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ORIGINAL RESEARCH

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Development and functional demonstration of a wireless intraoral inductive tongue computer interface for severely disabled persons

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ABSTRACT

Purpose: Individuals with tetraplegia depend on alternative interfaces in order to control computers and other electronic equipment. Current interfaces are often limited in the number of available control commands, and may compromise the social identity of an individual due to their undesirable appearance. The purpose of this study was to implement an alternative computer interface, which was fully embedded into the oral cavity and which provided multiple control commands.

Methods: The development of a wireless, intraoral, inductive tongue computer was described. The interface encompassed a 10-key keypad area and a mouse pad area. This system was embedded wirelessly into the oral cavity of the user. The functionality of the system was demonstrated in two tetraplegic individuals and two able-bodied individuals

Results: The system was invisible during use and allowed the user to type on a computer using either the keypad area or the mouse pad. The maximal typing rate was 1.8 s for repetitively typing a correct character with the keypad area and 1.4 s for repetitively typing a correct character with the mouse pad area.

Conclusion: The results suggest that this inductive tongue computer interface provides an esthetically acceptable and functionally efficient environmental control for a severely disabled user.

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Tongue computer interfaces; environmental control; neuro rehabilitation; tetraplegia

➤ IMPLICATIONS FOR REHABILITATION

- New Design, Implementation and detection methods for intra oral assistive devices.
- Demonstration of wireless, powering and encapsulation techniques suitable for intra oral embedment of assistive devices.
- Demonstration of the functionality of a rechargeable and fully embedded intra oral tongue controlled computer input device.

Background

Persons suffering from tetraplegia caused by, e.g., a spinal cord injury (SCI) experience exceptional challenges in their everyday activities, which often result in severe deterioration of their quality of life.[1] Even though these individuals are cognitively well-functioning, their disability significantly degrades their possibility of attending social and vocational activities, and their need for 24-h daily assistance may deplete them of any kind of privacy.

Current technological advances have virtualized and automatized daily social and vocational activities to a degree never seen before. Vocational and social activities are now greatly taking place through the Internet, and a wide range of the electrical equipment in homes and in assistive devices can now be controlled remotely. This technological development is potentially invaluable for tetraplegic individuals,[2,3] but the advantages of the technology may be compromised by the lack of accessibility for severely disabled persons. Therefore, the development of alternative control systems to interface to these technologies is crucial. For tetraplegic persons, the current control possibilities are to use, e.g., eye signals,[4–6] brain signals,[3,7,8] head movements,[9] voice control [10,11] and tongue/oral control.[12–16] Some challenges exist for all these systems, e.g., induced neck pain in the case of head control and issues related to invasiveness in the case of brain computer interfaces. Tongue-based control systems seem attractive due to the high flexibility of the tongue and the large area of its cortical representation suggesting a high capacity for selective manipulation of interfacing sensors. Further, a study by Lau [15] suggested that tongue control was preferable as compared with, e.g., head control. Recently, several tongue control systems have been suggested,[12–14,16] including a new inductive approach for tongue interfacing,[12] and in addition a magnetic approach was introduced.[13] The inductive system has been further developed to comprise up to 24 sensors in a partly intraoral version [17] while the magnetic system has up to six virtually active areas/sensors.[18] These systems do not require

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physical contact between the tongue and the sensors and, therefore, may compensate for the drawbacks of using force sensitive sensors in the interface as in the system used by Lau et al.[15]

Still there are issues to be addressed in order to develop efficient and acceptable tongue computer interfaces (TCI). The two systems suggested in references [12,13,17,18] require a metal unit attached to the tongue and external electronics to power and process the sensor system. Further, the systems based on force sensitive sensors and magnetic sensors are either configured for key-like activation or for directional mouse/joystick-like use while general computer input devices facilitate combined use of a keyboard and a mouse/joystick. The combined use of key and pointing devices is often lacking in assistive devices, further limiting the activity of a disabled computer user as compared with able-bodied users. Another issue is that many existing assistive devices only have single or very few modalities, which means that they can interface only to one type of electrical equipment, such as *either* a computer *or* a wheelchair. This results in cumbersome changes of control devices for each desirable activity; e.g., a mouth-operated table-mounted joystick used for typing on a computer has to be exchanged with a chin-controlled body-mounted joystick for wheelchair control.

In addition to the mentioned functional challenges in developing TCIs, esthetics also plays an important role in the acceptability of assistive devices since these devices are prone to become part of the user's self-identity.[3] In a study comparing four different assistive devices used by four tetraplegic users, the users preferred the most invisible device which was based on tongue control [15] even though it was far from being the most efficient one.

Therefore, this paper describes the design and the functionality of a tongue-based control system, which is invisible during use and thus esthetically acceptable. Further, this system provides a large number of control signals including both a mouse/joystick function and a 10-key keyboard function, that is, a fully intraoral Inductive Tongue Computer Interface (ITCI) for individuals with tetraplegia.

Methods

System overview

A fully intraoral tongue computer interface based on the variable inductance sensor technology described by Struijk [12] was developed and tested in four subjects.

To obtain a user-desirable assistive device, six overall requirements for the system were defined based on the issues of esthetics and functionality stated in the introduction and on general desires of computer users with tetraplegia previously obtained by the authors using a survey.[19] The six overall requirements were defined as:

The system must be:

- Invisible/discrete
- Hands off: controllable using the tongue only
- Wireless
- Mobile
- All-round: compatible with general electric equipment that has to be controlled.
- Used without interference with other user activities, e.g., the user should be able to speak and look around while wearing the system.

The overall diagram of the inductive tongue computer interface is shown in Figure 1, and the system can be divided into three main parts:

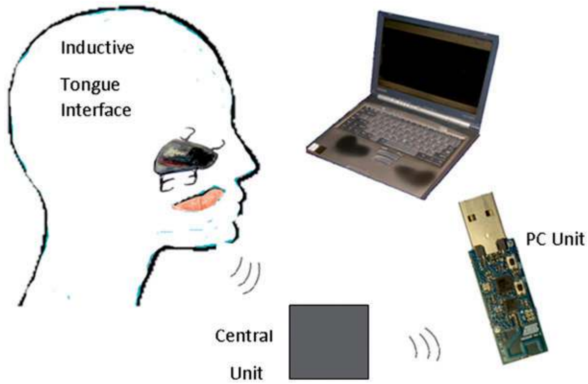

Figure 1. Overview of the Inductive Tongue Computer Interface. The Inductive Tongue Interface transmits the 18 sensor signals wirelessly out of the mouth to the central unit, which processes the signals and transmits the processed information to the PC unit, which emulates a mouse/keyboard function. The board used for the PC unit includes a microcontroller and radio chip.[24]

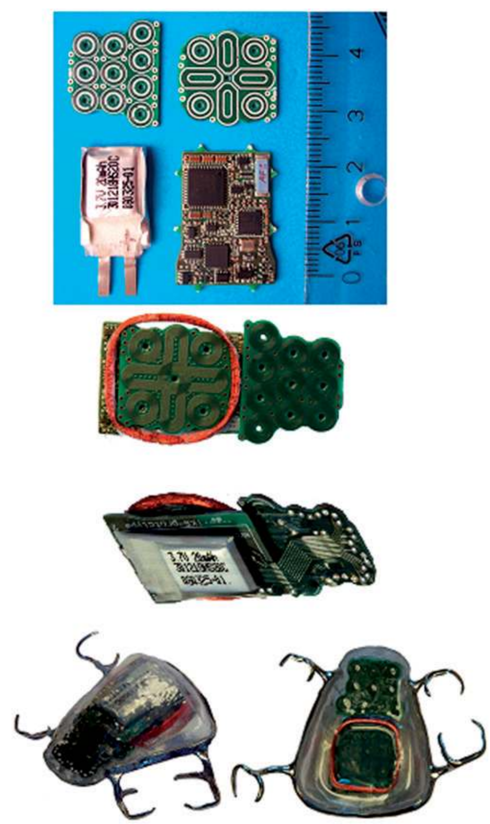

Figure 2. Overview of the ITI parts. **Top:** The Two 10-layer PCB constituting the key pad (left) and the mouse pad (right), the battery and the PCB for the electronics. The scale is in centimeters. **Middle:** Top middle: The assembled ITI parts, showing the charger coil and the sensor PCB. Bottom middle: The battery and one of the flex prints used to connect the parts. **Bottom:** The fully embedded ITI dental appliance.

I: The inductive tongue interface (ITI), which is placed intraorally and wirelessly transmits sensor data to an external central unit (CU). The tongue interface is thus invisible during normal use with a closed mouth.

II: The CU, which processes the data from the mouth piece and further wirelessly transmits the data to the PC Unit (PCU).

III: The PCU, which is implemented as a USB stick simulating keyboard and mouse function.

During use, the ITI was placed in the mouth, and the sensors of the ITI were activated by a ferromagnetic metal unit glued or

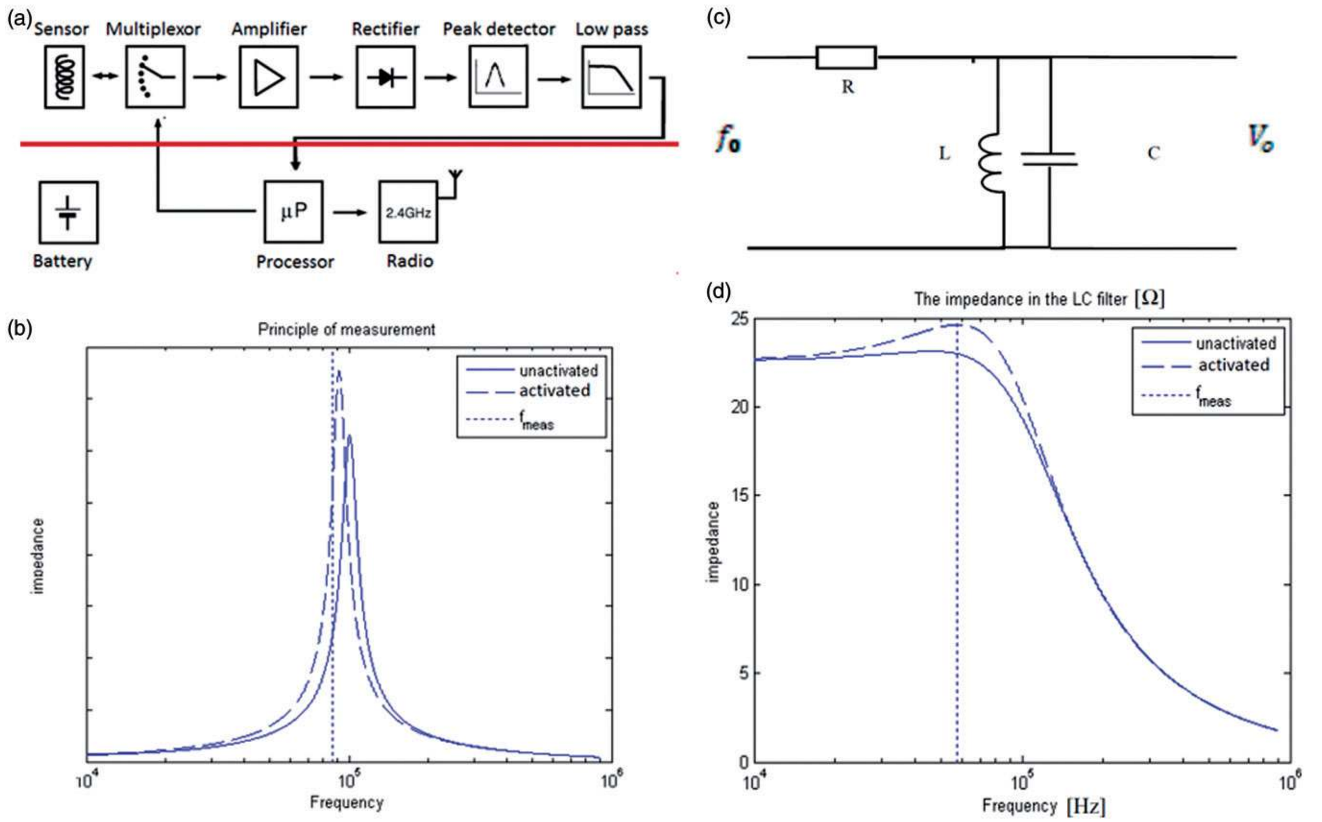

Figure 3. Overview of the main parts of the ITI signal processing and detection system. (a) The steps in the signal processing system. (b) The ideal principle of measurement: a band-pass filter was created by connecting a capacitor to each sensor coil. (c) During activation the impedance of the LC band-pass filter changed, and the activation was detected at the frequency, $f_{meas,}$ indicated by the vertical punctured line. (d) The real frequency characteristics of the detection LC band pass filter with and without sensor activation.

pierced to the user's tongue. When the user moved the tongue with the metal unit close to a desired sensor, the resulting change in the sensor signal was detected, processed and transmitted to the CU for further processing, and from here it was wirelessly transmitted to the PCU, which emulated the function of a normal keyboard or computer mouse. Since the PCU was based on a USB stick, it could be attached to any standard windows-based personal computer in the same manner as a standard computer keyboard/mouse without the need for additional software/hardware.

The ITI

The ITI is shown in Figure 2 and consists of:

1. Two 10-layer sensor PCBs with inductive sensors allowing for separate keyboard and mouse/joystick functionalities
2. A signal processing system
3. A wireless transmitter
4. A rechargeable battery
5. A coil for charging the battery
6. Two connecting flexible PCBs
7. Encapsulation in removable dental appliance
8. Activation unit on the tongue

The different parts were connected with two flex prints and embedded in a removable dental appliance comparable with a removable partial denture or orthodontic appliance (Figure 2). All parts were optimized in size in order to keep the mouthpiece small and to allow for speaking and eating during use.

The sensor PCBs The sensor method was based on the variable inductance principle as described by Struijk.[12]

The inductive sensors consisted of "air cored" electrical coils in which the inductance was changed during activation by moving a small cylindrical piece of ferromagnetic material close to the core of the coil. The positioning of the sensors at the palate made special requirements on the size of the coils used as sensors. Further, the appropriate positioning of the sensors to facilitate accessibility by the tongue had to be considered. Different types of coil designs were studied [20] to optimize the signal size. The maximum available number of layers in the PCB was 10 layers (Figure 2). Each layer carried 10 coil turns for each coil and the turns of each layer were connected using plated thru-holes. This resulted in coils with an outer diameter of 6.2 mm and an inner diameter of 4.3 mm and a total number of turns of 100. The total thickness of the coil PCB was 1 mm.

To allow for quick and direct typing on, e.g., a PC and to allow for direct joystick-like control of a wheelchair,[21] it was decided to introduce both a keypad area and a mouse pad area on the sensor (Figure 2). In the mouse pad area, some coils were oval-shaped to allow for a more continuous and direct mouse/joystick function (Figure 2) as used in an earlier partly oral version of the system.[27]

Previous studies have analyzed how many sensors could realistically be placed in the hard palate, and further, the ability of humans to learn selecting a large number of sensors with the tongue has been analyzed.[17,22] In a tongue interface with external sensor electronics, these results showed that up to 22 inductive sensors could be placed and controlled in the human palate. In addition, the most effective relative positioning of keypad and mouse pad areas has been studied [17] to obtain knowledge about which functionality should be placed more anterior in the palate. These studies showed that the more central and the more anterior the sensors are placed, the more accessible they are. Based on these results, and the fact that the keypad sensors require more precise activation than the sensors of the mouse pad, the 10 sensors in the keypad area were placed in the frontal part of the palate, and an 8-sensor mouse pad area was placed in the more posterior part of the palate resulting in a total number of sensors of 18. The choice of having less than 22 inductive sensors in the device was based on the need for sufficient space to integrate the required electronic circuits in the device.

The signal processing system An overview of the signal detection and processing in the ITI is given in Figure 3. The current through the sensor coils was implemented as ~50 kHz square wave signal, f_0, generated by the microprocessor in the ITI (Figure 3). The amplitude of f_0 was 63 μA in order to obtain sufficiently large signal amplitude for detection of sensor activations while avoiding electrical safety issues. Each sensor coil was coupled with a capacitor to create a band pass filter (Figure 3(c)). When the channel was selected by the multiplexor (Figure 3(a)), the square wave signal, f_0, was applied to the band pass filter through the resistor R. The output voltage, V_o, was proportional to the impedance of the LC band pass filter, which was determined by the inductance of the coil, the capacitance of the capacitor, C, and the frequency of f_0. When activated, the inductance of the coils increased, and thus the impedance of the band pass filter changed and thereby the output voltage changed too. Having a 25 μH coil, L, changing to 30 μH during activation, and a 100 nF capacitor, C (Figure 3(c)), the frequency characteristics of the LC band-pass filter was as shown in Figure 3(d). The resulting amplitude of V_o. was in the range 1–1.5 mV. The series resistance internally in the coils was in the range of 20Ω, and caused a detection (Figure 3(d)), which differed from the ideal detection principle shown in Figure 3(b).

The sensor signals were multiplexed every 33 ms, and the analog sensor signal was amplified, rectified, passed through a peak detector and low pass filtered. The microprocessor then sampled the signal and fed the resulting amplitude information from each sensor into the transmitter (Figure 3). The circuit was implemented as a two-layer PCB (Figure 2).

The transmitter The transmitter transmitted the signal within the 2.4 GHz Industrial Scientific and Medical (ISM) band, and transmission was made every 0.033 sec. The transmitter was based on the small low power radio chip nRF24L01 from Nordic Semiconductor. The signal transmitted included amplitude and sensor identity information for each of the 18 sensor coils.

The battery The ITCI was powered by a 3.7 V, 20 mAh rechargeable lithium polymer battery able to supply the system for 15 h of use before recharging (Figure 2, Top). This low-power battery was chosen in order to limit electrical risks. The dimensions of the battery were 12 × 19.5 × 3mm (Figure 2, Top).

The charger coil A coil for charging the battery was handmade to fit the circumference of the mouse pad area. This assured a tactile guide/border for the tongue while sliding on the mouse pad area (Figure 2).

The connecting flex-PCB To allow for the great variability in the dimensions and shape of the human palate, which may easily vary more than one centimeter in both width and height in adults, two flexible PCBs were used to connect the sensor PCBs, the electronics PCB and the battery (Figure 2).

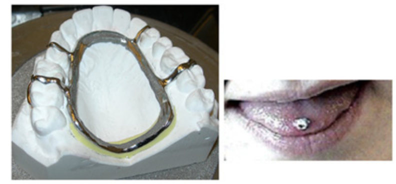

Figure 4. **Left:** The stainless steel frame forming the base of the encapsulation of the electronic parts. **Right:** The activation unit glued to the tongue.

Encapsulation The system was encapsulated in a removable dental appliance comparable with a removable partial denture or orthodontic appliance using standard dental materials (Figure 2, Bottom). Firstly, epoxy was used to encapsulate the electronics, next dental acrylic was used to create a plane surface and finally the embedded electronics was laminated with two sheets of dental, thermoplastic material, make Duran™. The encapsulation was completely sealed by melting the borders of the two Duran™ sheets together and finally mounted in a frame made of stainless steel. The frame allowed for mounting of the mouth piece at the teeth by clamps attached to the frame, and further, the frame stabilized the more flexible encapsulation materials during, e.g., mounting and chewing (Figure 4).

The activation unit Two different types of activation units were developed using the ferromagnetic dental stainless steel alloy Dyna© in order to test the system in both users with and without tongue piercings. One type of the activation unit was shaped as a cylinder with a height of 2 mm and a diameter of 4.5 mm. This was designed to be glued to the tongue (Figure 4). The latter type was shaped like a soft cone and attached to a titanium rod for use in a tongue piercing. The height of the cone was 5.2 mm and the diameter at the base was 4.5 mm. The height of the piercing-based activation unit exceeded the height of the glue-based unit in order to compensate for the deeper embedment in the tongue due to the weight of the ball at the end of the piercing stick, which would otherwise compromise the ability of the user to reach sensors far from the central part of the palate.

The CU

The CU processed the raw data transmitted from the mouth piece. The signals from the sensors were processed (filtered) to adaptively remove individual sensor offset and drift using a filter with adjustable weights as shown in Figure 5. The method for weight adjustment is shown in Figure 6, it ensures that active sensor signals are not included in the calculation of the weights for the removal of the baseline signal. The microcontroller then monitored the processed signals to decode the user's actions and change the control mode accordingly. The user could switch the control mode between, mouse mode, keyboard mode, wheelchair mode and standby mode by activating sensor number 10 for 10 sec. The signals were then further processed depending on the current control mode. Finally, the control commands were transmitted to the target device to be controlled; in this case the USB-based mouse/keyboard emulator. The CU applied fuzzy logic to the output of the mouse pad sensors in order to interpolate the eight mouse movement directions defined by the eight mouse pad sensors (Figure 7). This was done to obtain a joystick-like output from the mouse pad with multiple directions for the mouse cursor motions. In addition, radial interpolation was performed from the centre of the mouse pad in order to obtain velocity

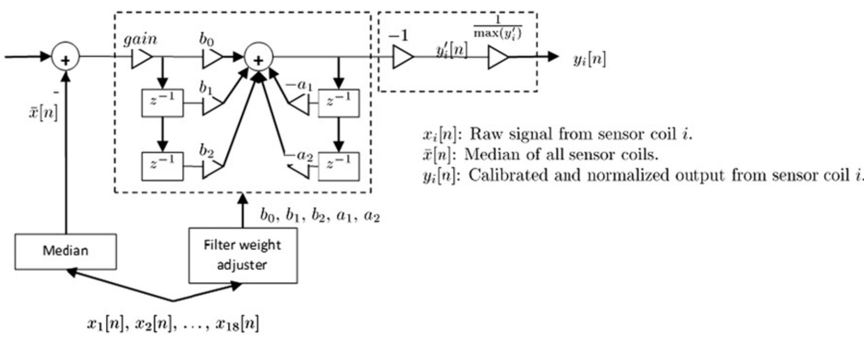

Figure 5. The filter structure used for removal of the baseline from the sensor signals.

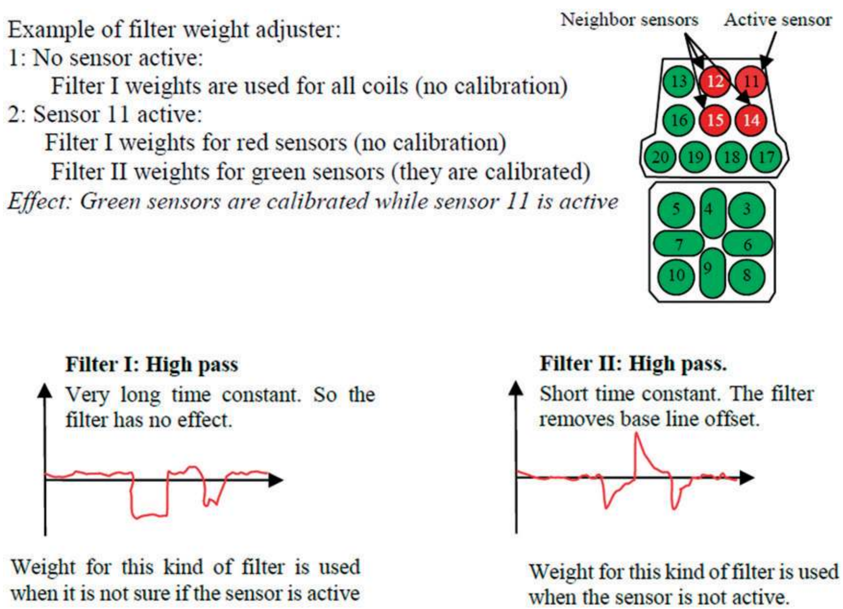

Figure 6. The method for adjustment of the filter weights for the filter (Figure 5) for removal of the sensor offset and drift.

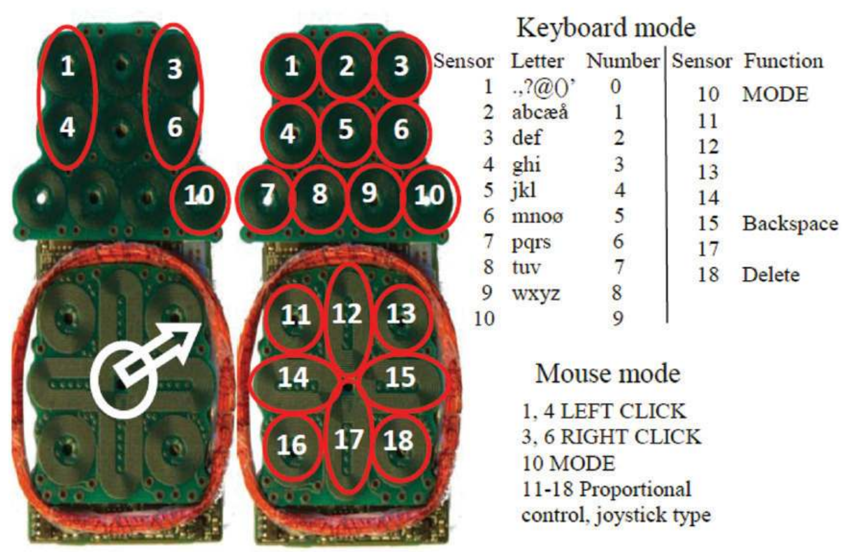

Figure 7. The sensors and the related typing functionality in mouse mode (left sensor layout) and keyboard mode for full alphabet text input (right sensor layout). Switching between keyboard and mouse modes was performed by activating sensor number 10 for 10 sec. Adapted from Lontis et al. [29]

control of the mouse cursor in such a manner that the further the activation unit was placed radially from the centre of the mouse pad, the faster the cursor would move on the computer screen. The fuzzy logic implementation was adapted from Caltenco et al. [23] The central unit was implemented in a separate box, which was ~7 cm wide, 7 cm deep and 2,5 cm high, which could be mounted on the user or on e.g. a wheelchair.

The PCU

The PCU received information about the sensor being activated on the keypad area during Keyboard mode and about the fuzzy output of the mouse pad area during Mouse mode. It was implemented as a keyboard/mouse emulator using a composite USB device and was responsible for mapping sensor activation to specific USB commands such as keyboard key codes, mouse button status, and mouse movement. Details on the USB implementation can be found in Lund et al. and USB Implementers' Forum.[24,25] The board used for the PCU print had a USB connector so that the whole unit could be regarded as a USB stick ready to be plugged into a standard PC (Figure 1). The PCU was implemented as a state machine, which was adapted from Lund et al.[24] A group of characters were related to each sensor of the key pad in a manner resembling a key-based mobile phone (Figure 7). The PCU was implemented in such a manner that a character related to an activated sensor would appear at the cursor on the PC screen as soon as the activation unit was placed at that sensor in order to provide a visual feedback for the user. If the user removed the activation unit or moved it to another sensor within short time, the displayed character was deleted, and instead a character related to the new sensor was shown at the cursor of the PC. In order to actually type a character, a sensor was to be activated for a certain amount of time called dwell time (Figure 8). This method was chosen in order to embed the software for the visual feedback in the USB stick requiring no additional software on the PC, thus allowing the use of the ITCI at any PC.

General system functionality

The user could toggle between two ITCI modes: a keyboard mode and a mouse mode. Mode switching between keyboard mode and mouse mode was facilitated by continuous activation of sensor 10 for 10 seconds (Figure 7). In the keyboard mode, the 10 sensors on the keypad were associated with characters in a mobile phone-like manner, and some additional functions were associated with the mouse pad sensors (Figure 7).

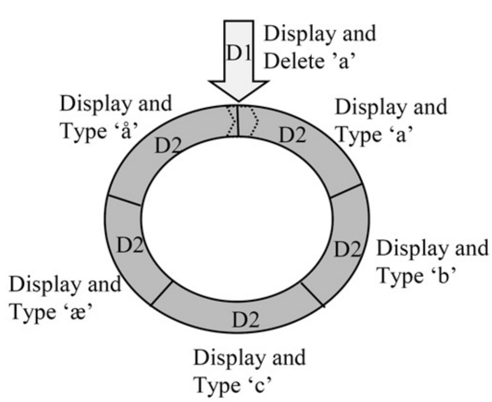

Figure 8. Typing procedure: when a sensor on the keypad area was activated, in this case sensor 2, the first character related to that sensor was displayed as a visual feedback for the user. If the sensor was still activated after a time period, called dwell time 1 (D1), it could be typed during the following time period, dwell time two (D2), during which deactivation of the sensor would result in typing of an "a". If the sensor was activated beyond D2, the next character related to sensor 2 which was "b" was displayed, and deactivation of the sensor would then cause a "b" to be typed. If the sensor was still not deactivated, the next character related to the sensor would appear, and this procedure would continue in a circular manner until the sensor was deactivated. If the sensor was deactivated during D1, the "a" would be deleted and no character would be typed. This gave the user a time period, D1, to slide on the keypad area, with visual feedback, without typing undesired characters.

System functionality – mouse emulation

In the mouse mode, the mouse pad sensors were used in a joystick-like manner to control a cursor on the PC screen, and some of the keypad sensors were used for mouse clicks (Figure 7). The speed of the mouse cursor increased as the activation unit was moved radially from the centre of the mouse pad, and the cursor stopped as soon as the mouse pad area was deactivated by removing the activation unit from the mouse pad area.

System functionality – typing with the keypad area

Typing using the keypad area was performed by sliding the activation unit on the sensor PCB activating the sensors for a short time D1 (Figure 8). This resulted in a display of the first character in the character group related to the activated sensor. As long as the activation time D1 was not exceeded, the displayed character served as a temporary visual feedback for the user. If the activation time D1 was exceeded, a new dwell time period, D2, began during which the character was still displayed but was typed if the sensor was deactivated. If the activation persisted for longer than D2, the next character in the character group related to the activated sensor was displayed and was typed in case of sensor deactivation. This would continue in a circular manner until deactivation occurred and a character was typed (Figure 8). In this study, D1 was pre-set to 0.9 s and D2 to 1 s, but these values were adjustable.

System functionality – typing with the mouse pad area

In addition to the keypad typing, characters could also be typed with the mouse pad area using an on-screen keyboard. The on-screen keyboard, Click-N-Type, was used. When the cursor was successfully placed on a character on the on-screen keyboard, the character was typed by activation of the sensors on the on keypad area related to a mouse click function (Figure 7).

Experimental software

For experimental use, a real-time Matlab© interface was implemented to provide a graphical visual feedback of the position of the activation unit when sliding over the sensors and for displaying the association between characters and sensors. Further, it displayed a character string to be typed and, in addition, the character string that was actually typed by the subject (Figure 9). The Matlab© interface received data about sensor activation through a dedicated COM port from the PCU; these data were saved on the hard disk. In addition, the raw sensor data from the ITI were saved by the CU. For typing in Word©, the TongueWise software developed for use with the ITCI was used.[26]

Experimental procedure and materials

The experimental protocol was approved by the local ethical committee. Two female spinal cord injured subjects, S1 and S2, with tetraplegia performed typing with the key pad. In addition, two able-bodied females, S3 and S4, with long term, jewellery tongue piercings performed keypad area typing and on-screen typing with the mouse pad. The subjects were 57, 48, 27 and 35 years old, respectively. The experiment was a one-day experiment for the tetraplegic subjects and a two-day experiment for the able bodied subjects. During the experiment, the subjects were trained in using the ITCI. Training tasks included typing using the Matlab© interface and typing in Word© using either the custom-made graphical interface software

TongueWise [26] or using an on-screen keyboard. In addition, games were performed for 5–10 min sequences (Table 1). The games were: a modified version of "Whack-A-Mole" [27] for keypad training and "Born to Be Big" [28] for mouse pad training. The tetraplegic subjects used the keypad area for typing while the able-bodied subjects additionally did on-screen keyboard typing with the mouse pad area after completing typing with the keypad area. The typing tasks were similar for typing with the keypad area and the mouse pad area.

The trial sequences are shown in Table 1. The character typing sequences typed using the Matlab© interface was used as experimental results and is displayed in the results section.

Custom-made ITCIs were produced for each subject. In the case of the tetraplegic subjects, the activation unit was glued to the tongue during the trials using the tissue glue Histoacryl©. In the case of the able bodied subjects, their own piercing jewellery was exchanged with an activation unit, designed as a piece of piercing jewellery during the trials. One subject, S2, was using a dental prosthesis and in this case the ITCI was integrated in a full upper denture.

During the trials, the subjects were seated comfortably in a chair or a wheelchair and were instructed to perform the trials shown in Table 1. Each trial lasted for 30–60 sec.

Results

The inductance of the sensor coils in the PCB were measured to 15–16 µH for the keypad coils and 25–27µH and 34–36 µH for the round and oval coils of the mouse pad, respectively. The resistances of the coils were measured to 12–13 Ω for the keypad coils, and 15–17 Ω and 20–21 Ω for the round and oval mouse pad coils, respectively. The resulting sensor signal amplitudes were in the range of 1 mV, and the activation of the coils resulted in an amplitude change of up to 10–15%.

The time required to type a correct character depended on the dwell times D1 and D2 together with the search time. Typing the first character related to a sensor required a minimum activation time longer than 0.9 s (D1) and shorter than 1.9 s (D2). The least average time required to repeatedly find and type a character was 1.8 s for repeatedly typing the character "a" on day 2 for subject S4, suggesting that less than 1 s was needed to search for and find that character (Table 2). The total number of correct activations within 30 s is shown in Figure 10 for the healthy subjects and in Figure 11 for the tetraplegic subjects. For the tetraplegic subjects, S1 and S2, the mean time required to type a correct character was 6.5 s and 8.1 s, respectively.

For the healthy subjects, S3 and S4, the mean time required to type a correct character was 5.9 s and 10.0 s on the first day of training, and 5.3 s and 3.3 s, respectively, on second day, indicating that significant learning was taking place as suggested in Boudreau et al. and Caltenco et al.[22,27] This increase in typing ability form the first training day to the second training day indicates that significant learning is taking place, confirming the results of a neuroplasticity study of an inductive tongue interface.[22] Despite having as many as nine sensors for selective activation of characters, the users in that study rated the difficulty of typing to be between 3 and 6 on a 10-cm numerical rating scale after two-days experiments, where they were still in a learning phase

The results of keypad area typing for day 1 and 2 are shown in Figure 10 for the healthy subjects and in Figure 11 for the tetraplegic subjects across the trials. The maximum number of correctly typed characters in one trial was 16 for the tetraplegic subjects and 17 for the able-bodied subjects on day 2.

Figure 9. The Matlab© based visual feedback used in the experiments. The given character string to be typed is shown with the currently desired character in capital. In the text field above, the characters typed by the subject are displayed. Correctly typed characters are shown in capital. A figure below the text field shows the position of the characters on the keypad area of the ITCI. As default, all sensors were marked with a green circle. When the activation unit was placed at a sensor/character for less than the time D1, the circle around the character turned yellow, and the character was temporarily typed at the cursor in the text field. When D1 was exceeded, the colour turned from yellow to red and deactivation of the sensor resulted in sustained typing of the character in the text field after which the cursor moved one step forward to provide feedback for the next character to be activated by the subject. If no deactivation occurred within the time D2, the next character related to the activated sensor was displayed.

Table 1. Tasks for typing with the Matlab interface.

	Trials of 30–60 s
1	.,?" ()@abcæådefghijkl
2	Mnopqrstuvwxyz
3	heprjå(lb, sagpd
4	repqg.åfb)usdt8æ
	"Wack-A-Mole" or "Born to Be Big": 5–10 min
	Trials of 30–60 s
5	Aaaaaaaaa
6[a]	abababab
7	Abcæå
8	.,?!"()@
9	Def
10	Ghi
11	Jkl
12	Mnoø
13	Pqrs
14	Tuv
15	Wxyz
15[b]	Space ↵
16	.ad.ad.ad
17	Gjmgjmgjm
18	ptw ˽
19	type a character and delete
	Trial running–max 5 min
20	jeg er færdig! (use Delete)
21	jeg er færdig! –(use delete and easy write)
	Trials of 30–60 s
22	.,?()@abcæådefghijkl
23	Mnopqrstuvwxyz
24	heprjå(lb, sagpd
25	repqg.åfb)usdt8æ

[a]Only performed by S1 and S2,
[b]not used for data analyses, Trial 17–25 were only performed by S3 and S4.

Table 2. Mean and average typing times for all subjects in trials of 30 sec.

	Keypad correct characters mean/max/min [No.]	Keypad time/correct character mean/max/min [s]	Mouse pad correct characters mean/max/min [No.]	Mouse pad time/correct character mean/max/min [s]
S1, Day 1	4.6/16/0 (SD 4.0)	6.5/–/1.9		
S2, Day 2	3.7/7/1 (SD 1.9)	8.1/30/4.3		
S3, Day 1	5.1/14/0 (SD 3.8)	5.9/–/2.1	5.4/13/1 (SD 3.24)	11.1/60/4.6
Day 2	5.7/15/1(SD 3.5)	5.3/30/2	4.8/12/1 (SD 2,6)	6.25/60/2.5
S4, Day 1	3/11/0 (SD 2.7)	10/–/2.7	1.4/4/0 (SD 1.3)	21.4/30/7.5
Day 2	9.2/17/4 (SD 3.8)	3.3/7.5/1.8	5.3/21/2 (SD 4.2)	5.715/1.4

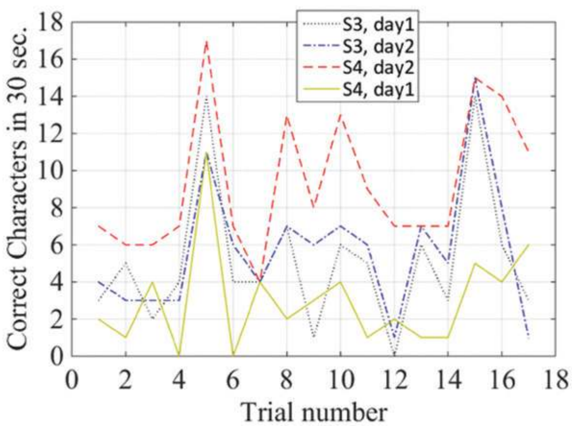

Figure 10. The number of correctly typed characters in trials of 30 sec duration. Trials for the healthy subjects S3 and S4 using the keypad area. The results are for trial 1 to 17 in Table 1.

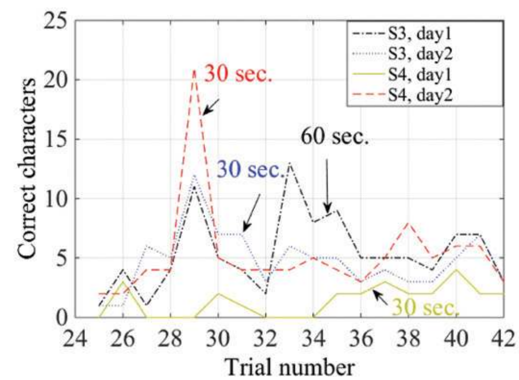

Figure 12. The number of correctly typed characters for S3 and S4 using the on-screen keyboard with the ITCI mouse pad area. The trial number refers to the numbers in Table 1 + 24, e.g., the characters typed in Trial 29 are "aaa". Trial durations of the trials are shown in the figure.

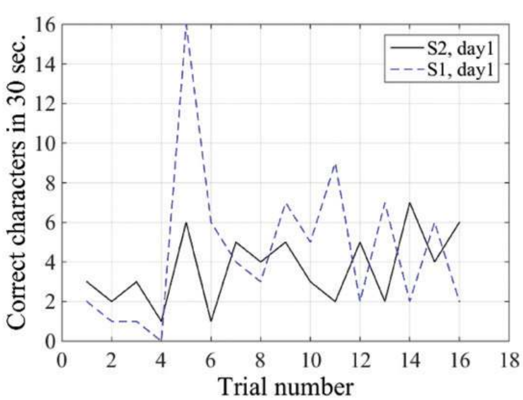

Figure 11. The number of correctly typed characters in trials of 30 sec. for the individuals with tetraplegia, S1 and S2 using the keypad area. The shown results are for trial 1 to 16 in Table 1.

The results for on-screen keyboard typing are shown in Figure 12. S3 had 60 s keyboard typing trials on day one.

Discussion

The ITCI is based on the change of the inductance of the inductive sensors by changing the core material of the inductor. In order to create a fully implantable and biologically acceptable interface, several compromises that could result in insufficient signal size were made. Firstly, in order to increase the number of possible commands, a relatively large number of sensors were desirable, but at the same time the small available space at the human palate in the oral cavity restricted the possible number and size of the sensors. Therefore, the size, including the number of turns on the coils of the sensors, was restricted and thus challenging the signal amplitude. Secondly, to reduce the size of the sensors and facilitate a uniform sensor design, the sensor coils were implemented as PCBs. This restricted the activation of the coil as the activation unit could not enter the core of the inductor, thus obtaining less than optimal activation. Nevertheless, a change of inductance of ~10–15% was obtained during activation, and the subjects could successfully type characters and words with the system.

The minimum time required to type a correct character was 1.8 s with the keypad area and 1.4 s with the mouse pad area. Even though these high rates were obtained only in repetitive typing, they may suggest the possibility of obtaining a high typing rate after practice since a considerable amount of learning seems to take place. The fastest subject went from a maximum typing rate of 7.5 s per character on day 1 to 1.4 s/character on day 2. There is a limit of the maximum achievable typing rate due to the dwell times of the system. These may be reduced as the user becomes more familiar with the system.

Current available systems allowing users with tetraplegia to control computer cursors generally rely on joystick-based functionality due to the restricted mobility of the user. This may introduce a slower control as compared to an actual mouse control. Other tongue control systems, such as the TDS [13] and the system from new abilities,[15] provides discrete control comparable to using the 4 arrows on a keyboard to move the cursor. The control provided by the ITCI is a discrete cursor control providing eight discrete directions instead of four and in addition fuzzy logic combining the signals from adjacent sensors facilitates a more continuous directional movement pattern. Further, the velocity of the cursor increases with the radial position of the activation unit on the mouse pad.

The design of the ITCI showed to be flexible in such manner that it could be adapted to the four subjects despite the great variability in the size and form of their hard palate and despite the need for integration of the ITCI in a full upper denture. For the three subjects who were not using a dental prosthesis the speech seemed affected when wearing the ITCI, but it was improving throughout the experiment. For the subject with a denture, the speech was not notably affected, and the subject claimed that her speech was comparable to her speech while wearing her own prosthesis without the ITCI. This suggests that speech can be improved when wearing the ITCI for long periods. However, further studies have to be made on this issue. A drawback of the system is the demand of a tongue piercing for long-term use. At the same time, the tongue piercing facilitates a higher selectivity by restricting the sensor-activator contact area as compared with systems using pressure sensors [15] and the TTD system with more virtual activation areas,[13] thus facilitating a large number of sensors and commands. Whether a piercing is worthwhile for a user in order to obtain an ITCI, is an individual decision, but studies on acceptability and pain related to such piercings [18,29,30] in tetraplegic subjects suggest that the insertion of the piercing itself may not induce unacceptably high discomfort.

Conclusion

This study describes a method for a full and safe integration of a battery-powered, wireless inductive tongue computer interface into the human oral cavity. Compared with other TCI systems, this system incorporates the largest number of sensors for environmental control completely embedded into the human oral cavity. The aim was to obtain an esthetically acceptable and empowering interface for severely disabled individuals facilitating a wide range of commands for environmental control.

The experiments showed that the ITCI fulfilled the six requirements listed for such a system in the methods section.

The experiments demonstrated that the system can be safely embedded into the oral cavity and further interfaced to various Windows-based computers using a USB stick only. Typing exercises showed that two able-bodied and two tetraplegic subjects were able to perform typing with the system. The able-bodied subjects obtained an average typing rate of 3.3 s per character – 5.3 s per character on the second day of the experiment, which is higher than for the system using pressure sensors.[15] The two-day trials indicated that a large amount of learning was taking place indicating that a higher typing speed of up to 1.4 s per character may be expected after long-term use. Studies on more simple and not fully intraoral ITCI systems have indicated that long-term training results in typing speeds of 1.1 s per character.[27]

This study focused on the design and demonstration of the ITCI and thus the participating tetraplegic individuals did not have their tongue pierced which is required for long-term use of the system. Preliminary studies have suggested that a piercing is acceptable when required for tongue computer interfaces.[18,29,30,31] However, more detailed clinical studies of the ITCI, including more subjects, are desirable for a clinical evaluation of the efficiency of this intraoral system.

During use, the ITCI was fully embedded into the oral cavity and thus invisible avoiding compromising the self-identity of the user. Both the tetraplegic subjects evaluated the system positively and expressed willingness to undergo a tongue piercing in order to use the system. In the current study, the ITCI was used for computer interfacing but may also be used for control of other applications such as active movement-assistive devices [32] and for control of hand prosthesis.[33] Future studies will consider evaluation of text typing in generally available computer applications such as Word©, including comparison with other existing computer interfaces for severely disabled individuals. Further, the general use of the system such as speaking and eating while wearing the system will be evaluated.

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Ethical issues

This study was approved by the local ethical committee: Den Videnskabsetiske Komité for Region Nordjylland. This ensured that consent forms were signed and that the subjects were informed about their rights. Further, consent was obtained regarding publication of the experimental results.

Disclosure statement

The authors report no declarations of interest.

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