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Design and evaluation of a noninvasive tongue-computer interface for individuals with severe disabilities

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***Abstract*—Tongue-computer interfaces have shown the potential to control assistive devices developed for individuals with severe disabilities. However, current efficient tongue-computer interfaces require invasive methods for attaching the sensor activation units to the tongue, such as piercing. In this study, we propose a noninvasive tongue-computer interface to avoid the requirement of invasive activation unit attachment methods. We developed the noninvasive tongue-computer interface by integrating an activation unit on a frame, and mounting the frame on an inductive tongue-computer interface (ITCI). Thus, the users are able to activate the inductive sensors on the interface by positioning the activation unit with their tongue. They also do not need to remount the activation unit before each use. We performed pointing tests for controlling a computer cursor and number typing tests with two able-bodied participants, where one of them was experienced with using invasive tongue-computer interfaces and other one had no experience. We measured throughput and movement error for pointing tasks, and speed and accuracy for number typing tasks for the evaluation of the feasibility and performance of the developed noninvasive system. Results show that the inexperienced participant achieved similar results with the developed noninvasive tongue-computer interface compared to the current invasive version of the ITCI, while the experienced participant performed better with the invasive tongue-computer interface.**

***Index Terms*—Tongue-computer interfaces, assistive devices, noninvasive sensor activation, tetraplegia**

I. Introduction

Severe neurological disorders such as high levels of spinal cord injury (tetraplegia) is a traumatizing experience for the affected individual. The loss of sensory-motor functions commonly results in the inability to perform activities of daily living (ADL), limited independence, increased depression risk, and decreased quality of life [1], [2]. To restore functions of individuals with severe disabilities, assistive devices such as robotic manipulators [3] and exoskeletons [4], [5] have been developed. These devices can assist disabled individuals to perform ADLs, and thereby increase their independence and quality of life.

Control interfaces for assistive devices can be based on eye movements, head orientation, brain electroencephalography (EEG) signals, voice commands, or tongue motion [6]–[10]. Among many methods, tongue based control interfaces with high number of control signals are preferable for disabled individuals due to the aesthetic concerns and requirement of low physical effort [11].

In recent years, several tongue based control interfaces have been developed [10], [12]–[14]. The tongue-drive system (TDS) providing 9 command signals [12] was used to access computers [15], [16], to control a powered wheelchair [17], and to control a single degree of freedom of a hand exoskeleton [18]. The inductive tongue-computer interface (ITCI) providing 18 command signals [10] was first introduced in [19] and used as a control interface for several applications. A version of the ITCI has been commercialized under the name Itongue® which can be used to control personal computers and powered wheelchairs [20].

The ITCI system is composed of a mouthpiece that is mounted on the hard palate surface of the mouth (Fig. 1c), and a central unit that receives signals from the mouthpiece wirelessly (Fig. 1a). The mouthpiece incorporates 18 inductive sensors made of 10-layer printed circuit board, electronic circuits, wireless communication elements and a battery [21]. Inductive sensors are divided into two sections constituting the keypad area with 10 sensors (Fig. 2a, lower part) and the mouse area with 8 sensors (Fig. 2a, upper part). Sensors on the ITCI are activated by a metal activation unit (AU) that is attached to the tongue by gluing or piercing (Fig. 1b). The validity and performance of the ITCI was evaluated on able-bodied or disabled individuals for typing tasks [21], [22], pointing tasks to control a computer cursor [22], [23], and controlling an assistive robotic manipulator [10], [24].

The major drawback of available tongue based control interfaces is their invasiveness. The TDS incorporates a magnetic tracer attached to the tongue by gluing or piercing [18]. Likewise, the ITCI requires gluing or piercing an AU to the tongue. However, placement of a tongue piercing for a long-term use is undesirable for one third of potential users [25].

Therefore, in this paper, we proposed a novel noninvasive

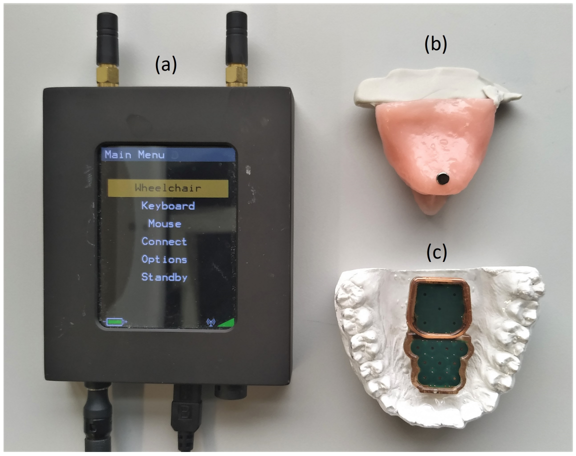

Fig. 1: Components of the ITCI. (a) The central unit, (b) The activation unit on a phantom tongue, (c) The mouthpiece glued to a thermoformed plastic sheet.

(a) (b)

Fig. 2: (a) The ITCI with the mouse area (upper part) and the keypad area (lower part). The center of the keypad is the origin (red circle) and an AU contact with a sensor creates a vector from the origin (blue arrows) in the pointing tests. (b) A gamepad joystick (red circle).

tongue-computer interface (TCI) based on the current version of the ITCI, to avoid the need of current invasive methods of gluing or piercing the AU to the tongue. We designed the noninvasive TCI by integrating an AU on a frame, and attaching the frame on the keypad area of an ITCI. Thereby, the inductive sensors on the ITCI can be activated by positioning the AU with the tongue. To test the developed sensor activation method and its effect on the tongue's ability to manipulate and navigate the AU for sensor activation, we performed pointing tasks and number typing tasks with two able-bodied participants among the authors. Finally, we evaluated the performance and feasibility of the developed system.

II. Methods

A. Design of the noninvasive tongue-computer interface

For the design of the noninvasive tongue-computer interface, first, thermoplastic sheets (Biolon 0.5 mm) were thermoformed using the vacuum forming process and 3D models of the participants' upper jaw. Resulting thermoformed plastic sheets can be fitted to the upper teeth of the participants and stay inserted in their mouth until they remove it using their fingers. Afterwards, biocompatible acrylic materials were used to glue the tongue computer interfaces onto the thermoplastic sheets.

MENZANIUM® coil wire with a diameter of 1 mm, which is used for dental applications, was cut and bended in order to make a frame for the keypad part of the TCI (Fig. 3). An AU with a 2 mm diameter drilled hole was integrated to the frame. Thereby, users are able to move the AU in 2D plane by a push from the tongue. The difference in the diameters of the wire and hole in the AU, and the bended loop in the bar with attached AU ensure that the AU is not normally in contact with the inductive sensors due to the gravity effect. Users are required to push the AU upwards to activate the sensors. In order to fix the frame onto the thermoplastic sheet, biocompatible light curing resin based composite materials, which were polymerized by a dental curing light were used. The custom made noninvasive TCI developed for one of the participants can be seen in Fig. 3.

For the development of custom made invasive tongue-computer interface, acrylic materials were used to glue the tongue computer interfaces onto the thermoplastic sheets, which were thermoformed using the vacuum forming process as done for the noninvasive interface (Fig. 1c). Prior to using the invasive TCI interface, the AU is required to be glued to the tongue with a medical tissue glue (Histoacryl®) for a temporary attachment.

B. Input/Output mapping and software for testing

To estimate the analog position of the AU on the TCI, signals from the sensors were mapped to a 2D Cartesian coordinate system using a weighted average of neighbors (WAN) algorithm as previously done in [23]. This algorithm detects the sensor with the highest activation and estimates the position of the AU based on the weighted average of the position of that sensor and its neighbors.

Fig. 3: Noninvasive tongue-computer interface.

For the pointing tests, a virtual joystick was emulated in a graphical user interface (GUI) (Fig. 4, left). Since the accuracy of the AU position estimation is higher for the keypad area than the mouse area [23], the keypad area of the ITCI was used as a joystick. The center of the keypad was the origin (Fig. 2a, red circle) and an AU contact with a sensor created a vector from the origin (Fig. 2a, blue arrows) as similar to [26]. The length and direction of this vector determined the moving velocity and moving direction of a pointing cursor. Thus, the ITCI can function like a gamepad joystick (Fig. 2b).

Similarly, for the number typing tests, a virtual numpad was emulated in a GUI (Fig. 5, left). The keypad was divided into 10 sections, each corresponding to a number between 0 and 9 with respect to the position of the AU. Dwelling time determined the period of time that should elapse to type a number after a contact with a sensor.

C. Pointing tests

To evaluate the performance of the developed noninvasive tongue-computer interface, we designed two different types of tests: a pointing test and a typing test. The procedure for the tests has been approved by the National Ethics Medical Committee. First, we performed pointing tests with the emulated joystick. Pointing tests are based on the guidelines for pointing input devices provided by the ISO9241-Part 411 standard [27].

To perform pointing tests, we used FittsTask software developed for evaluating the performance of pointing devices which is available in [28]. In this software, the task is moving the computer cursor into the highlighted targets that are placed through the circumference of a circle, and selecting the targets (Fig. 4, right). The number of targets, distance between targets, and width of the targets for each sequence of trial can be set with the software. When the cursor enters a target and remains in the target for a specified time (target selecting dwelling time), the target is selected. The sequence of trials ends when all of the targets are selected.

Selected task levels for pointing tests can be seen in Table I. d represents the diameter of the layout circle that determines the distance between target circles in pixels and w represents the width or diameter of the target circles in pixels.

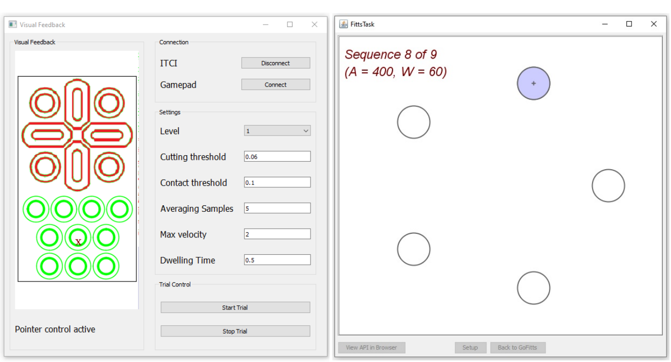

Fig. 4: GUI (left) and FittsTask software (right) for pointing tests.

TABLE I: Task levels for pointing tests. d is the distance between targets and w is the diameter of targets.

Level	d (pixel)	w (pixel)	ID (bits)
1	200	80	1.81
2	200	60	2.12
3	200	40	2.58
4	300	80	2.25
5	300	60	2.58
6	300	40	3.09
7	400	80	2.58
8	400	60	2.94
9	400	40	3.46

Corresponding index of difficulty (ID) for each sequence in bits, which depends on the distance between targets and the width of target, can also be seen in the table. The number of targets was selected as 5, and the target selecting dwelling time was set to 0.5 seconds for each trial. The trial ended when all of the 9 sequences of tasks were completed.

For the pointing tests, two performance measures were calculated: throughput and movement error. Throughput (TP) is quantified in terms of transferred data over an amount of time and its unit is bits per second (bps). It corresponds to both speed and accuracy in responses. TP is calculated by,

$$TP = ID_e/MT \tag{1}$$

where MT is the movement time in ms (sum of the pointing time and target selection time) and ID_e is the effective index of difficulty in bits calculated as,

$$ID_e = \log_2(d_e/w_e + 1) \tag{2}$$

where d_e (effective distance) is the mean movement distance between the initial cursor position and the target in pixels and w_e is the effective width of the targets in pixels defined as,

$$w_e = 4.133 \times SD_x \tag{3}$$

where SD_x is the standard deviation of distances between the selected coordinates and the center of target measured along the task axis [29].

Movement error (ME) is the average deviation of the cursor position from the task axis in pixels. A deviation from a straight line when moving the cursor between two targets means an error in the movement. ME is calculated by,

$$ME = \frac{\sum |y_i|}{n} \tag{4}$$

where y_i is the distance between the sample point and the task axis, and n is the total number of sample points [29].

The two able-bodied participants performed pointing tests under the following five conditions,

- A standard gamepad joystick (Thrustmaster® Dual Analog 4, Fig. 2b) as a baseline for evaluation
- Noninvasive TCI held in one hand and operated by moving the AU on the frame with the other hand without seeing the interface
- Invasive TCI held in one hand and operated by moving the AU on a stick with the other hand without seeing the interface

- Noninvasive TCI in-mouth and operated by moving the AU on the frame with the tongue
- Invasive TCI in-mouth and operated by the tongue-glued AU

Initially, 3 trials with each condition were planned. Participant (P1) was inexperienced with using tongue-computer interfaces. In day 1, before the tests for invasive interface in-mouth, the AU did not stick to the tongue of P1 and some modifications for the AU were required. Therefore, tests for invasive interface in-mouth were needed to be done in the next day. To avoid the possible effects of learning overnight [30], P1 performed 3 more noninvasive interface in-mouth tests and 6 invasive interface in-mouth tests in the next day. Additionally, in the 8th task of the first trial of testing of invasive interface, the AU fell. The AU was glued to the participant's tongue again, and therefore, this task was repeated at the end.

Participant 2 (P2) had about 40 hours of experience with the tongue-computer interfaces, while P1 used the system for the first time in this experiment. P2 performed 6 noninvasive interface in-mouth and 6 invasive interface in-mouth tests as P1. In the 8th task of the third trial of testing of invasive interface, the AU fell and was glued to the participant's tongue again. Therefore, this single task was repeated at the end.

D. Number typing tests

For the further evaluation of the performance of the developed noninvasive tongue-computer interface, the same two able-bodied participants (one inexperienced and one experienced) performed number typing tests using,

- Noninvasive TCI held in-hand and operated by the other hand
- Invasive TCI held in-hand and operated by the other hand
- Noninvasive TCI in-mouth and operated by moving the frame-integrated AU with the tongue
- Invasive TCI in-mouth and operated by the tongue-glued AU

Number typing tests for each condition were performed with 2 different numbers and 2 different dwelling times. Number 1 was determined as "1236547890" with respect to the order of numbers in the GUI layout (Fig. 5, left) and Number 2 was determined randomly as "2937548601". Additionally, dwelling times was set as 1 second (DT1) and 0.8 seconds (DT2). Participants performed each trial 3 times. Therefore, there were 48 trials in total for each participant. Each trial lasted 30 seconds. Participants repeated the specified number until the time was up. Typed numbers were saved into Microsoft Word© documents for each participant (Fig. 5, right).

For the performance evaluation, the typing speed and accuracy were calculated for each trial. If one character was missed, mistyped, or typed more than one, it was counted as a mistyped character. The total number of correctly typed characters in 30 seconds gave us a performance indicator of speed in characters/30 sec. Additionally, the ratio of the number of correctly typed characters to the sum of total number of typed and missed characters gave us the accuracy as another performance indicator.

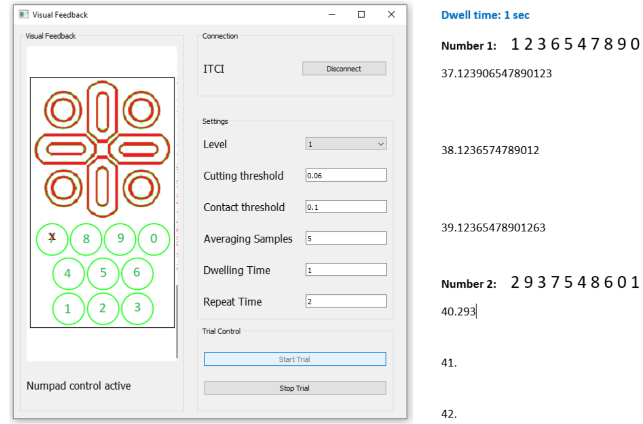

Fig. 5: GUI (left) and Microsoft Word© document (right) for number typing tests.

III. Results

A. Pointing tests

Table II shows the mean throughput in bps and mean movement error in pixels for each input method and participants. The values in parentheses show the standard deviations.

The highest TP and the lowest ME results were achieved with the gamepad joystick for both participants. The throughputs were higher when the TCIs were used in-hand compared with using it in-mouth for both participants (Table II).

For the pointing tests with the TCIs operated by hand, P1 achieved higher TP (0.64 bps) and lower ME (19.3 px) with the noninvasive TCI compared with the invasive TCI (0.56 bps and 22.4 px). On the other hand, P2 achieved lower TP (0.51 bps) and slightly lower ME (20.3 px) with the noninvasive TCI compared with the invasive TCI (0.67 bps and 21.4 px) (Table II).

For the pointing tests with the TCIs in-mouth, TP results of the noninvasive TCI and invasive TCI were the same (0.41 bps) for P1. However, P1 achieved lower ME (17 px) with the invasive TCI than the noninvasive TCI (32 px). P2 achieved similar TP (0.4 bps) with P1 by using the noninvasive TCI in the mouth. However, P2 achieved 47.5% higher TP (0.59 bps) with the invasive TCI than the noninvasive TCI. Similar to P1, P2 achieved lower ME (16.9 px) with the invasive TCI than the noninvasive TCI (25.4 px) (Table II).

B. Number typing tests

Table III shows the mean speed results in correct characters/30 sec and mean accuracy results achieved by P1 with four input methods, two numbers, and two dwelling times. Table IV shows the same results for P2.

Overall, both of the participants achieved higher speed and accuracy results with the noninvasive TCI compared with the invasive TCI, when the TCIs were operated by hand (Table III and Table IV).

In the typing tests with the TCIs in-mouth, P1 typed 9 - 12.67 correct characters in 30 seconds with 80% - 92% accuracy by the invasive TCI, while the results for the noninvasive

TABLE II: Effective throughput (TP) and movement error (ME) results from different input methods. Mean values and standard deviations in parentheses.

	Participant 1		Participant 2	
Input Method	**TP (bps)**	**ME (px)**	**TP (bps)**	**ME (px)**
Gamepad Joystick	1.17 (0.25)	9.6 (3.1)	1.09 (0.23)	8.9 (2.6)
Noninvasive TCI in-hand	0.64 (0.15)	19.3 (4.5)	0.51 (0.15)	20.3 (8.3)
Invasive TCI in-hand	0.56 (0.16)	22.4 (4.9)	0.67 (0.13)	21.4 (8.0)
Noninvasive TCI in-mouth	0.41 (0.11)	32.0 (12.9)	0.40 (0.11)	25.4 (7.6)
Invasive TCI in-mouth	0.41 (0.12)	17.0 (4.9)	0.59 (0.15)	16.9 (4.5)

TCI were 8 - 11.67 correct characters in 30 seconds with 59% - 83% accuracy (Table III). On the other hand, P2 typed 12.67 - 14.67 correct characters in 30 seconds with 88% - 100% accuracy by the invasive TCI, and 10 - 12.33 correct characters in 30 seconds with 68% - 92% accuracy by the noninvasive TCI (Table IV).

For both participants, the performance difference between the invasive and noninvasive TCIs were higher when the tasks were typing Number 2 compared with the tasks with Number 1. P1 achieved on an average 7.1% higher speed and 12.2% higher accuracy results with the invasive TCI in Number 1 tests. However, in Number 2 tests, P1 achieved on an average 11.5% higher speed and 34.7% higher accuracy results with the invasive TCI (Table III). Similarly, in Number 1 tests, P2 achieved on an average 13.9% higher speed and 3.3% higher accuracy with the invasive TCI, while the difference for the Number 2 tests were 37.8% for speed and 31.3% for accuracy (Table IV).

IV. Discussion

In the pointing tests, for both participants, performances of the TCIs in-hand tests were higher than the TCIs in-mouth tests due to the higher dexterity of the hand compared to the tongue. Additionally, able-bodied individuals have more experience and skill with using their hands to manipulate objects.

For the pointing tests with the TCIs in-mouth, performances of noninvasive TCI and invasive TCI were similar for P1 due to the lack of experience with the use of TCIs. On the other hand, since P2 had 40 hours of experience with using the invasive TCI and had no experience with using the noninvasive TCI, P2 achieved higher performance with the invasive TCI. As both participants were inexperienced with the noninvasive TCI, they achieved similar performances by using the noninvasive TCI.

For the typing tests with the TCIs in-mouth, P1 achieved on an average 9% higher speed results with the invasive TCI compared to the noninvasive TCI, while P2 achieved on an average 26% higher speed results. This difference is estimated to be related to the lower level of experience of P1 with invasive TCI. It should also be noted that the difference in performances is mostly caused by the relatively more difficult typing tasks with random numbers (Number 2).

For P2, the difference between the invasive TCI and non-invasive TCI was higher for the pointing tests than typing tests due to the training with the noninvasive TCI while performing pointing tests. Additionally, as the number typing results show, the developed noninvasive TCI worked slightly better than the invasive TCI to activate ordered or random sensors on a TCI, when the AU was manipulated by the hand for both participants. Therefore, it can be concluded that, the performance of the noninvasive TCI can be as good as the invasive TCI in the case of adequate training.

Both of the participants experienced the loosening and falling of the AU during the pointing tests with the invasive TCI. Additionally, P1 with no experience using a TCI found it less comfortable using the invasive TCI, which requires gluing the AU to the tongue, compared to using the noninvasive TCI.

Only one target selecting dwelling time was tested in the pointing tasks as increased duration of tests might bore the participants. However, testing different target selecting dwelling times would provide an additional variety of task difficulty for the evaluation of different input methods. Both of the pilot tests involve two participants with different experience levels. Further studies will involve more participants to obtain more reliable results.

V. Conclusion

The main objectives of this study were to develop a non-invasive sensor activation method for the ITCI and to test the feasibility and performance of the developed system. For that purpose, we developed a frame with an integrated AU, and mounted the frame on the keypad area of an ITCI. Thereby, the inductive sensors on the ITCI can be activated without

TABLE III: Mean speed and accuracy results for Participant 1. Number 1 and Number 2 are 1236547890 and 2937548601, respectively. DT1 and DT2 are 1 sec and 0.8 sec, respectively.

Participant 1	Speed (characters/30 s)				Accuracy			
	Number 1		Number 2		Number 1		Number 2	
Method	**DT1**	**DT2**	**DT1**	**DT2**	**DT1**	**DT2**	**DT1**	**DT2**
Noninvasive TCI in-hand	13.67	15.33	12.33	14.00	0.98	0.96	0.93	0.86
Invasive TCI in-hand	14.00	14.00	10.33	13.33	0.93	0.93	0.76	0.89
Noninvasive TCI in-mouth	11.67	11.67	8.00	9.33	0.80	0.83	0.59	0.62
Invasive TCI in-mouth	12.67	12.33	9.00	10.33	0.91	0.92	0.80	0.83

TABLE IV: Mean speed and accuracy results for Participant 2. Number 1 and Number 2 are 1236547890 and 2937548601, respectively. DT1 and DT2 are 1 sec and 0.8 sec, respectively.

Participant 2	Speed (characters/30 s)				Accuracy			
	Number 1		Number 2		Number 1		Number 2	
Method	**DT1**	**DT2**	**DT1**	**DT2**	**DT1**	**DT2**	**DT1**	**DT2**
Noninvasive TCI in-hand	14.67	14.33	14.33	13.33	1.00	0.98	0.96	0.96
Invasive TCI in-hand	12.67	14.00	13.33	12.67	0.96	0.96	0.88	0.98
Noninvasive TCI in-mouth	12.33	11.67	10.33	10.00	0.92	0.88	0.76	0.68
Invasive TCI in-mouth	12.67	14.67	13.33	14.67	0.88	0.98	0.89	1.00

attaching the AU to the tongue. To test the developed sensor activation method, we performed pointing tasks and number typing tasks with two able-bodied participants. Results show that, the developed system's performance was similar to the current invasive version of the tongue-computer interface for the inexperienced participant. However, it was lower for the participant who was experienced with the invasive TCI.

This study will pave the way for research on tongue-computer interfaces where the activation unit does not need to be pierced to the tongue or remounted before each use. Further, it will increase the aesthetics and adoption of the system by the users and expand the system usability to other applications, e.g. gaming and work.

The developed system is a proof of concept for noninvasive tongue-computer interfaces that can be used to control assistive devices including robotic manipulators and exoskeletons. The next step will be the development of a noninvasive tongue-computer interface with a flat interaction surface.

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