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DEVELOPMENT OF A TONGUE MACHINE INTERFACE FOR QUADRIPLEGIC PATIENTS

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Abstract

This article presents the development and validation of a wheelchair mobility solution. The solution is based on a Tongue Machine Interface (TMI) involving the use of Force Sensing Resistors (FSRs). The semantics and functionality of the development are compared with two other interfaces: a Joystick and a Brain Computer Interface (BCI) implemented on the same wheelchair. Each development is described from the electric, mechanic and informatic domains. Surveys and user's tests were performed in order to explore which technology had a more positive impact on the mobility of quadriplegic persons in terms of effectiveness, better ergonomics, lower costs and better functionality. The quantitative and qualitative results are described and analyzed.

Keywords: Biomedical design, Case study, Design engineering, Inclusive design, Integrated product development

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1 INTRODUCTION

Tetraplegia or quadriplegia is a condition in which patients suffer total or partial paralysis on all four limbs. It is mainly produced by a Spinal Cord Injury (SCI) on the cervical vertebrae or by neurological damage due to degenerative or congenital diseases. The permanent assistance required by patients causes a severe impact over the psychological, social, labor and economic aspects of patients, their families and careers (Forner, 2011). Hence, every effort that allows patients to improve their condition also means a significant impact over the quality of life of other people around them. In addition, the number of patients suffering from tetraplegia increases every year. Only in the United States, approximately 273000 people have been diagnosed with SCI, with around 12000 new cases arising annually. From these cases, approximately 50% have complete or incomplete tetraplegia as seen in Figure 1 (NSCISC, 2012).

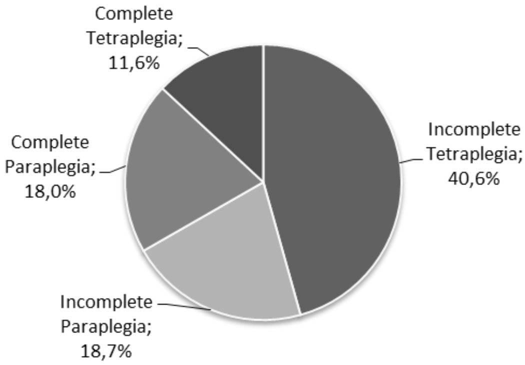

Figure 1. Neurologic level and extent of injury

For these patients, several approaches to improve their independence and mobility, to some extent, exist. Many are based on signal acquisition from different parts of the body such as the tongue, brain, or muscles in order to control a powered wheelchair. Tongue based systems (mainly Tongue Machine Interfaces (TMIs)) take advantage of the fact that patients whose tetraplegia was caused by SCI can still control their tongues. Table 1, Table 2 and Table 3 summarize some of the interfaces that have been developed for people who suffer tetraplegia.

Table 1. TMI's review

Source	Description
TongueTouch (Lau & Oteary, 1993)	Battery-operated radio frequency transmitting device similar in appearance to an orthodontic retainer. It contains nine Braille keys which are activated by raising the tongue tip to the mouth superior palate. The device sends signals to a controller that transmits them to a computer.
Tongue-operated switch array (Johansen, et al., 2011) (Kim, et al., 2005)	Consists of five switches inside a dental palate mold which are activated by the tongue. It works as a digital mouse or as the arrow keys of a standard computer keyboard. It provides an alternative computer input method for those unable to use their hands or need an additional input mechanism such as patients with tetraplegia.
Inductive Tongue Computer Interface (Lothe & Struijk, 2006)	Consists of five coils placed in the oral cavity by a palatal plate and an activation unit with magnetic material which is placed on the tongue using n-butyl-2-cyanoacrylate tissue glue (Histoacryl). This device is intended to be used with a computer to trigger tongue-activated commands.
Tongue Drive System (Xueliang, et al., 2008)	It uses a permanent magnet piercing in the tongue as a tracer, whose movements are detected by a magnetic field sensor mounted on a headset outside the mouth or on an orthodontic brace inside. This system is designed to be used in conjunction with a computer for controlling a power wheelchair or moving the computer mouse.

Table 2. Brain Computer Interfaces (BCI) review

Source	Description
(Guangyu, et al., 2011)	A high-speed word spelling system based on a BCI, which allows patients to choose a letter from a matrix in a monitor and complete entire words, enabling them to write text in a computer.
(Khare, et al., 2011)	The control of a powered wheelchair using a BCI based system using Wavelet Packet Transform (WPT) and Radial Basis Function neural networks.
(Collinger, et al., 2013)	Robotic prosthesis with seven degrees of freedom, by the use of a Brain-Machine Interface (similar to a BCI).
(Fattouh, et al., 2013)	The Cognitiv™ and Affectiv™ Suites of the Emotiv® EPOC system were used in order to control a Smart Wheelchair. The use of the Affectiv TM Suite as a frustration evaluator permitted to reduce the concentration time improving the performance while driving the Smart Wheelchair.

Table 3. Other interfaces

Source	Description
Quadcontrol (Dockery, 2011)	A system which permits quadriplegic patients to access video games - healthy people would use both hands. This has been improved over the past years allowing access to game consoles such as PlayStation 2® and XBOX360™. This device combines lip controls, puff & sip tubes and a head operated joystick.
(Jimenez, 2006)	Keyboard for quadriplegia patients that allows typing on a computer, taking advantage of a selected voluntary movement by the user. It consists of a keyboard with LEDs which sequentially turns rows and columns on until the user performs a key action for selecting the desired character.
Breath Bird (Dillow, 2011)	App which helps individuals with disability by detecting their breath strength through a microphone and converting it to keyboard inputs for twitting with the help of an iPad.
Drop Point (Diebold, 2011)	Tool for quadriplegia patients that allows them to interact with their world by using a simple movement of the chin. This tool can be used for writing on a keyboard and also for using a cell phone answering calls or dialling a number.
Audeo (Callahan & Coleman, 2012)	Sensor that processes electrical signals from the muscles near the larynx and transforms them into speech sounds without the need of further modulation. The voiceless commands can also be used to make a voiceless cell phone call or to control a power wheelchair.
NeuroSwitch	Enables a user with disability to control communications (text, text-to- speech, emails, internet, word processing, games and environmental control systems) using their body's own Electromyography (EMG) signals (Ford, 2010). NeuroSwitch also has been used to accurately control a power wheelchair.

A common disadvantage of these technologies is that they require a computer (usually a laptop), increasing the cost of the product for the final user and limiting the access only to patients that can afford it. Another disadvantage is the invasiveness of some of the developments, such as the TDS (Xueliang, et al., 2008), which requires a magnet pierced in the tongue. Other devices like the QuadControl (Dockery, 2011) draw too much attention on the person wearing it, due to external components that are required for the solution to work correctly.
After the previous review, TMI devices are feasible for helping the majority of the people affected by SCI offering advantages such as: it offers multiple degrees of freedom (Kandel, et al., 2000), it is hardly affected by SCI because it's motor supply is the hypoglossal nerve (Bademci & Yasargil, 2006), it does not fatigue easily (Lau & Oteary, 1993), it does not require as much concentration as with a BCI, it is easy to use and it has a relative low cost for the final product.

This article proposes a cost-effective, non-invasive and easy to use TMI for SCI patients, specially designed for those suffering from complete and incomplete quadriplegia categories, allowing them to use their tongue to control a power wheelchair. Other activities such as TV remote control, working on a computer, switching lights, among others can be performed with such TMI.

2 DEVELOPMENT

In order to assess and compare the developed TMI with a BCI and a joystick, a flexible architecture was proposed (Figure 2). This architecture allows for the possibility of switching between three different methods of operation: (i) the power wheelchairs' joystick, (ii) a commercial BCI and (iii) our TMI. For the TMI, a four action control (forward, backward, left and right) was proposed, since these are the commands usually needed to operate a power wheelchair. These movements are transmitted wirelessly from tongue operated sensors (transmitter circuit) to a power wheelchair joystick coupling system (receiver circuit).

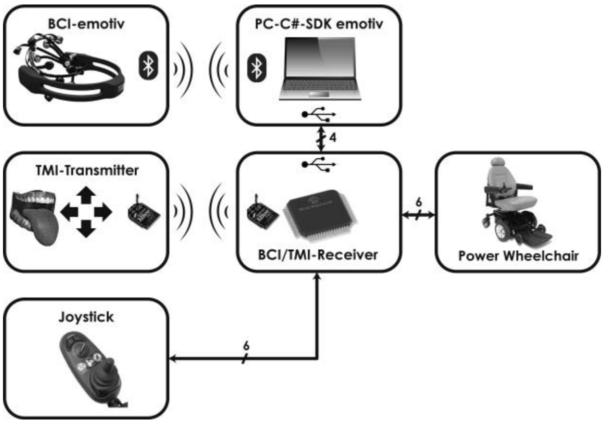

Figure 2. System architecture for interface switching

2.1 Concept survey

An initial survey was conducted to decide among a set of design concepts. A heterogeneous group of subjects was taken for this survey in order to get points of view from different users:

- Group A: people with some type of mobility issue (18 quadriplegic and 4 paraplegic).
- Group B: people without movement impairment (50 healthy persons).

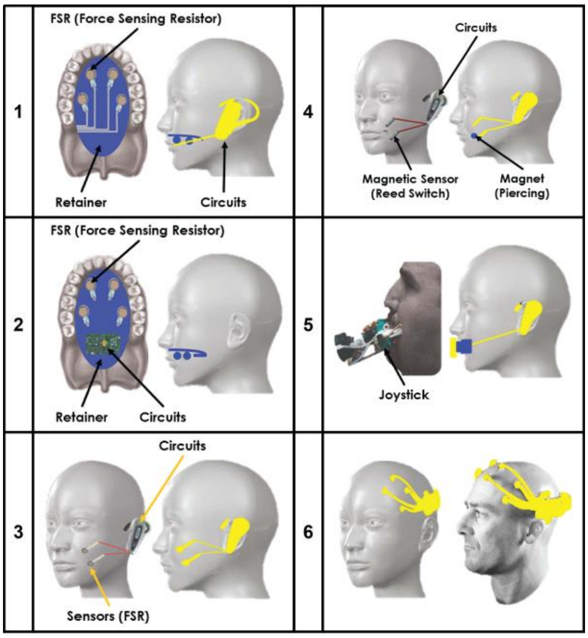

Figure 3. Survey's solution concepts (1, 2, 3 and 4) and comparison products (5 and 6)

Within the survey's forms, four types of solution concepts (concepts 1, 2, 3 and 4 in Figure 3) were presented inspired on some TMI practices of the state of the art, while the two other were obtained from existing products for comparison purposes (concepts 5 and 6 are respectively QuadControl and Emotiv® in Figure 3). Each concept is explained as follows:

1. Force Sensing Resistors (FSRs) within a retainer inside the mouth, and electronic circuits inside an earphone that are activated by pushing the sensor with the tongue.
2. FSRs within a retainer inside the mouth and circuits inside the retainer that are activated by pushing the sensor with the tongue.
3. FSRs on the user's cheek and circuits inside an earphone that are activated by pushing the cheek with the tongue.
4. Magnetic sensors on the cheek and circuits inside an earphone that are activated by a magnet pierced into the user's tongue.
5. QuadControl: joystick operated by the user´s tongue.
6. Emotiv®: BCI which uses thoughts and/or facial expressions to operate.

Group A assessed the concepts in terms of invasiveness and preference, while Group B assessed the concepts in terms of perception of sickness and preference. The difference between the two surveys was due to the fact that the first one was designed for direct users, while the second one was intended for secondary users or caretakers. The criteria are explained below:

- Functionality: The easiness of using the device.
- Invasiveness: Refers to the comfort (ergonomics) and the level of intrusion that the device has on the user's face.
- Perception of sickness: Related to how sick the person looks when using the device.
- Preference: Refers to which device the user prefers.

The survey's results (Figure 4) show that concept 2 scored better than the others.

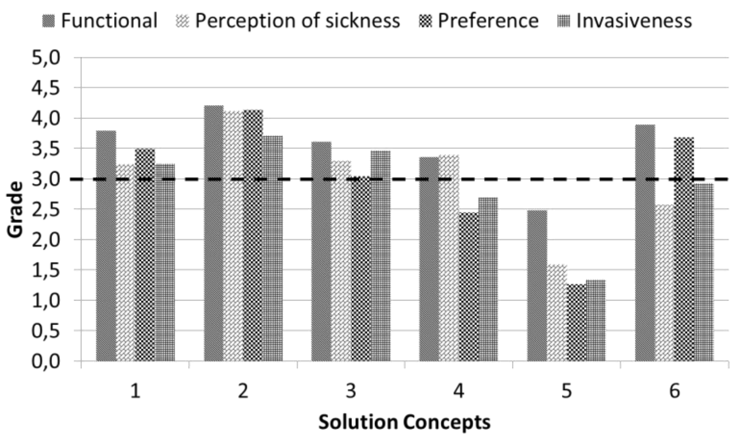

Figure 4. Survey´s results (lowest=0 and highest=5). The dashed line indicates the threshold for a proposal to be acceptable

As a first approach to concept 2, the first development should have an earphone with circuits as shown in the Figure 3 (solution concept 1) and as future work it is suggested the development of the electronic circuits inside the retainer.

2.2 Mechanical design

In order to improve the positioning of the tongue directly on the desired sensor, a "dome" made of odontology acrylic (for biocompatibility) was built and adhered to the FSR as shown in Figure 5(a) and Figure 5(b), following the technique of (Jensen, et al., 1991) cited in (Hall, et al., 2008).

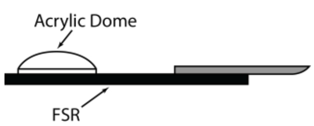

Figure 5. (a) Side View of FSR with acrylic dome (b) Upper View of FSR with acrylic dome

The sensor's distribution depicted in Figure 6 showed less tongue's fatigue by having the sensors (i) distributed in a cross shape, (ii) as close as possible to the frontal teeth, (iii) outside the soft palate to avoid nausea sensation and (iv) with a distance of 15 mm between them, which can be compared to the tactile skin resolution from 2 mm to 3 mm (Velazquez & Pissaloux, 2008).

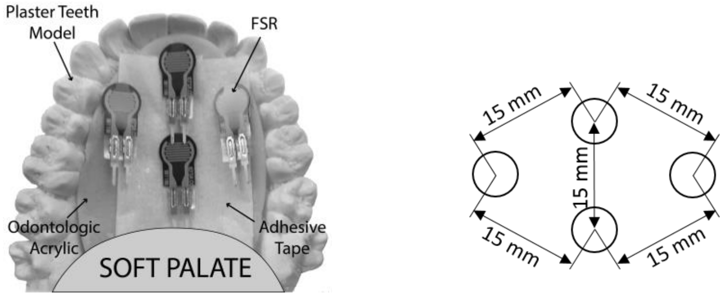

Figure 6. (a) FSR's distribution (b) FSR's distance detail

In order to house all the electronic circuits, an earphone was designed and built using a 3D printer. The size of it depends on the transmitter PCB, which is described in the electronic and informatics design chapter. Figure 7 shows a 3D render of the two parts of the earphone and the assembly.

Figure 7. Virtual 3D Earphone render

2.3 Electronic design

The sensor chosen for the TMI was a FSR due to its mechanical flexibility, commercial sizes and ease of operation. This type of sensor changes its resistance with an applied force. The mechanical flexibility eases the assembly of the four sensors into a dental retainer. The electronic circuit uses four operational amplifiers in comparison mode, in order to digitalize the analog signals from the four FSRs. This type of configuration uses a reference signal from a potentiometer in order to adjust the sensitivity of the sensor. In order to send the digital data from each sensor, an Xbee® Pro Series 1 was implemented in "virtual cable" configuration, avoiding the use of a microcontroller that would increase the cost and size of the final circuit (Figure 8(a)).

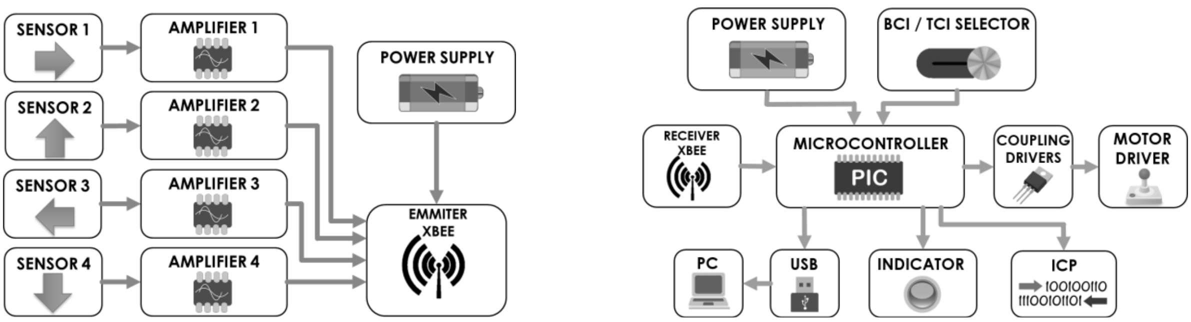

Figure 8. (a) Transmitter´s electronic architecture (b) Receiver's electronic block diagram

The receiver's circuit (Figure 8(b)) consists of a microcontroller (Microchip® PIC 18F4550) which has a USB connection for acquiring the signals coming from the BCI and its further interpretation with a PC. It uses an Xbee® Pro Series 1 in "virtual cable" configuration to receive the four digital signals sent by the transmitter circuit (forward, backward, left and right) directly to the microcontroller. A circuit jumper was added in order to toggle between different modes of operation (BCI mode or TMI mode).

This circuit has also a built-in In Circuit Programming (ICP) feature, in order to ease the programming of the Surface-Mount Device (SMD) microcontroller. The coupling drivers to connect the receiver circuit to the controller of the power wheelchair are shown in Figure 9 (a). These circuits allow the user to switch between joystick and external modes (BCI or TMI) using a toggle switch.

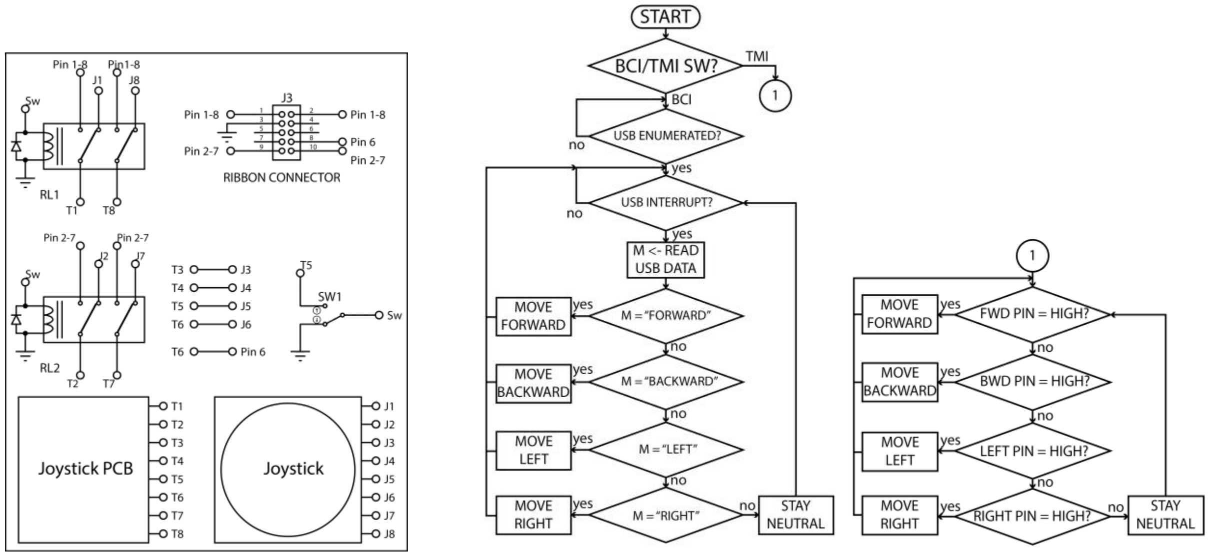

Figure 9. (a) Coupling driver schematic (b) Flowchart of the receiver's microcontroller algorithm in BCI mode (c) Flowchart of the receiver's microcontroller algorithm in TMI mode

2.4 Informatics design

A flowchart of the algorithm implemented on the microcontroller is shown in Figure 9(b) and 9(c). With the aid of a jumper it allows to switch between the two external modes (BCI and TMI). If the jumper is in BCI mode, it waits for an usb interrupt signal to get the command extracted from the BCI gestures and then moves toward the commanded direction. In the other case (TMI mode), it waits for any of the four digital inputs from the Xbee® (forward, backward, left or right) and depending on the one being activated, it moves in that direction.

3 TEST DESCRIPTION AND ASSESSMENT

3.1 Effectiveness measurement

In order to assess the reliability and the user experience of the developed system, the PIDA protocol and the NASA- TLX index are used. The PIDA protocol (Dawson, et al., 2006) was developed to assess the reliability of the system and the performance of people who need help for their mobility on devices such as wheelchairs in indoor spaces. Through this protocol the user grades the performance from 1 to 4, as follows: (1) unable to complete the task, (2) achieved but with damages to objects, (3) achieved with doubts and (4) achieved with optimal performance. On the other hand, the NASA-TLX index was developed to assess the required user's resources to complete a task, such as mental and physical demand; hence it was implemented to assess the user's experience while performing the activities proposed by the PIDA protocol, with a score from 0 to 100%, being 100% a very difficult task. With both scores, an effectiveness indicator is obtained (Equation 1) in order to compare the different interfaces.

$$\text{Effectiveness} = \text{PIDA} / (\text{NASA\_TLX}) \quad (1)$$

3.2 PIDA activities

The activities proposed by the PIDA protocol take place at seven different scenarios such as a bathroom, a bedroom, an elevator, among others. The activities chosen were:

- In a bathroom: Opening and passing through the bathroom's door, approaching the sink and toilet, and exiting and closing the bathroom door.
- In a bedroom: Accessing a bed from both sides, and approaching a closet and dresser.

- In an elevator: Accessing an elevator and spacing in it, and exiting the elevator.
- Other maneuverability activities: Parking in different ways, driving up and down a ramp, turning, driving straight backward, driving through different kinds of automatic doors and through narrow regular doors, and avoiding obstacles in different situations (Figure 11) such as facing unexpected obstacles, driving through a crowd space and following a prefixed course.

Figure 10. Obstacle avoidance test performed by a healthy female user (Location: Universidad EAFIT, Building 19th. Date: 04-12-2013)

4 RESULTS

4.1 Prototype

The transmitter of the TMI (Figure 12(a)) was located in a 3D printed earphone (Figure 12(b)). Its function is to detect which FSR has been pushed, sending this signal wirelessly to the receiver circuit.

Figure 11. (a) Transmitter PCB (b) Earphone case (c) Receiver PCB on wheelchair

The receiver circuit was located below the wheelchair's joystick holder (Figure 12 (c)), where it hacks the joystick's signals in order to replace them with the TMI control signals. It also receives continuously the sensor data from the transmitter to drive directly the power wheelchair motors (without the need of a computer, which is required in the TCIs and BCIs design concepts described previously). This allows the user to move in any desired direction. Finally, the functional prototype to be assembled in the retainer can be seen in Figure 13.

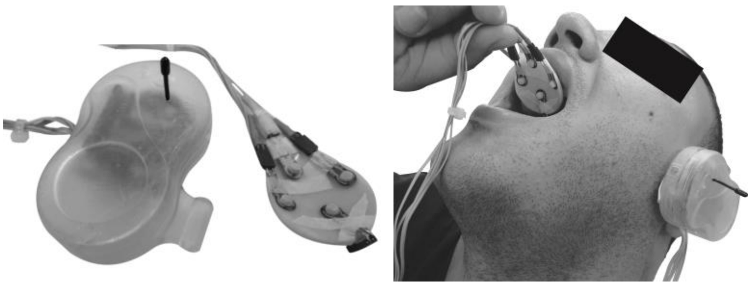

Figure 12. (a) Functional prototype of the TMI (b) Functional prototype of TMI on a user

4.2 Assessment

In total 27 proposed activities were completed by 15 different healthy users between the ages of 20-35 years and of both genders. All 15 users controlled the wheelchair using the TMI; eight of them with the original joystick and six of them with a BCI. Each device was tested with different groups, mainly due to the length of the tests which elapsed on average 2 hours per user. In order to correctly compare the data, a Statistical Hypothesis Test was performed among TMI vs. Joystick, TMI vs. BCI and Joystick vs. BCI. Table 4 and Figure 14 present the test samples and results.

Table 4. Test effectiveness´s results

Group	Device	Sample (n)	Mean Value ($\bar{x}$)	Standard deviation (s)
1	TMI	15	19.55	7.882
2	Joystick	8	21.13	9.190
3	BCI	6	9.21	8.067

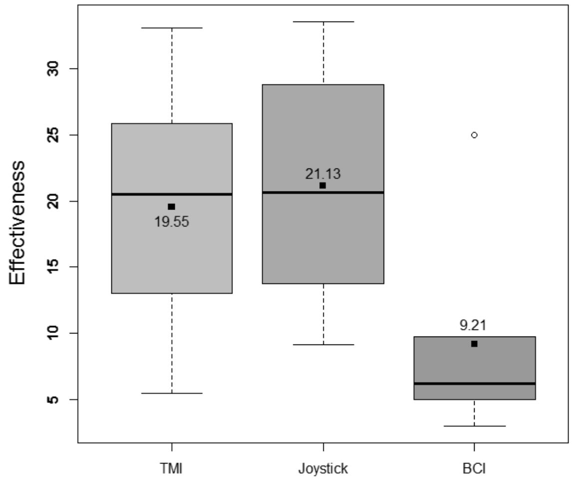

Figure 13. Assessment statistical results

From Figure 14 two hypothesis arise regarding the TMI's effectiveness: 1) it is similar to the Joystick's and 2) is higher than the BCI's. Another hypothesis also can be proposed: 3) the Joystick effectiveness is higher than BCI's. These three hypothesis are analysed in Table 5 by using the two sample test mean value method.

Table 5. Two sample test (Cliffsnotes, 2013)

Hypothesis Test	Hypothesis	Degrees of freedom	Two Tailed Significance Level (p)	T distribution critical value	Critical value
TMI's effectiveness similar to Joystick's.	Δ=0	15+8-2=21	0.05	2.080	0.43
TMI's effectiveness higher than BCI´s.	Δ=15	15+6-2=19	0.05	1.729	1.22
Joystick's effectiveness higher than BCI's.	Δ=15	8+6-2=12	0.05	1.782	0.65

5 CONCLUSION

User tests performed with 15 healthy patients suggest that the current TMI prototype could replace the joystick for driving a power wheelchair, improving the mobility of the quadriplegic patients by using the tongue as an actuator. This is supported by the results displayed on Table 5, where the critical values were less than the T distribution respective ones, meaning that none of the proposed hypotheses can be rejected. The TMI prototype had an average effectiveness of 19.55, which compared to the joystick's (average effectiveness of 21.13) is approximately equally effective, consequently it is concluded that the TMI can replace the joystick achieving a similar performance. The TMI also presents a greater

effectiveness compared to the evaluated BCI (average effectiveness of 9.21), indicating that the TMI is more effective than the Emotiv™ BCI for the task of moving on a powered wheelchair.
Finally, comparing our TMI to previous developments (Table I) the main advantages are the sensors being used. FSRs are mechanically flexible, lack moving parts and are fairly cheap, adding good value to the product ergonomics, lifespan and cost.

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