy to learn TMIS which can be utilized for training and strengthening of tongue musculature. The selection and incorporation of design features important to the target patient demography are also discussed.

INDEX TERMS Rehabilitative exercise device, dysphagia therapy, tongue strengthening 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 have also assisted vision-impaired people through tactile vision to substitute form-perception [1], [2], [3], [4], [5], [6], [7], [8]. TMIS's were also effectively employed for improving human balance and preventing people from non-voluntary fall using tongue as part of the biofeedback system [9]. Some recent works also highlight the need for consistent and comprehensive swallowing exercise dosage reporting in dysphagia studies [10]. TMIS's also promise the potential to optimize swallowing exercise dosages.

As TMIS's require movement of the intrinsic and extrinsic tongue musculature, their applications could help in oral motor exercises to facilitate indirect therapy for patients

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with dysphagia [11]. This device could allow patients to participate in tongue strengthening exercises while using a TMIS (without swallowing food). Recent literature suggests that non-swallowing exercises have a high degree of efficacy in strengthening oropharyngeal muscles including the suprahyoid muscles [11]. The benefits of isometric lingual exercises were supposed to be transferred to increase tongue strength and improve swallowing [12] but new works suggest neuroplasticity should be a preferred way of functional training [12], [13], [14]. Similar to skeletal muscles benefit from endurance exercises, oropharyngeal muscles benefit from tongue strengthening exercises [15], [16]. Furthermore, it is believed that biofeedback during tongue strengthening exercises can work as a behavior change technique for improving patients' adherence to rehabilitative regimen. Note that patient's adherence is often used as a measure of compliance with health practice requirements [11], [14]. The TMIS's could help to improve neuroplasticity in oropharyngeal muscles as they were able to help in pushing the musculature in an intense and persistent way to strengthen the lingual musculature [13], [15], [16], [17].

Despite their utility and potential, clinicians and therapists have not adopted TMIS's in usual clinical care. TMIS'S received less attention compared to other non-traditional Human-Computer Interaction (HCI) systems, for example, systems 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], [17], [18], [19].

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. The on-campus tests of this TMIS were carried out during the pre-COVID-19 years and the off-campus tests were administered in post-COVID-19 years.

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

Let's begin by citing an investigation [14] that used Electro-Magnetic Articulography (EMA) to determine tongue position. Using EMA would require sensor coils to be attached to the tongue and/or to the mouth for localizing their positions and monitoring their movements during the time in which the person under investigation is assessed. The entire process is invasive and poses difficulties to the patient. Even the commonly used sensing modalities such as surface electromyography (sEMG) are only partially effective in monitoring and analyzing the mechanical characteristics of the tongue muscles. The signals from laryngeal musculature are generated on the surface of the suprahyoid muscles (muscles superiorly on the hyoid bones) viz., digastric, stylohyoid, mylohyoid, geniohyoid and geniohyoid. Fewer investigations have explored functioning of the four pairs of extrinsic muscles of the tongue, including the genioglossus, hyoglossus, styloglossus and palatoglossus. Thus, understanding the tongue-muscle movement patterns 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 [21], [22], [23]. 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. The signal acquisition approach used in this study was extended to classify tongue positions and during a dry swallow in 12 elderly subjects without dysphagia [24]. 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 an appropriately designed tongue-computer interface, the tongue position and direction need to be dynamically determined with a high degree of accuracy. A large majority of existing TMIS's use variations in either electromagnetic fields or inductance level for monitoring and determining the tongue movement and 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 (usually) metallic, components inside the mouth. Mounting such components inside the mouth would usually require patients to go through a procedure [5], [6], [8], [20], [21], [22], [23]. 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, patients' dependability in a variety of real-life situations, portability, size, volume and mass.

Many recent works have 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 is also being paid to the cost and operational difficulty related issues of the TSIS's [7], [24], [25], [26].

III. AN OVERVIEW OF EXISTING TMIS'S

Several highly sophisticated tongue-computer interfaces and mechanisms have been developed. 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], [27], the employed sensing modality would determine the nature of the interaction mechanism in a TMIS. Table 1 presents a representative list of TMIS's. Brief details of the employed tongue-computer interaction approach are also presented in Table 1.

The technology and accuracies of TMIS's reported in Table 1 have evolved during the last two decades or so. With the 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 to overcome the aforementioned limitations in TMIS's, a novel set of features was developed that would help in designing the tongue-machine interface. These features were reported in the wider literature on designing medical devices and their evaluation [33], [34], [35], [36], [37]. The design features, considered essential, for developing a minimally invasive and more acceptable TMIS are listed in column 1 of Table 2. The relevance of 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 tertiary hospital staff whose expertise helped in enhancing the proposed criteria. These design features were incorporated in a minimally invasive tongue-supported interaction system, which uses a novel tongue position and movement monitoring method and could be mounted without a procedure [7], [25]. Thus, the demanding and expensive procedure that discourages TMIS's application in real-life situations was avoided.

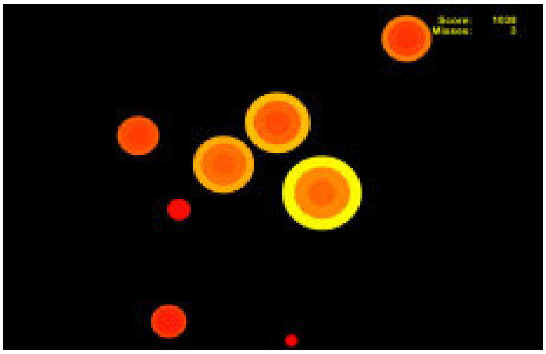

FIGURE 1. Disc dash screen shot.

The selection of design features for the proposed TMIS is presented in section V and its design execution details are presented in section VI. TMIS's performance results are reported in section VII. The design, implementation and tests are discussed in section VIII and a conclusion is shared in section IX.

V. FEATURES OF TMIS FOR INDIRECT NON-SWALLOWING EXERCISES

A. TONGUE-COMPUTER INTERACTION MODALITIES

In order to select the most effective tongue-computer interaction modality, six possible modalities were considered. The 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 [38] 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 2. Table 3 reports the employed assessment features and the evaluation schema. Table 4 shows the outcome of the Dominic analysis.

The analysis, shown in Tables 3 and 4, 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 literatures [18], [39], [40], and [41].

Studies suggest that positional accuracy and speed of the tongue movement increased after going through a few

TABLE 1. **Tongue-Computer interface design in existing TMIS's.**

Author/(s)	System/ application	Tongue-computer interface design
Sheriff and York 1988[27]	Oral machine controller	Two tooth-shaped dentition grips are attached to the teeth and a tongue -actuated micro-switch controls the machine operation. Obtrusive.
Buchhold 1995 [6]	Peripheral device controller	Tongue receptacle attached to the tongue and a mouthpiece is disposed into oral cavity. Obtrusive.
Strujik. 2006[5]	Inductive tongue computer interface	An activation unit glued to the tongue. A palatal plate attached to the mouth top. Obtrusive.
Krishnamorthy, and Ghovanloo, 2006 [28]	Tongue Drive	Permanent magnet pierced on the tongue. Sensors mounted on a dental retainer attached to the teeth. Obtrusive
Huo et. al. 2008 [20]	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.
Caltenco et. al., 2008 [4]	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.
Vuillerme, N., et. al. 2009 [9]	Tongue tactile biofeedback system	A wireless radio-controlled tactile output device placed on the tongue and worn as a dental retainer. Obtrusive.
Huo et al. 2009 [21]	Tongue motion based wheeled body control	Extension of [22]. Minimally invasive.
Park at al. 2012 [26]	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.
Sandy and Khan 2012 [25]	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.
Draghici, et al. 2013 [29]	A tongue-computer interface	An intraoral touchpad requires touch of the tongue for input. Obtrusive.
Quain and Khan 2014 [17]	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.
Sasaki, M. 2014 [19]	Tongue motor training support system	Surface electromyographic (sEMG) signals acquired using electrodes. Intraoral arrangement.
Sasaki, M. 2020 [24]	Oral motion classification	Surface electromyographic (EMG) signals acquired using electrodes and classified using a support vector machine.
S. Niu, L. Liu, and D. S. McCrickard [30]	Camera-based tongue-computer interface	Camera-supported determination of tongue position.
M. Mohammadi et al. [31]	Tongue-based joystick to control a robot	Inductive tongue computer interface for controlling robots
K. Gorur et al., 2019 [32]	Glossokinetic potentials supported tongue-computer interaction	Glossokinetic potentials signal processing using deep Convolutional Neural Network and Support Vector Machine for tongue-machine interface

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 III$^{\text{TM}}$. The study concluded that the tongue remained 5 to 50% slower than a finger-supported pointing device [42], [43].

These results suggested that in the given test conditions, tongue's overall performance is typically lower than that of the finger. However, the tongue can still be effectively used in human-computer interaction though at a slow speed and with relatively lower accuracy. Therefore, it was safe to posit that tongue could be used as an input medium for interacting with machines and so for indirect dysphagia therapy.

Having established that tongue's efficacy, it's use with a capacitive screen was explored. An android phone was connected to a laptop through WiFi and an application software called Remote Droid [43], [44] was run. This application allows the phone to be used as a mouse for tracking and clicking on the screen in left-click and right-click modes. The capability of the tongue was compared against the human thumb using an online game called Disc Dash [45]. The game tests the user's mouse movement skills, speed and accuracy.

TABLE 2. Proposed TMIS design features.

Feature	Significance and relevance
Affordability	• Should be affordable (for the patients and/or carers) • Should cost less than $ 300.00 • Should have low power consumption and have a long battery life • Should require minimal maintenance and part replacements
Compatibility	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)
Effectiveness	• 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)
Dependability	• 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)
Learnability	• 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
Storability	• Should not require any surgical or medical procedure for mounting, dismounting and application • Should be unobtrusive, comfortable and small
Accessibility	The system volume should be as minimum as possible. The system should weigh less than 500 grams
Repeatability	The system should be able to produce the same output given the same input
Accuracy	The system should be able to achieve a high level of accuracy and should provide very low levels of tolerance

FIGURE 2. Mobile phone screen displaying the remote droid.

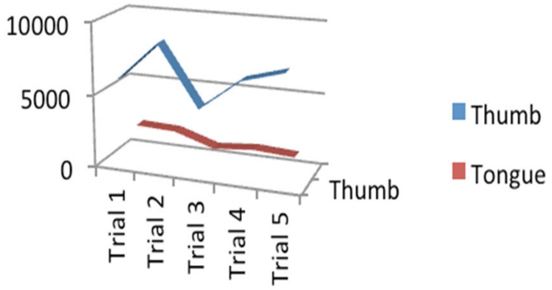

FIGURE 3. Comparison of points scored (along the y-axis) using thumb and tongue while playing an online game disc dash. Results were gathered by touching the rings 7.5cm x 5.5cm screen.

The aim of the game is to click upon the rings as they appear on the screen, 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 [43],

[44] was configured on the android phone such that 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. A total area of 41.25 cm^2 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.

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 2). 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 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 [17]. 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).

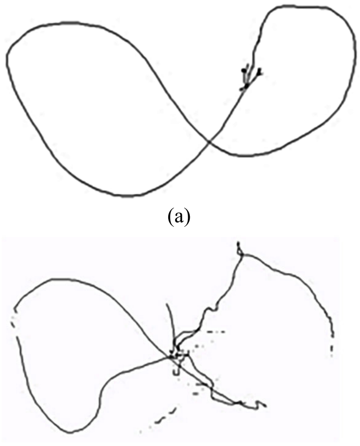
(a)
(b)

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

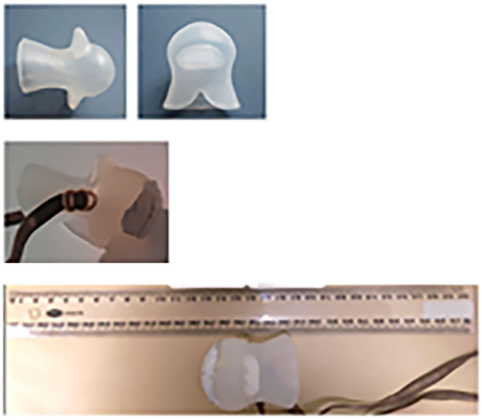

FIGURE 5. Silicone tongue device (top) two views of the device (snoring cessation); (middle) reflective tape attached to the device; and (bottom) physical dimensions of the tongue device: L = 65 mm, W = 55mm.

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 two-dimensional (2D) space with the help of an IR camera and a Wii remote. A similar approach was employed in a previous system [46] 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. Three different configurations of this arrangement were trailed progressively. 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 3 reports features that were considered, assessed and used in designing the TMIS.

Table 4 presents analyses of various design configurations and their results. Closely examining Tables 3 and 4 would suggest that keeping a reflective surface on the tongue (to be used as a signal transmitter) and an IRLED array on the receiving end would be a suitable option. This option would also be the most plausible method of implementing the system in a wireless configuration. Furthermore, this option would result in a low-cost, portable and energy-efficient tongue-computer interaction mechanism.

Having determined the best possible TMIS design, we tested use of tongue as a pointer to achieve (1) reasonable levels of pointing accuracy, (2) control over the tongue movement and (3) a suitable operational range (user-to-system distance).

TABLE 3. 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 4. Dominic analysis of various tongue-computer interface features and their respective significance levels.

Rank	Very Important (H)	Important (Moderate)	Desirable (Low)
Excellent (E)	🟦 D E E F B	🟦 C C D D E F	🟦 D E F F B B
Good (G)	🟩 A C C F F B B	🟦 A E F F B B B	🟦 A A C D
Fair (F)	🟩 A A D	🟩 A	🟦 C
Poor (P)	🟧 C D E	🟧 A C D E	🟧 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 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).

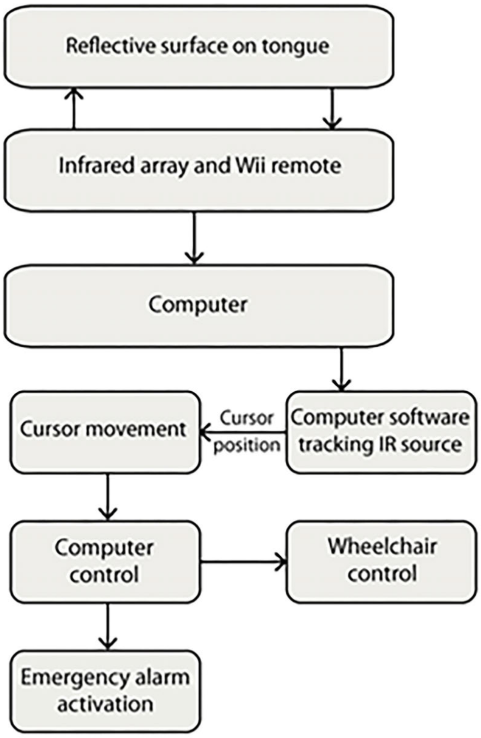

FIGURE 7. Architectural and functional details of the TMIS.

As a reflective surface was needed to reflect the IR light on the IR camera, two types of reflective surfaces, regular aluminium foil (alfoil) and reflective tape, were tested with the Wiimote 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. It is possible that the alfoil had a rough surface so light rays would 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 tongue was required. The snoring device, its tape-mounted version, and its physical dimensions are shown in Figures 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 used. An IR light array was developed and used 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 × 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 ± 12° 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 6.

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 user-friendly software was needed to process the input of the Wii remote's IR camera and translate the incoming data into both cursor movements and commands. 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

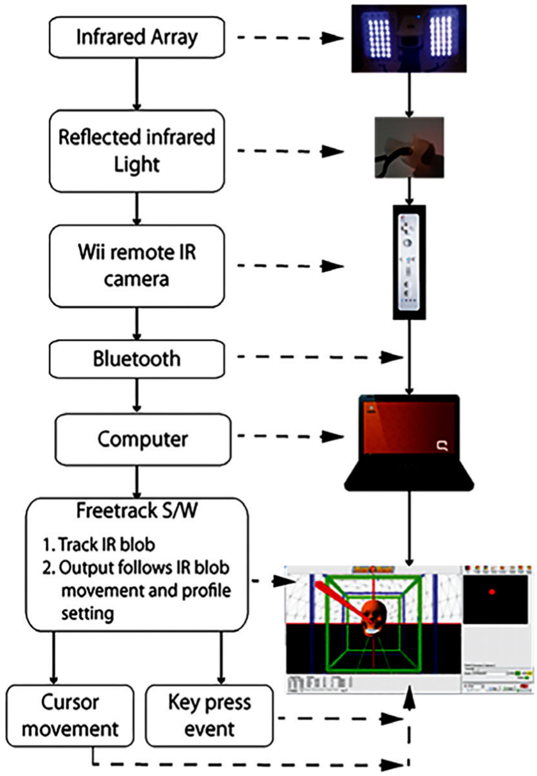

FIGURE 8. Flow of information through various components of the TMIS.

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

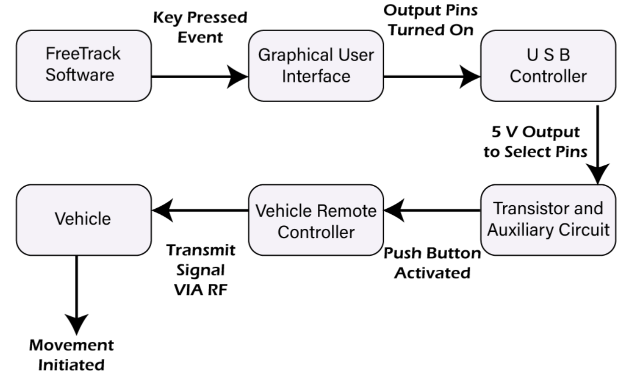

FIGURE 10. The proposed vehicle (wheelchair) navigation scheme.

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 [47]. To incorporate the tongue tip tracking ability, a dwell-clicking program was used with the FreeTrack software. This dwell-clicking program provides 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 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 [48].

VII. IMPLEMENTATION DETAILS

Effectively incorporating the design criteria in the TMIS 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 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.

TABLE 5. TMIS-Disc dash test results.

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

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 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 care-taker was able to make the necessary adaptations in 2 to 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. 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 appropriateness of 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 (pre-COVID 19) and then off-campus (post-COVID 19). Three male European origin students volunteered for the on-campus tests and eight international students (three female and five male) of Central Asian and South Asians origins, volunteered for the off-campus tests. All volunteers were does not have a disability and young students whose ages varied between 17.5 to 23 years.

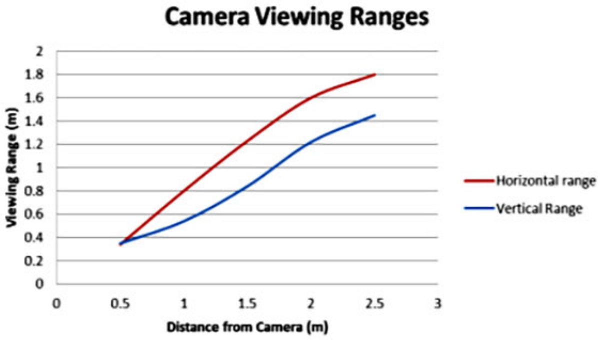

FIGURE 11. **Measured horizontal and vertical usable distance range of the TMIS.**

B. RANGE OF OPERATION

For effectively using the TMIS, its horizontal and vertical sensing ranges were tested and measurements were taken at various distances from the Wii Remote's IR camera. Results are shown in Figure 11. 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 [49]. The minimum operating distance of the TMIS 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 TMIS was found to be within the 5 m range. 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 5) were recorded. As shown in Table 5, the system performance was compared against two other system; one of them uses the human fingers on a capacitive screen and the other system uses the tongue on a capacitive screen [50], [51], [52]. As shown in Table 5, 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 5, 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 range of 25-30 words per minute (wpm) could be considered apt for extensive personal needs (see more information on Yulian Electronic Technology Co., http://gzyulian.com/en/home/ and Shenzhen Hua Shun Tong Technology Co. Ltd. http://www.hsttp.com/en/?index.html). Based on these findings, 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 the 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 a person'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], [57], [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 our 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,

TABLE 6. TMIS performance evaluation.

TESTING CRITERIA	TARGET	TMIS
System Operation		
Minimum Range of Operation (meters)	0.5m	0.08m
Maximum Range of Operation (meters)	3.6m	5m
Effectiveness		
Typing (wpm)	25 wpm	6.2 wpm
Mouse control score	>1411.8 average point score in Disc Dash	2112.8 average point score 33.2% improvement
Playing games	Yes	Yes
Functionality		
Activate Emergency alarm	Hospital Alarm System	Hospital Alarm System Local Alarm Buzzer
Using Computer	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
Potential control of an electric Wheelchair	Yes	Yes Navigated a remote controlled car Controlled a Smart line following robot

TABLE 7. The ITR-based performance of TMIS and some previously implemented systems.

System	Description	ITR
TMIS	This system	~37.36
Huo, Wang & Ghovanloo, 2008 [20]	*Tongue-computer interface*	~130
Lao & O'Leary, 1993 [56]	Head-operated computer-mouse interface	120
Huo, Wang & Ghovanloo, 2007 [58]	Tongue-computer interface	97
Sera, 2014[43]	Tongue-computer interface	87

activation of alarm systems and, use of a word processor. These assessment features, their target values and the test results are summarized in Table 6. 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, 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

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], [59], [60].

The IRT is calculated as:

$$ITR = \frac{1}{T}\left[log_2 N + Plog_2 P + (1-P)log_2 \frac{(1-P)}{N-1}\right], \quad (1)$$

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 7 using the previously published data [20], [43], [58], [60]. As reported in Table 7, the TMIS in [58] 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 almost 10 times larger set of commands, the TMIS'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 8 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 (the used 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 TMIS, though affordable, can be reduced further.

G. LIMITATIONS

The physical size of the silicon 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 also 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 to the user 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 does not have a disability volunteers; and not on patients with mobility and/or dexterity impairments. Several biomedical device design and

TABLE 8. Overall cost of the TMIS (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.

development related investigations use data collected from young and does not have a disability 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 does not have a disability subjects are employed for testing the prototype systems. Hence, use of data collected from young and does not have a disability people is common in the realms of biomedical engineering 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 provides a cost-effective option for tongue exercise training which could be used to assist patients with oral and pharyngeal swallowing difficulties. Mapping of the tongue position with the required amount of time might also help in estimating the exercise dosage. Patients can use the TMIS for interacting with computers, communication devices and mobility support systems vis-à-vis going through tongue muscle strengthening exercises. This system can be beneficial especially for patients who cannot use their fingers to interact with a computer. We propose and demonstrate a set of design criteria that could be incorporated to achieve the desired functionality in a TMIS. The presented system can help in improving the mechanical properties of the tongue musculature. The design details outlined in this paper can be used for building a HID class, portable, small, lightweight, low power, easy to learn, and easy to mount/dismount TMIS's. In future, the feasibility of using low power protocols such as BLE (Bluetooth Low Energy) in the TMIS can be evaluated to further reduce the power requirements. It is very important to prolong the battery life by reducing the power consumption for systems that are used on wheelchairs because electric power cannot be used for the TMIS. In addition, the proposed system may also be tested on patients for the assessment of its usefulness and effectiveness. Development of such systems would help impaired patients interact with machines and a variety of devices like computers, toys and different types of assistive and mobility-support systems. As demonstrated, the overall performance of the TMIS was comparable to the existing TMIS's. The TMIS requires patients to put on a sleep apnea silicone device on the tip of the tongue. This arrangement is more convenient and more portable as compared to the ones that require attaching system elements to the tongue and mouth of a patient.

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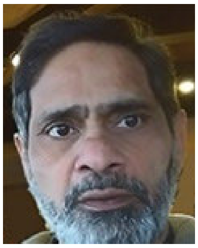

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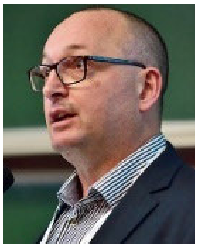

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