UNIVERSIDADE TÉCNICA DE LISBOA
INSTITUTO SUPERIOR TÉCNICO

Myographic Mobile Accessibility for Tetraplegics

Tiago João Vieira Guerreiro
(Licenciado)

Dissertation for the degree of Master of Science in
Information Systems and Computer Engineering

Adviser: Doctor Joaquim Armando Pires Jorge

Thesis Committee

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Resumo

Actualmente, o uso de dispositivos electrónicos é transversal aos cenários que compõem o nosso dia a dia. Bombardments, os dispositivos moves, de dimensões reduzidas mas capacidades semelhantes às dos computadores de secretária, aumentaram drasticamente as nossas capacidades comunicativas oferecendo disponibilidade total, em qualquer local e para qualquer local. Estes dispositivos tornaram-se essenciais para a comunicação pessoal mas reúnem também um conjunto de aplicações que os transformaram em, além de simples telefones, ferramentas de produtividade e lazer.

No entanto, a interacção com estes computadores de dimensões reduzidas é altamente exigente ao nível físico. Em particular, pessoas com tetraplegia têm grandes dificuldades ou incapacidade total de interagir voluntariamente com dispositivos moves. Neste documento, apresentamos uma abordagem para a interacção de tetraplégicos com dispositivos moves. Esta baseia-se no uso de informação miográfica (Electromiografia) recolhida em áreas com movimento residual e no redesenho geral dos diálogos entre o sistema e o utilizador. Através de estudos com utilizadores, foram desenhados esquemas de interacção que permitem adaptabilidade aos vários níveis de lesão mas também aos vários cenários que compõem o dia a dia. Foram realizados estudos com utilizadores que validam a Electromiografia como mecanismo de interacção, bem como a capacidade de adaptação aos vários cenários possíveis.

Abstract

Nowadays, electronic devices are used across the several scenarios that compound our day. Mobile devices, with their reduced dimensions but capacities increasingly similar to desktop computers, have drastically augmented our communicative capabilities offering total availability, everywhere and to everywhere. These devices have become essential for human-human communication but also gather an application set that make them, more than simple phones, high productivity and leisure tools.

However, tetraplegic persons face great difficulties or total inability to voluntarily interact with these devices. In this document, we present an approach to allow interaction between tetraplegic users and mobile devices. This interaction is based on myographic information (Electromyography) collected from residually controlled body areas and on the redesign of the dialogues between the system and the device. Through user studies, we designed interaction schemes that allow adaptability to the several lesion degrees but also to the several scenarios that make the users' daily life. We undertook user studies that validate Electromyography as an interaction mechanism as well as the capacity to adapt to the several possible scenarios, offering real mobile devices accessibility.

Palavras Chave

Acessibilidade Móvel, Tetraplegia, Tecnologias Assistivas, Comunicação Alternativa, Electromiografia, Interface Utilizador

Keywords

Mobile Accessibility, Tetraplegia, Assistive Technologies, Alternative Communication, Electromyography, User Interface

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I would also like to thank all the users that participated in the evaluations performed during this thesis. Particularly, during the months that this dissertation longed, I won two new friends. To Pedro Freitas and Luis Pereira, more than the availability for the studies present in this dissertation, I would like to thank for being two excellent men. To Luis, who passed away before I finished my studies, I dedicate this dissertation. Thank you for everything!

All the people at INESC-ID Intelligent Multimodal Interfaces Group have contributed to this dissertation and this group is an important part of my life. As I believe to be a part of the group also. Those who deserve my gratitude are too much to mention but I would like to give my special thanks to Daniel Gonçalves, Bruno Araújo, Paulo Lagoá, Ricardo Gamboa, André Martins, Alfredo Ferreira, Ricardo Jota and Filipe Dias. My thanks to INESC-ID for giving me the conditions to undertake my research and Paula Monteiro and Manuela Camal for helping me whenever I needed. Last but not the least, I give my special thanks to my supervisor, Professor Joaquim Jorge. More than thanking for this dissertation, I thank you for the introduction to research, contagious motivation and for being always available. Regardless of the respect I will always maintain and the relation student-supervisor we will keep in the following years, I also see you as a friend. Once again, Thank you.

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1

Introduction

Nowadays, we can find ourselves surrounded by technology, whether in public spaces, our homes or even within our body space. Indeed, it is difficult to imagine how we could survive without some of the devices, and their functions, that we take for granted today but were not available a few years ago. What is true is that technology touches our lives in ways we no longer think about. Besides these technological components and functions that we take for granted, technology is creating new opportunities for the majority of the population offering new forms of social interaction, instant access to information, constant availability and higher control of our surrounding environment.

Moreover, although a few years ago computers were meant to be used only in static environments, the extraordinary development on mobile technology dictated the success of mobile computing devices. Communication technology development and component miniaturization were the main reasons for the mobile technology success and its enormous society penetration. These small, portable and stylish devices extend our capacities through several different scopes in our daily lives. Considering available functionalities, these devices are increasingly becoming similar to desktop computers. Therefore, we are now able to edit a document on a mobile device and send it to a colleague in another country. Indeed, and the most important and basic function, one can be always available and communicate with anyone in the world just by composing a number. Once again, what is true is that technology touches our lives in ways we no longer think about. Because we can.

While the majority of the population is able to operate both static and mobile devices, there is still a large set of users that is not able to do so. While such inability can be due to different impairments, we will only focus on severely motor disabled individuals, particularly, tetraplegics. A tetraplegic is an individual with motor limitations on both upper and lower limbs. Tetraplegia is mostly caused by traumatic spinal cord injuries. Thus, usually the limitations are physical but the cognitive capabilities are intact. Even though some diseases that can cause tetraplegia are also connected with some cognitive disabilities, we will only focus on spinal cord injury related tetraplegia.

1.1. Motivation

The limitations due to tetraplegia deprive the injured individual from operating electronic devices like computers or mobile devices. Besides the drastic quality of life reduction directly imposed by the impairments, individuals also face a communication bottleneck as they are often incapable of operating devices that make possible to communicate with others (computer, cell phone, PDA).

Moreover, as new technologies appear and communication channels increase, the distance between full-capable individuals communication capabilities and the severely disabled ones also increases. The technological evolution influences negatively the disabled population as their inability to operate and communicate with the new technologies damages the social interaction but also their integration in the society as active members and, particularly as workers who also need to guarantee survival.

It is a world wide concern to restitute disabled users communicative and control skills to improve their life quality. Hence, by regaining computer control disabled persons can through it operate any other device, easing communication, movement and overall autonomy.

Moreover, studies show that nearly 60% of the lesions occur between 16 and 30 years old and that nearly 60% of the impaired were working before the injury while only 20 % are working, one year after the injury. Several factors affect the employment after the lesion and those include the severity of the injury, gender, race, age, marital status and level of education. Although impairments prohibit to execute some functions, it is possible to aid a great percentage of spinal cord injured individuals to achieve their working goals with auxiliary mechanisms and proper training. The ability to continue working faces benefits that go beyond financial and social advantages: studies suggest that employment is related to prolonged survival (McKinley, 2004).

While we can find several assistive technologies for tetraplegics (reviewed in Section 2.2) aiming at computer, wheelchair or environmental control, the same efforts have not been done considering mobile devices [1] control. Although the majority of the tetraplegics own a mobile device, the interaction is completely passive (i.e., wearing a bluetooth earpiece that automatically gets a call). However, the portability, lightweight and communication capabilities of these devices present them as excellent candidates to offer tetraplegic individuals a constant communication and control tool. Thus, if interaction means are offered, the user will be able to communicate, or even control other devices through them, independently from position or scenario (i.e, wheelchair, laying in bed, couch). On the other hand, offering constant interaction capabilities outlines several issues that must be dealt with it. It is required to study approaches that permit a transversal use through the day and through the several possible scenarios that constitute the user's daily life while minimizing caretakers required assistance.

Although there are several assistive technologies to overcome motor impairments and offer tetraplegic persons control and communication capabilities, they are still insufficient and fragmentary. Generally, existing technologies and interfaces try to focus on the emulation of the interaction traditionally realized by full capable individuals. As an example, computer control is normally achieved through mouse pointer emulation. This emulation is advantageous as it provides the possible users with access to the same applications a full-capable individual interacts with. However, the downside is that the achieved interaction and control are restricted to the one achieved by full capable individuals although the user needs are greater and capacities are lower. Overall, the independent scenarios are somehow covered but the full picture is not. Even with the latest assistive technologies, tetraplegic users are not able to control devices through the day as position, ambient shifts or miscalibration issues still require constant caretakers assistance. As an example, looking back to the pointer emulation approaches, they normally require the user to be placed in front of the computer (i.e., gaze-tracking approaches) and the truth is that the users may not be in the required position and, most important, may not be able to achieve those requirements without third-party help. Therefore, although the interaction is designed to be similar, the pre-requisites are not fulfilled equally by full-capable individuals and tetraplegic users.

1.2. Mobile Device Control for Tetraplegics

In this document we present a mobile device control approach for tetraplegics. Our approach offers tetraplegic users the ability to control a mobile device, particularly, making a call, sending a message, managing contacts but also dealing with incoming events, receiving information on the event and responding to it (i.e., accepting or rejecting a

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[1] In this document, the term ”mobile device” refers to a portable device with reduced dimensions, communication and organization functionalities. This group of devices includes cellular telephones, smartphones and personal digital assistants (PDA).

call). We achieve this goal by focusing the design on the users, gathering information on their actual daily lives, their daily scenarios and consequently their capacities and limitations. In our preliminary user studies, we were able to identify several issues regarding the actual panorama on disabled-computer interaction. Overall, although some assistive technologies allow some degree of control, for the most severe cases, interaction with technology is very limited and occurs during time slices that do not depend exclusively on the user's will. Although caretakers assistance is necessary at certain times, we believe it to be possible that this assistance can be extremely reduced. It is important that the system deals with the user's definitive or momentary incapacities, slight position or ambient shifts and fatigue.

To develop a system suitable for tetraplegic individuals we had to study their life habits and accommodation scenarios. It is clear that most of the control and communication solutions do not take into account the user's daily habits and needs. Motor disabled users cannot move themselves properly and, in most cases, cannot change body position nor pick a cell phone or other device.

Focusing on an extensive approach that is able to deal with the various shifts that are possible during the day without the need for constant manual assistance, we designed our system to automatically deal and *negotiate* with the user the best interaction profile. Actually we must consider several scenarios: the user can be sitted in the wheelchair with the mobile device in his line of sight but he can also be laying down with no visual feedback.

Although offering the most severe impaired users a mean to interact with the mobile device, it is also important to consider the differences within the target population. Particularly, considering tetraplegic users, the capabilities between individuals are highly diverse. It is important to cope with this diversity, extending the interaction to the most severe cases but offering those with higher control degrees with suitable interaction schemes.

All the considerations and goals above lead to the design and development of an electromyographic mobile device control interface for tetraplegics, a system where the disabled user can control the device through muscle contractions. A large set of target muscles is available so we can interact widely with the computer. Being able to detect and to evaluate muscle activity in an individual gives us the possibility to associate it with predetermined interface commands, thus having the myographic signal as input. By using this technique (EMG) we can focus on a wide target group (as any voluntarily contracted/moved muscle can be monitorized) and be exhaustive (explore the capacities the user has to offer while keeping the system usable and simple). Once again, Electromyography provides the setup liberty and adaptation to all the scenarios providing the necessary mobile device interaction tool. Furthermore, with an EMG based solution we can develop a solution that is independent from a display and offers the real scenario adaptation we looked for. The number of voluntarily contracted muscles is large creating several acquisition scenarios, including cases where the impairments are enormous. The inputs commands are selected accordingly to the lesion and the user's residual capacities: the neck, jaw and temporal areas are good choices. The independence from a display creates the possibility to use EMG in a mobility scenario. It also makes possible to interact when the users lay down with no visual feedback, as long as alternative feedback is provided. Besides the control interface, electromyography, we have also studied how the information should be presented so the interaction can be accurate and effective, in the aforementioned scenarios.

To validate our approach, we undertook user studies both on the control interface, presenting electromyography as a suitable command issuer for interface control, and on the overall approach presenting the body residual capacities as suitable to control an adequate and re-designed mobile device interface. It is important to notice that although we tried to follow a user-centered design approach, we were not able to gather a significant user sample. During this dissertation, we fought to enlarge the target user set but the users' impairments and situational characterisitcs along with the difficulties found to reach them, reduced our success. However, in all the stages of our studies we were in contact with at least one tetraplegic user.

1.3. Contributions

The main contribution of our research is the design of a mobile device control interface for tetraplegics. In the path to achieve this goal, we also yielded the following contributions:

- *Mobile device control by tetraplegics.* We designed and developed a prototype interface and system for mobile device control by tetraplegics showing how the design guidelines gathered in preliminary user studies can be instantiated. Indeed, following a user-centered design approach, we developed a prototype that copes with the users daily limitations and offers reliable mobile device control. This prototype and the underlying approach were evaluated with target users in real life scenarios validating the performed choices and the approach characteristics.

- *A study on current assistive technologies panorama,* that besides identifying the state of development in the area, points out the major advantages and disadvantages of each technology and assesses its suitability to a certain user group or/and scenario. Furthermore, the surveyed approaches are compared taking into account a significant and comprehensive set of criteria.

- *An in-depth analysis and characterization on tetraplegics capabilities and needs,* aiming at real technology accessibility. This study points out several problems and concerns that have not been taken into account so far. Indeed, the majority of technological solutions for tetraplegics is not adapted to the users' daily scenarios. In this study we clarify the problems and limitations inherent to the life of a tetraplegic and their caretakers.

- *A set of guidelines for designing mobile assistive technologies,* based on user analysis. Although these guidelines were gathered from a specific target group user analysis, the implications for design are quite universal and can be taken into account across other assistive domains.

- *A platform to research physiological signals,* that besides the processing and analysis of physiological data, provides the necessary tools to improve user evaluation studies. This platform was designed to be used both during evaluation sessions and during data post-processing and it was essential to gather the information presented in this document.

1.4. Publications

The work presented in this dissertation resulted in seventeen original publications accepted in, both national and international, peer-reviewed Scientific Conferences and Journals. Below we list these, organized chronologically by date of publication:

1. Guerreiro, T., Jorge, J.. Assessing Electromyographic Interfaces. To appear in: *Journal of Virtual Reality and Broadcasting*.
2. Guerreiro, T., Gamboa, R., Jorge, J.. Mnemonical Body Shortcuts: Improving Mobile Interaction. To appear in: *Proceedings of the European Conference on Cognitive Ergonomics, ECCE 2008*
3. Guerreiro, T., Lagoá, P., Nicolau, H., Santana, P., Jorge, J.. Mobile Text-Entry Models for People with Disabilities. To appear in: *Proceedings of the European Conference on Cognitive Ergonomics, ECCE 2008*
4. Guerreiro, T., Lagoá, P., Santana, P., Gonçalves, D., Jorge, J.. Navtap and Brailletap: Non-visual input interfaces. *Proceedings of the Rehabilitation Engineering and Assistive Technology Society of North America Conference, RESNA 2008,* Arlington, VA, USA, June 2008.

5. Gamboa, R., Guerreiro, T., Jorge.. Mnemonical Body Shortcuts: Body Space Gesture Recognition. In *Proceedings of the 13th Portuguese Conference on Pattern Recognition*, Lisboa, Portugal, 2007
6. Lagoá, P., Santana, P., Guerreiro, T., Gonçalves, D., Jorge, J.. Mobile device accessibility for the Blind. In *Proceedings of the 15th Portuguese Conference on Computer Graphics*, Porto Salvo, Portugal, 2007.
7. Lagoá, P., Santana, P., Guerreiro, T., Gonçalves, D., Jorge, J.. Blono: a New Mobile Text-entry Interface for the Visually Impaired. In *Springer Lecture Notes in Computer Science, Universal Access in HCI Part II, HCII 2007, LNCS 4555, pp. 908-917*, July 2007, Beijing, China.
8. Gamboa, R., Guerreiro, T., Jorge, J..Mnemonical Gesture-based Mobile Interaction. In *Proceedings of the 12th International Conference on Human-Computer Interaction (HCII 2007)*, July 2007, Beijing, China.
9. Gamboa, R., Guerreiro, T., Gamboa, H., Jorge, J.. Mobile Interaction Based On Human Gesture Analysis. In *Proceedings of the International Symposium on Measurement, Analysis and Modeling of Human Functions (ISHF 2007)*, May 2007, Cascais, Portugal.
10. Guerreiro, T., Jorge, J.. Assistive Technologies for Spinal Cord Injured Individuals: Electromyographic Mobile Accessibility. In *Proceedings of the 7th International Workshop on Gesture in Human-Computer Interaction and Simulation (GW2007)*, May 2007, Lisbon, Portugal.
11. Gamboa, R., Guerreiro, T., Jorge, J.. Mnemonical Body Shortcuts. In *Proceedings of the 7th International Workshop on Gesture in Human-Computer Interaction and Simulation (GW2007)*, May 2007, Lisbon, Portugal.
12. Guerreiro, T., Jorge, J. Controlo Miográfico de Dispositivos Moves para Tetraplégicos. In *Proceeding of the 2nd National Conference on Human-Computer Interaction (Interacção 2006)*, October 2006, Braga, Portugal.
13. Guerreiro, T., Jorge, J. Controlo Miográfico de Dispositivos Moves para Tetraplégicos. In *Proceeding of the First National Conference on Software Development for Enhancing Accessibility and Fighting Info-exclusion (DSAI 2006)*, March 2006, Vila Real, Portugal.
14. Lagoá, P., Santana, P., Guerreiro, T., Gonçalves, D., Jorge, J.. Blono: Bloco de Notas para Portadores de Deficiências Visuais. In *Proceeding of the First National Conference on Software Development for Enhancing Accessibility and Fighting Info-exclusion (DSAI 2006)*, March 2006, Vila Real, Portugal.
15. Guerreiro, T., Jorge, J. EMG as a Daily Wearable Interface. In *Proceedings of the First International Conference on Computer Graphics Theory and Applications (GRAPP 2006)*, February 2006, Setúbal, Portugal.

1.5. Document Outline

To capture the assistive technologies for tetraplegics panorama we studied and analyzed the existing technologies across several human-computer interaction scenarios. Those studies are presented in Chapter 2. To provide tetraplegic users with an effective mobile device control interface, we needed to study the actual capabilities, needs and characterize the daily scenarios of the target population. Chapter 3 describes the studies performed to assess interface requirements, as well as a set of guidelines for mobile device control interfaces for tetraplegics. Our proposed approach is presented and the concept preliminary evaluation results is presented. With those guidelines in mind we were able to design the prototype systems described in detail in Chapter 4. The developed prototypes allowed us to validate the system with users within the interaction scenarios gathered in Chapter 3. The performed usability evaluations are presented and discussed in Chapter 5 while Chapter 6 outlines our conclusions and future work proposals.

2

Background

2.1. Tetraplegia

Tetraplegia, also known as quadriplegia, is a condition where a human experiences weakness of all four limbs (Greenberg et al., 2005). Depending on the location and severity of the lesion, the patient can lose partial or total mobility on all four limbs as well as in the trunk.

2.1.1. Spinal Cord

The spinal cord is the largest nerve in the body extending from the brain to the waist. The nerve fibers inside the spinal cord carry *messages* between the brain and other body parts to enable sensory, motor and autonomic functions. The nerves within the spinal cord, named upper motor neurons, carry messages back and forth between the brain and the spinal nerves. The nerves that branch out from the spinal cord, named lower motor neurons, carry sensory information and motor commands between the spinal cord and other areas of the body. These nerves exit and enter at each vertebral level and communicate with specific areas of the body.

2.1.2. Spinal Cord Injury

Spinal cord injury (SCI), or myelopathy, is a disturbance of the spinal cord that results in sensory and motor loss. Spinal cord injuries can affect the communication between the brain and the body systems that control sensory, motor and autonomic function below the level of injury. It is important to note that the spinal cord does not have to be completely severed for there to be a loss of function. In fact, the spinal cord remains intact in most cases of spinal cord injury. In general, the higher in the spinal column the injury occurs, the more dysfunction a person will experience.

The eight vertebrae in the neck are named cervical vertebrae (Figure 2.1). The top one is called C1 and the next C2. Injury of cervical nerves between C1 and T1 (first thoracic vertebrae) could result in tetraplegia. Depending on its vertebral level and severity, the individuals with tetraplegia experience a loss of motor and/or sensory functions in their head, neck, shoulders, upper chest, arms, hands and fingers. Injury between C1 and C4 is usually called high tetraplegia, while injury between C5 and C8 is called low tetraplegia. A person with low tetraplegia may still have partial motor/sensory function in his shoulder, arms, and wrists. Injury between T2 and S5 could cause Paraplegia. Depending on the severity of the SCI, individuals with SCI may experience complete or incomplete loss of motor/sensory function below the level of injury. The exact effects of a spinal cord injury vary according to the type and level injury, and can be:

- In a total injury, there is no function below the level of the injury.Total injuries are always bilateral, that is, both sides of the body are affected equally.
- Partial injuries are variable, and a person with such an injury may be able to move one limb more than another, may be able to feel parts of the body that cannot be moved, or may have more functioning on one side of the body than the other.

While the majority of the tetraplegia situations are due to traumatic spinal cord injuries, there are several non-traumatic diseases that can lead to this type of paralysis (i.e., Multiple Sclerosis, Amyotrophic Lateral Sclerosis, Muscular Dystrophy) (Greenberg et al., 2005; Kotzé et al., 2004).

2.2. Assistive Technologies for Tetraplegics

Assistive Technology is a generic term that includes assistive, adaptive, and rehabilitative devices that promote greater independence for people with disabilities. Computer control and the subsequent electronic device or even ambient control is a actual worldwide concern because it offers people with disabilities the ability to improve their quality

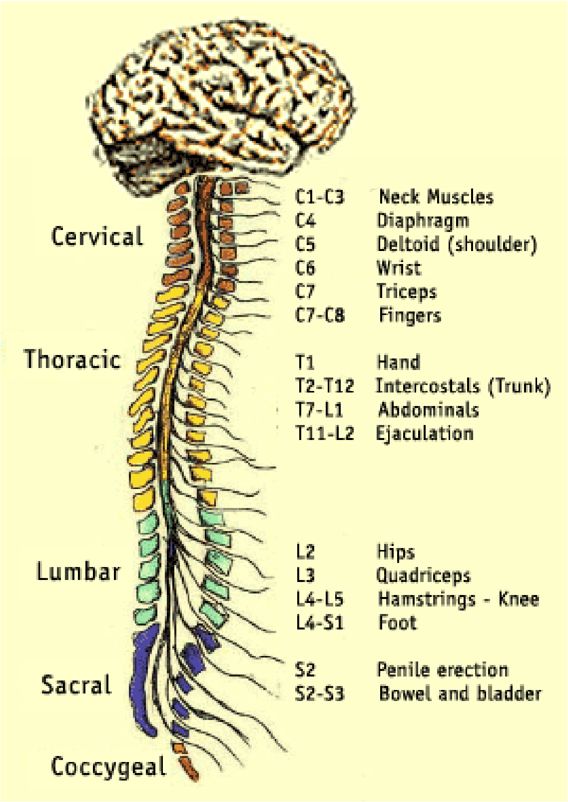

Figure 2.1: Motor Map

of life. Actually through computer control several others devices can be actuated and therefore offer disabled persons higher freedom and independence levels.

The ability to operate a computer is extremely valuable nowadays, particularly for persons with disabilities. Among other things, computers can be used to access the Internet, read or compose emails, listen to music, watch movies, or play games. Given the right interfaces, computers can even control a mobile robot or an electric-powered wheelchair, as well as switch lights or other appliances on and off. To say the least, computers can help very much with the integration of disabled individuals into society.

Particularly, mobile devices are increasing their importance in society as they offer everywhere availability besides a set of applications that make them essential organizing and working tools.

Unfortunately, the standard way of operating a computer requires the reliable use of hands and arms, since it involves a keyboard and a manual mouse device, which is unsuitable for a large number of people with disabilities. Therefore, developing an alternative user interface, which does not require manual input, is of great importance. This fact is even more dramatic when we consider mobile devices where other variables appear.

Although there haven been several efforts to approach motor impaired users and technology, the truth is that tetraplegic users are still far behind the technological reality that a physically capable individual faces. Nowadays, we are facing an exceptional development on mobile technology and as we see our mobility and on-the-move productivity increasing, the exclusion of motor challenged users increases. Indeed, if we consider the characteristics of most assistive technologies, we can observe that they are not suitable for the conditions brought up by a mobility scenario.

For individuals with high tetraplegia, input sources for human-computer interface are limited. Possible input sources include head movements, voice, eye movements, or muscles on the face. For individuals with a lower injury degree some other options can be explored accordingly to the individuals disabilities, like hand joysticks, switches or even monitoring arm muscle .

Interfacing Schemes

The human/technology interface is composed by three elements that contribute to the operation of the device: the control interface, the selection set and the selection method. The control interface (i.e., keyboard, switch) is the hardware by which the user operates the device while the selection set is the items available to select from (i.e., icons, letters) and the selection method is the way the user makes selections using the control interface [reviewed in (Cook and Hussey, 2002)].

Considering selection method or interfacing scheme, we consider two different approaches: direct selection, indirect selection (scanning and coded access).

Direct selection involves a one to one correspondence between input acts and selections (i.e., QWERTY keyboard). In this method, the user identifies a target in the selection set and goes directly to it. As an example of direct selection, we can mention the traditional QWERTY keyboard typing. Obviously, direct selection methods offer a direct correspondence between selections and actions, thus are normally easier and quicker to use . On the other hand, if a selection set is large and the control interface (selected according to user capabilities) has a reduced communication bandwidth, direct selection is not feasible.

Scanning entails offering the user, sequentially or otherwise, selection alternatives until the user has indicated his choice. Scanning input is widely exploited in cases of severe disability, since it remains feasible even when a user is only capable of single switch operation (Damper, 1986). In this scenario, even with a large selection set and a reduced communication bandwidth, the user is able to operate the device and accomplish the desired task.

Encoding employs a specific pattern of input acts to make a given selection (i.e., Morse code). In coded access, the user uses a distinct set of actions to input a code for each item in the selection set. Like scanning, coded access requires less physical capabilities

Figure 2.2: Keyguard

than direct selection (Cook and Hussey, 2002). However, in an encoding scenario, the control is on the user side while in a scanning scenario, the device times and controls the interaction.

The choice of an assistive technology must consider these three components and must always be focused on the user and his needs. Almost all devices permit access though any type of control interface and selection method. Moreover, the selection set can be adapted to the user. Although this chapter follows a control interface-based organization, the research projects and available products' description takes the possible selection set and selection method into account. In fact, the connection between a control interface, selection method and selection set defines human-technology interface effectiveness.

Evaluation and Assessment Criteria

In this chapter we survey the main assistive approaches considering computer control by severe motor disabled persons. The goal of this analysis is to observe the actual panorama on assistive technologies and the capacities and limitations of each technology in particular. Overall, we will also be able to discuss the general restrictions that the projects and products detain.

To select an appropriate assistive technology several factors must be considered. The level of impairment strongly influences the decision but residual capacities should also be taken seriously into account as a good matching between the user and the selected modality can highly influence his life quality. For example, it is important to notice that individuals with low tetraplegia, with restricted but residual finger and arm motion, can be provided with some keyboard adaptations to achieve its control with no need for an extra entry interface (i.e., a Keyguard (Figure 2.2) for individuals with finger function compromised who are willing to make several typing errors). On the other hand, for the most severe injuries an extra computer communication channel must be supplied.

When selecting an input device and interfacing scheme it is very important for clinicians, technologists, caretakers and the disabled themselves to be aware of the assistive technologies characteristics and their suitability to specific cases (Bates, 2002). In this chapter we will review several assistive technologies presenting the methods' advantages and disadvantages and comparing them considering:

Potential users range (Card et al., 1990) argued that the manipulation and control requirements of an input device maybe mapped using a design space. Considering a certain input modality we can also argue its suitability to a certain person according to the input requirements and the person's sensory and motor characteristics (Bates, 2002). Thus it is possible to create a map that relates physical abilities with a certain input modality. This is the most important feature of an assistive technology as it presents the total inability of relations between certain impairments and input modalities. We will refer to the disability level but also include details on required capabilities as the spinal cord lesion level can sometimes be misleading (i.e., incomplete spinal cord injuries).

Dimensionality and Input Speed Several factors influence the interaction speed, whether on the user side (i.e., cognitive load, preparation time) as on the machine (i.e., recognition delays). However, one of the most important issues considering input speed is its dimensionality and therefore its suitability or restriction to a certain interfacing scheme (direct selection, encoding or scanning). Naturally, the input speed of a certain interface is highly connected to the interfacing scheme used and this one is normally determined by the individual and input source capabilities.

Accuracy, Robustness and Repeatability The accuracy of a certain input mechanism is vital to its adoption. Indeed, if a user is not confident in a certain system he will probably drop its use. This issue assumes great importance when considering assistive technologies where motivation and confidence must be built and maintained.

Ease of use As with accuracy, it is extremely important that a user can easily learn to use an input device. The first approach to a certain technology should be smooth and the user must be able to feel improvements in the first times he uses the system. Moreover, we must consider that some assistive technologies require the set up of extra components whether in the wheelchair or bed, whether in the user's body. This setup must be simple so caretakers can easily undertake it without any special aid. Also, this process must be evaluated considering the time to setup and train the system when needed.

Aesthetics, Hygiene and Acceptance Assistive technologies can be used to aid controlling the computer, an environmental control system or a telephone, among others. Although the majority of these functions are realized in a restricted environment where aesthetics and social acceptance can be minor issues, public scenarios must be considered. Several projects aim at wheelchair control, therefore considering situations in public. Also, in the communication era we are witnessing the widespread of mobile devices and mobile device control for the disabled is also a research issue nowadays. Therefore, it is important to evaluate the technologies aesthetics and social acceptance. Considering user acceptance it is also important to evaluate the awkwardness of some devices. This includes hygiene issues but also some intrusiveness that some technologies imply.

Mobility Adequacy The majority of the assistive technologies are aimed at special purpose devices, mostly personal computers and wheelchairs. Those are normally restricted to a rigid setup and require, for example, that the user faces the computer at a given distance (i.e., Tracking Interfaces). Also, mobile devices have had an enormous growth in the last few years and almost everyone has one. These small and lightweight devices are carriable and always available. Hence, we will evaluate assistive technologies considering their mobility adequacy, whether in an indoor environment, considering the distance of interaction, whether in an outdoor environment where the surrounding noise, illumination variations, and movement can restrict or deny its use.

In the next sections, we present the main approaches to assistive technologies considering tetraplegics, reviewing the state of the art on Switches, Tracking, Electrophysiological, Speech, Hybrid as well as other less explored approaches.

2.2.1. Touch Switches, Sticks and Pointers

The switch is a very simple widely used computer access interface consisting on an electrical device that the user activates according to its residual movement capacities. Switches are often Yes/No interfaces but this input set can be enlarged with multiple switches (Figure 2.3). Within a large set of switch-based interfaces we can find different switches operated by hand, tongue, chin, forehead, among others. These interfaces are regularly used with scanning interfaces (the user activates the switch when the desired option is highlighted) although switches can also function as a complementary control mechanism (i.e., perform mouse clicks).

Upper Limb Interfaces

Within tetraplegic patients, we can easily find ones that are able to move one or both upper limbs, although control may be limited. Moreover, although we can witness the control of the arm (biceps), it is also probable that no full limb control is achieved (triceps, forearm muscles, flexors and extensors). Looking back at the motor map, these muscle groups are controlled by different nerve roots, therefore a certain lesion degree will affect the muscle control differently, event within a smaller context, as the upper limbs (Table 2.1). As an example, we can identify cases where the impaired user controls his arm totally but has no forearm or finger control. In this case, the user cannot grab a mouse or

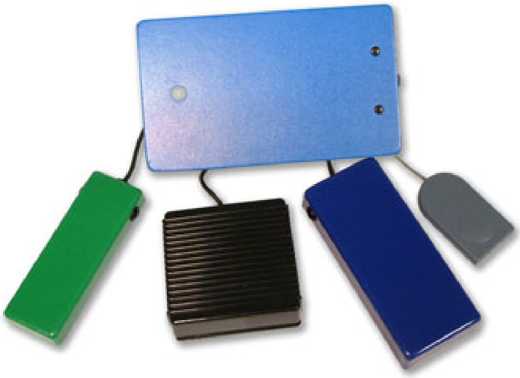

Figure 2.3: Several action switches

joystick, but for instance, he can point or press a button switch. Considering these situations there are several button-press switches and special joysticks, that take advantage from the impaired upper limb residual capacities, whether to emulate mouse movement or mouse clicks, whether to perform selections within a scanning interfacing scheme. There are also several applications that use the button switch as an input to a morse code communication system.

Level	Key Muscles	Related functions
C5	Biceps, Deltoid	Arm/Elbow Flexion, Shoulder Control
C6	Extensor Carpi Radialis	Wrist Extension, Tenodesis
C7	Triceps, Flexor Carpi Radialis	Elbow Extension, Wrist Flexion
C8-T1	Hand intrinsic muscles	Finger Flexion, Hand Grasp

Table 2.1: Upper extremity function by neurologic level (from (McKinley, 2004))

As an example, (Shannon et al., 1981) have developed a communication system for a non-vocal tetraplegic with motor control only in his right thumb. The system uses the user's thumb movement ability to generate Morse code signals, which in turn operates a personal computer. These signals can therefore be used to write text but also to control other applications.

Mouth and Tongue Interfaces

Even users with high level tetraplegia are likely to have some sort of control in or within their mouth. Although sometimes the impairment can affect intelligible speech, the majority of patients can still move their mouth, clench teeth and move tongue consistently. Therefore there are some approaches to control electronic devices, whether with a mouthstick, a bite switch or a tongue joystick/switch.

A mouthstick consists of a pointer attached to a mouthpiece. The user grips the mouthpiece be-

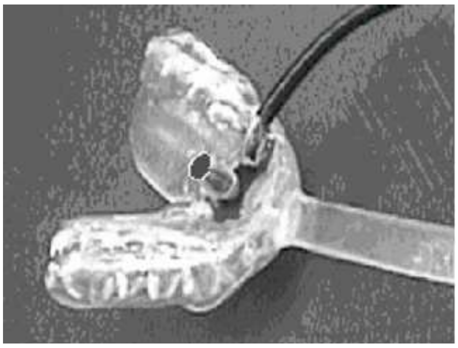

Figure 2.4: TonguePoint

tween his teeth and moves his head to manipulate control interfaces or other objects. The shaft of the mouthstick can be made from a wooden dowel, a piece of plastic or aluminum (Cook and Hussey, 2002). To control the mouthstick the user is required to have good oral-motor control and the regular use of the mouthstick (i.e. text-entry tasks) is potentially highly fatiguing (Beukelman et al., 1985).

Within mouth-based interfaces there is a distinctive subarea, the tongue-controlled interfaces that can be argued to be more aesthetic as the user may hide the device inside the mouth. However this approach can also be classified as less hygienic, less ergonomic and harmful to the user. Also, the tongue provides high selectivity as one can easily pick out every single of our 32 teeth (Struijk, 2006).

The Tongue Touch Keypad ^{TM}is a commercially available tongue touch system placed in the roof of the user's mouth and operated by the mouth. The system is composed by nine "buttons" that can be configured to control the environment, drive a wheelchair or control the computer.

(Struijk, 2006) presented an inductive tongue-computer interface composed by nine air cored inductors placed on a palatal plate resembling the ones used as dental retainers and an activation unit glued to the tongue. The authors evaluated the system associating each of the coils with a determined alphabet letter and prompting the user for a typing sequence, repeating it about 40 times during three days of measurements, without visual display of the position of the characters. Results presented a speed of 30-57 characters per minute with a 15-29 % error rate.

Salem and Zhai designed an isometric, tongue operated device, called the TonguePoint (Salem and Zhai, 1997) aiming at an alternative computer input. As pressure sensitive joysticks have became smaller and effective, is was possible to develop a device operated by the tongue (with its limited movement range). *A TonguePoint is a mouthpiece that, similar to a dental night or a sports mouth guard, is form fitted to each individual's upper teeth and hard pallet (Figure 2.4).*

Other mouth-related type of switches can be pointed like the bite switch that enables a

Figure 2.5: Head Pointer

user with good mouth abilities to achieve selection by biting a surface.

Other Head-Based Interfaces

The head pointer (Figure 2.5) is a physical instrument, similar to the mouthstick, but in this case, the pointer is held by the head instead of the mouth. As the mouthstick, this assistive device helps the user with head motion control to press a keyboard.

For wheelchair guidance, it is normal to see the manual joystick replaced by a chin joystick which functions are equal to the hand-operated one, but it is controlled with the chin. Normally the stick is replaced by a ball to ease control and to avoid injuring the user. There are several variations of the above mentioned sticks that can be controlled by the forehead, cheek or teeth.

Discussion on Touch Switches, Sticks and Pointers

Although similar in function the presented approaches vary widely considering the target user, dimensionality and user acceptance. Therefore, besides a general classification there are also differences between the approaches that are also revealed considering the predetermined evaluation criteria:

Potential users range The switch, as sticks or pointers, do not define a particular body part therefore the assistive devices described in this chapter are quite different considering the possible target population. However, one of these devices main advantages is their simplicity and easy adaptation to the user's capabilities. A button switch can be used by a user with hand motion control and a slightly different switch can be used, with the same interfacing scheme, dimensionality and input speed, by a user with head motion control (pressing the button with the cheek, forehead or chin, for example). Considering the most severe cases where no movement, or enough strong movement, is achieved, tongue interfaces appear as suitable solutions as even the most severe cases are able to control tongue movements.

Dimensionality and Input Speed The simplicity of the presented approach is generally reflected in the solution dimensionality and subsequent low input speed. Particularly, switches have a low communication bandwidth. The stick and pointer solutions (whether by head, mouth or tongue) represent an increase in the selection set and input speed but still have reduced performance.

Accuracy, Robustness and Repeatability In general, the approaches described in this chapter are accurate and robust as they normally depend on direct contact with a certain surface.

Ease of use Upper limb and head solutions are generally easy to use and no major problems have been reported in the surveyed projects and products. Although not naturally used for pointing, the tongue is constantly performing sophisticated motor control for swallowing, mastication or vocalization and can therefore be seen as a good control interface. However, in a first approach the user may feel some difficulties. Moreover, if several movements or points are defined there are no mnemonical or visual cues to ease interaction.

Aesthetics, Hygiene and Acceptance Tongue approaches have some hygienic, ergonomic and aesthetics issues. While a regular use of the device can harm the user's mouth, the solution aesthetics is prone to be rejected by the user if there are visible components out of the mouth. Also, speech can be complicated by the mouthpiece. However, if we consider in-mouth wireless solutions, the aesthetics issue disappears.

Mobility Adequacy The solutions surveyed in this chapter are quite independent from ambient shifts. The only requirement for the majority of switch, stick and pointer-based approaches is the distance between the user and the device as they must be within reach. Thus, whether in a wheelchair, whether in a bed or table, if the device is in an adequate position, control is achieved as solutions are not influenced by illumination, air flows or any electromechanical interference.

2.2.2. Sound-Based Interfaces

A conversational computer, a machine we could start a conversation with, has always been a dream (Cohen and Oviatt, 1995). The naturalness of speech between humans, its usefulness in eyes/hands busy situations and independence from other motor channels greatly motivated its study as a promising interaction modality. Considering disabled users, speech-based interaction can be truly useful as it maybe the only remaining mean of natural communication left, it requires no physical connection, it has high dimensionality offering maximum degrees of control freedom and it can be adapted to suit the user's needs and scenarios (Noyes and Frankish, 1992; Damper, 1986).

Several severe spinal cord injured individuals detain speech capabilities and therefore its use as an input mechanism is potentially advantageous. It is also important to notice that speech-based interfaces can go beyond its intelligibility. Considering a speaker-dependent speech recognition system (trained to a specific user) and its consistent use, the scope of possible users increase as consistent speakers, although not intelligible to other humans, can control applications, satisfying the requirements for the human-computer communication(Noyes and Frankish, 1992).

Speech-Based Interfaces

One of the main advantages of speech input is its high dimensionality. Considering the interfacing schemes classification (Damper, 1986), speech-based interaction is consistent with a direct selection or an encoding scheme, if one wants to reduce its vocabulary. Scanning schemes are not suitable with speech interactions as they are a waste of its dimensionality and degrees of control freedom.

Computer Control

The keyboard and mouse pointing devices are still the most widely used input devices by individuals who are able to achieve their control. It is therefore expectable that alternative interfaces for the disabled person try to replace these devices by emulating their functionality (Sears et al., 2001), offering the users transparent access to available software. The keyboard with a limited number of possible actions calls for direct selection or encoded interfacing scheme which suits perfectly with a speech-based interaction as its high dimensionality permits a natural mapping. In contrast, cursor emulation involves a continuous control that is still a challenge when considering speech interaction.

(Dabbagh and Damper, 1985) described two different speech speaker-dependent approaches to ease text composition by a motor disabled user. One of the systems was based on direct selection of letters and common words while the other is based on an encoding selection of letter-sequences (graphemes). Their first approach is very simple and maps every single character in a keyboard with its "name" enabling the user to select a key by speaking it. The authors proposed the use of the Pilot's Alphabet (i.e., Alpha, Beta, Charlie,...) which increases the recognition rate but also increases the cognitive load to issue a command. To improve performance, the authors also included some high-frequency words in their vocabulary, which was considered high (70 words) and was therefore structured in several subsets that can be selected. Considering the recognizer's limitations, the authors also developed a system featuring encoded selection and subsequently a smaller vocabulary. The system is based on a matrix of elements where the users select one element by speaking its row and column number. In contrast to previous works where the matrix is composed by single characters, Dabbagh and Damper's work featured a matrix composed by graphemes aiming at higher text composition performances. When comparing their systems, the direct selection scheme performed better although presenting a higher error rate. (Su and Chung, 2001), following the same transparent keyboard and mouse emulation principles, included mouse function commands(up, down, left, right, clicking, double-clicking, right clicking and dragging) and, considering a traditional keyboard, 104 commands [1]. To reduce the number of possible commands, the authors also adapted a matrix displacement requiring two utterances to select a character.

Cursor control is highly problematic when considering speech interaction due to several issues: recognition errors, delays and the mismatch of interaction schemes (Dai et al., 2004). It is generally accepted that speech is not optimal for naturally controlled continuous applications. Therefore, the few projects on cursor control presented in last few years had little or no success. However, there are several speech-based cursor control solutions that seek to overcome these problems and limitations and can be categorized either as target-based or direction-based. A target-based solution is one where the user identifies the desired location, whether a word, an icon, a menu or a region on the screen. As the number of targets increase, target-based solutions become more error-prone. *Problems include users having difficulty remembering the names of the targets, multiple targets having the same name (...), and increased recognition errors as the vocabulary increases* (Dai et al., 2004). Moreover, target-based solutions are not effective to position the cursor anywhere on the screen.

In a direction-based solution the user specifies the direction and distance creating a continuous or discrete movement (i.e., "Move Left two pixels" or "Move Left" followed by a "Stop" to limit the cursor movement). Although better than target-based approaches when considering cursor control, direction based solutions are also limited when the targets are far from the current cursor location and also face some accuracy issues when cursor speed increases due to spoken input delays. (Karimullah and Sears, 2002) tried to overcome this problem suggesting the use of a predictive cursor, based on known recognition delays that would increase performance and decrease error rates. However, the predictive cursor failed to prove beneficial. (Dai et al., 2004) explored the potential of a grid-based target-based cursor control solution where the user recursively selects a cell until he achieves the desired target with encouraging results.

(Manaris et al., 1999) presented results on a user interface model for providing access to computing devices (mobile or not) through a continuous speech speaker-independent engine. Their system, called SUITEKeys also provides a one-to-one mapping between user utterances and keyboard/mouse operations, *such as pressing/releasing a key and mov-*

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[1] Also known as the *Windows* keyboard, the 104-key keyboard is a keyboard found with most new computers today that incorporates three additional *Microsoft Windows* keys

Say one or more numbers, then say click

Figure 2.6: Windows Vista Speech Recognizer

ing a cursor to a certain distance/direction. The authors claim that *although speech is not the best modality for all human-computer interaction tasks, when delivered at the level of keyboard and mouse it allows for universal access to computing devices* (Manaris et al., 2001).

In the last few years, although speech recognition is evolving, there has not been great advances considering computer control. Recent operating systems (i.e., Microsoft Windows Vista) provide speech control capabilities but its use is still reduced, similarly to what we have been witnessing with mobile devices. It is interesting to observe that the recent accessibility package provided by Microsoft in the latest operating system Windows Vista gathers several of the surveyed control approaches, including grid-based mouse control (Figure 2.6).

Wheelchair control

There has been some research on speech wheelchair control which was pioneered by (Youdin et al., 1980). (Mazo et al., 1995) describe a wheelchair developed at the U.A.H (Universidad de Alcalá de Henares) Electronic Department controlled by voice commands with a set of only eight oral commands relative to eight functions: stop, forward, back, left, right, plus, minus and password. However, the control words attached to this functions are user-dependent and the only condition is that the sounds associated with each function are consistent every time. The ”password” function when pronounced stops/starts the recognition of other commands so the user can engage conversations where control words can appear. The response time of the system is of 0.3-0.5 seconds and present a recognition rate of 90% (with maximum noise level of 90dBA). The authors state that the system was ”successfully” tested with disabled users, even with vocalization problems, achieving wheelchair control ”in an easy and comfortable way”.

Although some other voice controlled wheelchairs appeared in the last few years, *voice control has proven difficult to implement within a standard power wheelchair* (Simpson et al., 2002). Safety considerations make fast and accurate responses essential and no speech recognizer can offer this kind of certainty. To deal with this problem (Amori, 1992) limited the time range of all the commands arguing that momentary commands were less likely to produce collisions or inadequate movements while (Simpson et al., 2002) combine voice control with a set of twelve sonar sensors that identify a safe path of travel. These solution, as others following the same ideas, using Ultra-sound or Infra-red proximity sensors, are yet to be proven as totally complementary to speech towards a secure control.

Environmental Control

In contrast, the tasks involved in control of the domestic environment (with the possible exception of alarms and emergency communications) are essentially non critical in terms of safety. Nevertheless, some speech environmental control systems contemplate mechanical emergency switches, if any malfunction occurs (Carvalho et al., 1999).

(Damper, 1986) proposed a voice-based approach to environmental control. The interaction scheme is structured as a two-level encoding selection in which the user identifies the appliance and, in a second phase, the desired action (i.e. <Lights ><off >). The presented approach tries to replace and overcome previous environmental control systems based on scanning schemes and electromechanical switches. The authors state that a direct selection scheme could have been employed (i.e. <lights_off >) but only with more sophisticated word recognition techniques.

(Jiang et al., 2000) described a voice-activated environmental control system to aid persons with severe disabilities. The proposed system provides voice control of household electronic appliances through *via the X10 protocol transmitted through both a radio frequency channel and household electrical wires*. The recognizer handles 20 different phrases each of them with 1.92s in length. The user must pause between the words spoken. Jiang et al.'s system is advantageous over other voice recognition approaches due to its low cost: it is based in a voice recognition chip, dismissing the need for a PC or a laptop. Also, the size and lightweight of the system make it really portable.

Non-Verbal Voice Interfaces

(Igarashi and Hughes, 2001) state that *traditional speech recognition interfaces are based on an indirect conversational model*. Although the authors think that speech interaction is suitable for tasks like flight reservations, they also argue that an approach to handle more direct interaction is required. Igarashi and Hughes proposed the use of non-verbal features in speech like pitch, volume and continuation to control interactive applications.

(Olwal and Feiner, 2005) also use prosodic features of speech as rate, duration and volume, as well as audio localization to control interactive applications. The authors developed a speech-based cursor control system using non-verbal features and the user's position. In the first approach the user controls the direction by issuing speech commands (left, right, up, down) and controls the cursor speed with the speech rate while in a second approach, the user controls direction by leaning to the left or right (audio localization).

The Vocal Joystick (VJ) (Bilmes et al., 2006) makes use of vocal parameters to control objects on a computer screen (buttons, sliders, etc..) as well as controlling mouse movement. This system goes beyond the capabilities of sequences of discreet speech sounds and explores other vocal characteristics such as pitch, vowel quality, and loudness which are mapped to continuous control parameters. Although several characteristics are to be explored, actually the authors extract *energy, pitch and vowel quality,* yielding four simultaneous degrees of freedom. Localized acoustic energy is used by VJ mouse application to control the velocity of the movement as vowel quality is used to select directions. Presenting the same motivation as Vocal Joystick and considering speech recognition flaws, Sporka et al. (Sporka et al., 2006) developed a system for controlling the mouse pointer using non-verbal sounds such as whistling or humming. This can be done in two modes: orthogonal, where the pointer, based on the initial pitch, is moved either horizontally or vertically, varying speed accordingly to the difference between current and initial pitch; and melodic mode, where the cursor moves in any direction with a fixed velocity (or idle). The direction of motion is dependent on the pitch of the tone. Left button click is emulated in both modes through a short tone.

Aural Flow Monitoring Interfaces

An interface capable of controlling devices in response to tongue movements and/or speech using the unique properties of the human ear as an acoustic device was presented by (Vaidyanathan et al., 2006; Vaidyanathan et al., 2007). This bi-modal interface makes use of changes in air pressure and sound waves (vibrations) in the ear to control a powered wheelchair. The authors rely on the fact that particular movements of the tongue and speech produce traceable pressure waves with strength corresponding to the direction, speed and/or intensity of the action. These waves are collected with a microphone, similar to a earplug hearing device, introduced in the user's ear (Figure 2.7).

One of the great advantages of the system when compared to traditional speech-recognition devices is the enormous noise reduction as no external activity is gathered. The authors defined four tongue movements and seven monosyllabic words (up, down, left, right, move, kill, pan) and tongue movements were observed to be faster, quieter and easier to the user for direct motion device control. On the other hand, speech requires less calibration and training and has higher dimensionality. Although very promising, we are still not sure about the scalability of the system considering the number of commands and

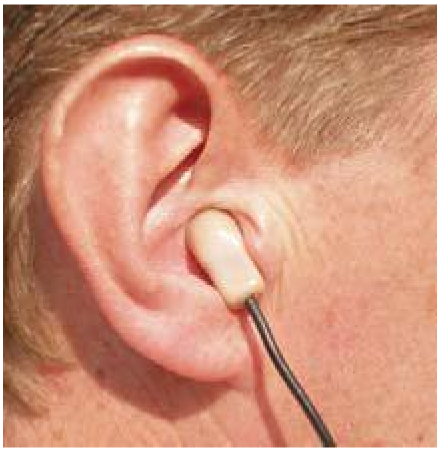


Figure 2.7: Earplug

word length. Using a similar setup (ear microphone), (Kuzume and Morimoto, 2006) research the tooth-touch sound as an input mechanism. The authors analyze the tooth-touch sound characteristics (amplitude, central frequency, period between sounds, duration), using a bone conduction microphone, which can be placed, if stable, anywhere in the head. Two approaches were discussed: ear microphone or an headset. The authors selected the ear microphone, gathering vibrations in the auditory canal. The prototype still insufficiently suppresses body movement noise.

Discussion on Sound Interaction

Besides the works presented, in the last few years we have witnesses the widespread appearance of speech recognition devices both in personal computers and mobile devices. However, although the technology is widely available, its use is still reduced, mostly due to social constraints and low recognition levels in noisy environments (Gamboa et al., 2007). This fact is also true for disabled users. Considering the technology characteristics and the study of its application as an assistive technology we can now analyze its advantages and disadvantages on the pre-determined focus points:

Potential users range Individuals with lesions above C3 typically lose diaphragm function and require a ventilator to breathe. This impairment can therefore make difficult or impossible for the impaired user to communicate. However, speaker-dependent recognizers can deal with speech that although not intelligible, is consistent, increasing the scope of possible users. On the other hand, it is important to consider that even below C3 lesions can, and normally do so, damage breathing function and reduce voice strength, hence limiting the interaction, specially considering the distance to a microphone.

Dimensionality and Input Speed One of the main advantages of speech input is its high signal dimensionality: assuming the user has normal speech, the number of possible issued commands is limited only by the size of vocabulary the recognizer can handle without an unacceptably high error rate.

Accuracy, Robustness and Repeatability Although research in this area has been active for many decades, robustness is still a key issue that should be considered. Despite significant research efforts in automatic speech recognition, existing ASR systems are still not perfectly robust to a variety of speaking conditions, noise and accented speakers, and they have not yet been universally adopted as a dominant human-computer interface (Bilmes et al., 2006).

Ease of use Speech can be argued to be a natural form of communication. However, although spoken language is effective for human-human interaction it often has severe limitations when applied to human-computer interaction (Shneiderman, 2000). The supposed interaction naturalness can possibly be translated in inappropriate expectations by the user (Damper, 1986) which results in a lack of interaction consistency, required for human-computer communication. Also, considering cognitive load, it is harder for an individual to speak and solve a tough problem, as the activity is handled in the same part of the brain, than to control a mechanical switch and think ate the same time (Shneiderman, 2000).Another limitation on speech interaction is its inadequacy to direct low-level controls, such as scrolling. Continuous interaction as well as any WIMP-based interaction is difficult to cope with speech interfaces (Igarashi and Hughes, 2001).

Setting up a voice based system has no difficulties which can be a great advantage for the impaired user and caretakers.

Aesthetics, Hygiene and Acceptance Considering aesthetics and hygiene, speech-based interaction is an optimal choice. There is no contact between the hardware and the user and due to microphone size and its availability in any regular mobile device it can be totally unnoticeable.

On the other hand, user and social acceptance is compromised. Privacy concerns arise and it is almost impossible to accept voice-based interfaces as suitable for public interaction.

Mobility Adequacy Speech-based interaction offers the promise of greater user mobility. This is true for an indoor environment with a personal computer and a fixed microphone as for an outdoor environment, using a mobile device. However, considering mobile scenarios voice-based approaches face several challenges as the recognition decays with additional noise.

2.2.3. Gaze and Motion Tracking Interfaces

There have been several approaches to control electronic devices, specially the mouse pointer in a computer, whether by head movements, eye movements or other body move-

Figure 2.8: Example of Electrooculographical Interface

ments with less population coverage but wider control capabilities. These approaches try to use more information, either from the visual line of gaze, head direction or other body part, to enrich the dialogue between the user and the computer (Jacob, 1993; Jacob and Karn, 2003). Although with the same purpose, the interfaces surveyed in this section are quite different and go from electromechanical approaches (electrooculography) to video appearance based interfaces.

Electrooculography

Electrooculography (EOG) is a technique for measuring the resting potential of the retina. Its main applications are in ophthalmological diagnosis and in recording eye movements.

Usually, pairs of electrodes are placed either above and below the eye or to the left and right of the eye. If the eye moves from the center position towards one electrode, this electrode ″sees″ the positive side of the retina and the opposite electrode ″sees″ the negative side of the retina. Consequently, a potential difference occurs between the electrodes. Assuming that the resting potential is constant, the recorded potential is a measure for eye position.

The ability to detect eye movements through head-mounted electrodes lead to the appearance of EOG device control interfaces. This approach is very interesting given that it is less expensive than reflectance eye-tracking interfaces and does not require a determined steady position as most tracking approaches do. The drawbacks of EOG-based interfaces are mainly aesthetic (Figure 2.8), although there are other disadvantages like the lack of accuracy on some eye-movements detection.

Computer Control

In 1990, (LaCourse and Hludik, 1990) presented DECS, discrete electrooculographic control system, a communication tool for persons with disabilities. As with other eye-movement based techniques, the authors justify the need for DECS with the slow response times and motor coordination required for the adaptive switches and scanning devices available. DECS relies on small eye movements both in horizontal and vertical directions. *A target is selected by staring at it for a preset length of time*. LaCourse and Hludik argued that DECS is a potential input for wheelchair, environmental, computer and communication devices control. On the other hand, the authors focused their efforts on the accuracy of the system and no practical results in those interaction scopes were presented.

(Kaufman et al., 1993) also presented an EOG interface stating it as an inexpensive and non-intrusive system. The system detected eye movement but also *eye-gestures*, such as left and right winking, blinking and types of movements (saccade, smooth pursuit). Users tests on menu selection (3*2 boxed menu, two-level menu) were performed with two experienced users achieving a 73% accuracy rate on menu selection. The authors stated that the error rate was mostly related with head and muscle movement interference, signal drift, and channel cross-talk. However, they also argued that considering applications where a rough resolution is used, such as driving a wheelchair (ex: forward, left, right, stop), head movements are negligible. Although it is true that reducing the possible actions also reduces the error rate, one must consider that an interface to drive a wheelchair requires high certainty and accuracy rates.

Several EOG control systems rely on direct mapping between the eye and cursor position. However, these systems must incorporate sophisticated instrumentation and software to null out the DC artifact always present due to variations in skin thickness, skin conductivity, electrode placement and electrode gel drying. Also, direct mapping systems need complex calibration procedures to assure the correct alignment of eye direction with cursor position. The Eye Mouse (Norris and Wilson, 1997) overcomes the unreliability and cost stated above with a joystick-similar approach. Therefore, if the user wants to move the cursor in a certain direction it is only required that he diverts his gaze 30º in that direction for half a second. The cursor continues the movement until the user blinks twice. Once it is stopped, two blinks will produce a single-click while three blinks will produce a double-click. Single blinks are ignored as they are commonly unintentional.

One of the most relevant disadvantages on electrooculography is the baseline drift that obscures eye-movement signal. To overcome this issue (Patmore and Knapp, 1998) investigated the use of the electrooculogram and visual evoked potentials (VEP) (Chapter 2.2.5). The authors use a two-phase approach to detect and cancel EOG drift where the first level uses the EOG signal first and second derivatives to measure drift and VEP to discriminate between static eye gaze and moving eye gaze. Thus, the computer cursor presents a flashing stimulus causing a high response when the gaze is directed at the pointer location and a null or soft response when the alignment is lost. When the system is misaligned with the user's gaze, a reacquisition algorithm is applied.

Another major issues concerning EOG-based interfaces is the necessary awkward setup prone to be rejected by the user but also, due to the setup complexity, the error rate in-

Figure 2.9: Headphone EOG interface

crease related to electrodes slippage. (Kwon and Kim, 1999) developed an EOG-based mouse focusing on user's convenience. Thus, the electrodes are positioned in five particular points on a glasses frame assuring good contact and requiring no electrolyte gel. Also, the authors use a microcontroller that estimates direction, amplitude, detects blinks and communicates the estimated information with a PC. The authors state that the users can control several Windows functions and play Tetris (right, left, up, down) after a training session of a few minutes.

(Manabe and Fukumoto, 2006) developed a headphone-type gaze detector which relies on the analysis of multiple EOG channels measured at the location of headphone cushions (Figure 2.9). The authors aim at a full time wearable interface, easy to wear, easy to use and that can be available whenever desired. The proposed system aims at cosmetic acceptability and to eliminate user's field of view limitation but other problems arise: low Signal-to-Noise ratio as the electrodes are far from the signal source; separation between vertical and horizontal components as the electrodes are placed near the ears in opposition to traditional approaches where the electrodes are placed above and below and right and left to the eyes.

Wheelchair Guidance

(Barea et al., 2002) implemented a wheelchair guidance system based on electrooculography. It consists of an electric wheelchair with an on-board computer, sensors and a graphical user interface. Besides studying an eye position model with good accuracy (less than 2^{o}), the authors devoted some effort on wheelchair guidance strategies developing three different interfaces: direct access guidance, guidance by automatic or semi-automatic scanning techniques and guidance by eye commands. Considering direct access guidance, the user controls the wheelchair by positioning a given cursor over the desired action button displayed on the graphical user interface and then validating his action. The authors are aware of the problems underlying this approach namely the fact that the human eye is always on and therefore prone to issue undesirable commands but also that the screen has to be in the user line of sight thus limiting visibility (this problem has greater significance with users that cannot move their head). The scanning guidance mechanism is aimed at users with little precision in their eye movements and it is based in a screen showing several commands that are scanned, whether automatically or semi-automatically, and can be selected by an action or only a given period of time. It is important to notice that although not requiring a precise aim at a target this approach still requires the user to look at the graphical interface limiting the guidance. The authors developed a third method, guidance by eye commands, that maps some eye movements to commands. Therefore, the user no longer needs to select an action within the graphical user interface. Although no extra display is required, this method still shows some problems as user involuntarily movements can be misjudged as commands and, on the other hand, a correct manipulation of the system certainly restricts the user ”looking freedom”.

Overall, eye-movement wheelchair guidance has several obstacles regarding involuntarily movements and safety but also voluntarily movements as the user still needs to see the surrounding environment.

Head Optical Pointers

An Head Optical Pointer is a device similar to the physical head pointing device (Chapter 2.2.1) but in this case the headpointer detects the raster scan of the computer display and calculates the position at which the user is pointing, similar to a lightpen (Hamann et al., 1990). Therefore, the physical interface is replaced by a beam (normally infrared or near infrared light). For instance, (Vanderheiden and Smith, 1989) present an approach where a keyboard image is displayed on one television screen and selection is realized through a long range optical pointer while the normal computer output is displayed on a second screen.

People with good head control can use an head pointing device to move a cursor on the screen or to point at a surface with photodetectors (i.e., a special keyboard). On the other hand, mouse selections can be made using an external switch (i.e., sip-puff switch). However this device fusion is error prone as the extra effort to activate the switch often causes the head to move.

As an example, *Lomak (Light Operated Mouse and Keyboard) is an input system that uses a light pointer affixed to the user's head or hand (Figure 2.10)*. Data is entered into the computer by aiming the light beam at the accompanying keyboard's rotary-style letter and number pads.

Figure 2.10: Light Operated Mouse and Keyboard

(Chen et al., 2007) presented an infrared-based home appliances control consisting of an infrared and low power laser transmitter mounted onto the eyeglasses and a board with infrared receivers (Figure 2.11). The system is focused at users with neck rotation movements and enables them to operate several home appliances by pointing at the desired ”device” and selecting, using a puff switch to turn the IR emitter on and off.

Figure 2.11: Infra-red home appliance control system

Within these systems and on gaze-tracking applications, simple pause or dwell time is a common technique to emulate single mouse click (i.e., select characters in an on-screen keyboard.). To accomplish a certain selection, the user holds the pointer over a target for a predetermined amount of time. Other actions (like double-click, left-click and drag) are commonly achieved by selecting the mode in a configuration area. This method enables users to fully achieve mouse emulation control although requiring several extra configuration movements (change between modes) and pause intervals.

(Hamann et al., 1990) propose a switchless selection approach based on head gestures (nod and shake) where several intentions are differentiated through a combination of pauses, head nods and head shakes. It expands the simple pause and button-based configuration to improve performance. Multi-level pauses are used to differentiate several single button actions as head movements are used to emulate other buttons and to accelerate selections. However, the complexity of the multi-level approach causes some confusion and the state feedback mechanisms should be further studied.

Reflectance-Based Tracking

Tracking the user's eyes and/or face has long been a research issue as this information can be useful in several scenarios. While gaze-trackers present large costs to the normal user, other less expensive approaches have been proposed. Therefore, although we can find some research projects and commercially available gaze-trackers they are mostly used within companies, namely to perform usability studies. However, some approaches rely on the same reflective principle, where a surface is illuminated with infra-red light and the desired position is tracked using the reflection surface.

Head Tracking

One reflective approach to track the user's head requires him to wear a small, reflective target on his forehead or on a glasses frame. In these kind of systems, the camera includes an illumination (infrared or near-infrared light) module targeted at the user's face. The approach is significantly easier and requires lighter processing as the camera only has to track the reflective dot. Also, the reflective dot is a small overhead as it is barely noticeable. The HeadMouse from Origin Instruments and Tracker from Madentec are commercial examples of reflective head tracking devices (Figure 2.12).

(a) Head Mouse^{TM} (b) Reflectance dot (c) Tracker^{TM}

Figure 2.12: Infrared Reflectance Tracking Devices

Gaze-Tracking

Gaze-tracking interfaces consist on a camera focused on one or both eyes. Most modern eye-trackers use contrast to locate the center of the pupil and use infrared and near-infrared light to create a corneal reflection (the video image is analyzed to identify a large bright circle (pupil) and a brighter dot (corneal reflection) and compute the center of each: the line of gaze is determined by these two points). Depending on initial calibration, the vector between these two features can be used to compute gaze intersection. Gaze tracking setups vary greatly; some are head-mounted, some require the head to be stable (for example, with a chin rest), and some function remotely and automatically track the head during motion.

As an example, MyTobii P10 is an integrated eye-controlled communication device, composed by a 15” screen, eye control device and computer (Figure 2.13). The authors argue that it can be used on a desk, wheelchair, bed and it is robust to large head movements, glasses use, eye color or light conditions. There are other similar approaches like Erica Eye Tracker TM, which can be bought with several additional products from keyboard emulators to environmental control appliances. The packages developed can therefore offer the user several devices’ control, which augments the system success.

Figure 2.13: My Tobii P10 TM

In opposite to traditional IR detectors that explore both eye-wink and eye-position, The Eye Wink Control Interface (EWCI) relies only on eye winks, therefore avoiding sacrificing head motion or speech (Shaw et al., 1990). The system enables device control through eye winks of varying length. The system is based on an IR emissor/detector combination both clamped on the earpiece of a normal pair of eyeglass frames (Figure 2.14). When the lid is closed the reflection will be weaker (more absorbent than the sclera) thus a threshold can be established between open/closed states. Although possible wink durations can be established, the authors presented a simple approach with 4 states where each eye can be winked, both can be opened or both simultaneously winked (reflexive winks are excluded by analyzing wink time). User evaluations on maze navigation with fully-capable individuals showed that the users were capable of issuing commands and remembering control sequences while still able to move their head and speak.

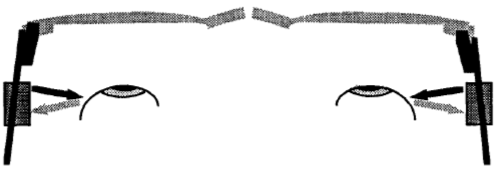


Figure 2.14: Eye Wink Control Interface

Appearance-Based Tracking

Although reflectance-based techniques take advantage of the eye and gaze direction, most of the solutions still require wearing extra instruments, such as infrared appliances, headset with cameras among others. Also, Infrared-based devices are generally expensive. Thus, thanks to the advances in the field of face recognition and computer hardware, appearance-based techniques have appeared in the last few years. These are characterized by the use of simple USB cameras that track a pre-determined feature in the user's body (normally the face) (Chen, 2003).

Face Tracking

The CameraMouse (Gips et al., 2000) tracks selected body features (i.e., nose, lips, eyes, finger, foot) with a video camera and uses the selected feature to directly control the mouse pointer on a computer (Betke et al., 2002). Selection is based on dwell time (automatic click after stopping the pointer for a predetermined pause time length). Several features are available to be chosen which offers a great variability considering target users. Also, the system requires no calibration (just feature selection) nor any body attachments which extends its usability and user acceptance.

Face tracking interfaces face several problems namely regarding position and orientation shifts, lightning variations as well as complex backgrounds. (Chen, 2003) presents a real-time face recognition approach focusing on robustness considering the refereed issues. The system uses a simple USB digital camera and uses eye and lip position as mouse control features.

Considering the precision required for direct *what I look is what I want* paradigm and the possible lack of ability within the target population to aim at a target, (Perini et al., 2006) developed the Face Mouse, an appearance-based tracking interface that uses a derivative paradigm (*"where I look is where I want to go"*). Hence, the user can interact with the computer even if his movements are spastic or not precise. (Perini et al., 2006) use a semi-automatic feature selection as this task is performed by an operator, trying to eliminate the reduced robustness directly connected with automatic feature selection methods. The nose tip is argued by the authors as a good feature and the interaction is realized through a 3x3 grid-based interface, whose size can be adapted considering the user's difficulties and capabilities.

The Facial Mouse (Granollers et al., 2006) is a user-independent mouse emulator system also based on the user facial movement, using a regular USB camera. However, besides dwell clicks, the user can generate mouse clicks through sound emission or even by using an external click (an extra switch used to that special purpose).

Pointing, Gesture and Motion Tracking

Besides face and head-tracking approaches, there are other vision-based approaches that explore other possible residual capabilities. For example, users with upper limb function can point at a certain target or issue a command through predetermined gesture. Also, the capacity to move or occlude objects can be used to replace touch switches, alternative mice and joysticks.

(Granollers et al., 2006) presented the WebColor Detector, a software package able to detect in real-time the presence or absence of a distinctive color and to track its position. This project focus on the emulation of switch, joystick and mouse functions through the manipulation of color markers (requires previous color selection) attached to a surface or the user's body. The switch functionality is very simple and can be performed whether by using a static marker where the user has to cover or uncover the marker when he wants to perform the action, whether by using a dynamic marker where the user must move a body part that has mobility (with the sticked marker) until it appears or disappears in the image. Mouse movement emulation is performed using the dynamic marker approach as moving the marker also moves the pointer in the screen while mouse click can be performed with dwell click technique. To emulate a joystick a 3x3 matrix is presented in the video window. Each cell represents a direction and the central cell represents the click.

(Do et al., 2005) developed a soft control system for the "Intelligent Sweet Home" where the user points at the device he wants to control and commands the device using predefined hand gestures and hand motions (Figure 2.15). Although the system requires large upper limb capabilities, the gestures can be personalized and suited to the user's abilities. The system is composed by three ceiling mounted zoom color cameras targeted at the user.

Inertial sensing is another method to retrieve information on user movements. Therefore, an accelerometer can be placed on a body area the user has control of and use the movement as a command launcher. (Chen, 2001) designed another head-operated mouse but employing two tilt-sensors placed in a headset to determine head position. As one tilt sensor detects lateral head motion (left-right displacement), the other detects head's vertical motion (up-down displacement). To ensure mouse function completeness a touch

Figure 2.15: Soft Remote Control System

switch was included to perform single clicks.

Ultrasound Interfaces

Ultrasound technology was originally developed as sonar to track submarines during World War I. It was first used medically in the 1950s and it is considered very safe. It is a cyclic sound pressure with a frequency greater than the upper limit of human hearing. It is typically used to penetrate a medium and measure the reflection signature or supply focused energy. The reflection signature can reveal details about the inner structure of the medium. The most well known application of this technique is its use in sonography to produce pictures of fetuses in the human womb.

Considering human-computer interaction, the ultrasound can also be used as a tracking mechanism. Actually, if one has a receiver and a transmitter, the distance between them can be estimated, if the ultrasound is regularly emitted.

The HeadMaster Plus$^{\mathrm{TM}}$is a device similar to the IR reflectance based approaches (i.e., HeadMaster$^{\mathrm{TM}}$) but instead of the reflection dot, the user wears a headset with three ultrasound receivers while an emitter is placed above the computer screen. Head orientation is determined according to the distance gathered in the three receivers. The computer cursor moves across the screen as the user turns head up, down, left, or right.

Researchers at the Palo Alto VA and Stanford University have developed a device to control wheelchair movement by head position. Two ultrasonic sensors monitor head position, and other sensors detect obstacles and walls to the side. In operation, the user controls forward movement and turns by moving his or her head in the corresponding direction. Obstacles are automatically avoided. A ”cruise control” feature is incorporated, and in the automatic mode the chair can travel parallel to a wall or other guide without user intervention (Jaffe, 1982; Ford and Sheredos, 1995). (E. D. Coyle and Stewart, 1998), motivated by the research undertaken by (Jaffe, 1982), investigated several hardware and software adaptations to improve the ultrasound control unit. Besides wheelchair control, the authors researched the ultrasound control unit as input for keyboard typing and mouse emulation. Also, the author studied a particular Graphical User Interface system, a Telephone Pad, which enables motor disabled individuals to work as telephone operators but also to use it for personal purposes (communication, help mechanism).

(Lukaszewicz, 2003) presents an approach based on the recognition of ultrasound images obtained from the bottom part of the chin to keep track of the tongue movement. Although the authors aim at speech recognition for the mute, the early results are quite limited to that purpose but, on the other hand, is suitable for wheelchair control or mouse emulation. Moreover, the authors presented results where eight tongue movements can be distinguished. (Huo et al., 2007) presented a similar system but instead of ultrasound technology, magnetic tongue tracking is used. In this case a permanent magnet must be placed in the tongue while sensors must be placed outside of the mouth (the authors used a baseball helmet).

Discussion on Gaze and Motion Tracking

Tracking residual movement on the user's body (including eye movement) is a widespread computer access approach. There are several commercial products across the several areas surveyed in this chapter. We analyze their main advantages and disadvantages considering:

Potential users range The target group for eye-based interaction is quite large. Actually, besides brain control, eye-based interfaces are one of the approaches that gather a wider number of possible users as only eye-control is required. Therefore, even individuals with C1/C2 impairments are candidate users, whether using simple eye-wink interfaces (if capable of winking) or eye-mouse control interfaces (if capable of full eye motion). However, although the majority of spinal cord injured users are gaze-tracking possible users, sometimes that is only possible with some extra aid mechanisms, like a chin rest to guarantee stability. Naturally, approaches based on head motion require an higher control degree (below C3 impairments).

Dimensionality and Input Speed Gaze-tracking and body-tracking approaches try to provide the user with a direct selection method. Therefore, if control is achieved, the user can control the pointer and through it achieve direct keyboard selection (using an on-screen keyboard) and event control directly other applications. On the other hand, there are some relative approaches that have decreased input dimensionality and therefore lower speed (i.e., EOG joystick, Ultrasound Head Controller,...).

Eye movement input is faster that any other input media as before the user operates any mechanical device, he usually looks at his destination target (Jacob, 1993). However the doubt lingers if it should be used to directly select or as an auxiliary interface serving as an indicator.

Accuracy, Robustness and Repeatability One of the most common application of a computer interaction assistive device is the direct substitution of the mouse. Considering tracking approaches, several projects try to use the movement as a pointer direct controller (Evans et al., 2000). Moreover, the concept can be enlarged to wheelchair navigation.

Although gaze-tracking devices require an initial calibration and initially the system may be accurate, after a while the calibration starts to drift (Majaranta and Räihä, 2002).

Vision based approaches, although facing constant evolution, are still error prone considering position, orientation and illumination shifts while electromechanical approaches have a low signal to noise ratio, are sensitive to myographic and surrounding interferences.

Ease of use Although the tracking systems have evolved a lot and can be argued to be robust, there is some debate whether it makes sense to overload a perceptual organ by a motor task. On the other hand, gaze-tracking systems are very easy to operate as no training or particular ambientation is required (Evans et al., 2000).

The eye, the jerky way it moves and the fact that it rarely sits still present gaze-tracking approaches as inadequate to direct human computer manipulation (Jacob, 1993) . Moving the eye is almost an unconscious act and the user must change is attention focus to intentional use an eye-tracker as a mouse ("Midas Touch" problem). When using a mouse pointer we can look at several points without creating an action and the behavior is not possible in a gaze-tracking setup. Also, eye-movements are always on, and unlike mechanical devices, it is not possible to turn on/off the device (unless a switch is added). This problem is reduced when considering face-tracking as the user may be looking at the results but if the head is steady no further commands are issued.

Aesthetics, Hygiene and Acceptance Reflectance and appearance based tracking approaches have no issues regarding hygiene, aesthetics or user/social acceptance. In fact, eye and face tracking devices do not require any special setup and there is no discomfort for the user. On the other hand, the fixtures inherent to an electrooculographic approach can be very annoying, creating high mental and physical awareness, although actual discomfort is low (Shaviv, 2002). However, recent user interfaces using EOG (headphone-alike) try to overcome this issue improving the user experience. Nevertheless, a complex setup is still required with awkward electrodes location and a rather unaesthetic scenario.

Mobility Adequacy The research around image processing is still evolving and none of the presented methods is really usable in a mobile scenario. Actually, light variations, voluntary and involuntary movements and the dependence on a significantly large target screen are still obstacles to be surpassed. EOG approaches and eye-tracking glasses solve some of the above issues although the latter are still prone to light variations and miss-calibration errors.

As well, one of the major issues when considering mobility is the surrounding environment. Hence, considering scenarios where attention is required, eye-based approaches are inadequate as the required eye control is incompatible with the need to observe the environment.

2.2.4. Myographic Interfaces

Electromyography (EMG) is defined as the study of the muscular function through the analysis of the electric signals generated during muscular contractions. The potential difference obtained in the fibres can be registered in the surface of the human body through surface electrodes due to biological tissues conducting properties (De Luca, 1997; Correia et al., 1992).

Considering assistive technologies several EMG-based systems have been developed aiming at computer keyboard and cursor control, wheelchair guidance and environment control.

Computer Control

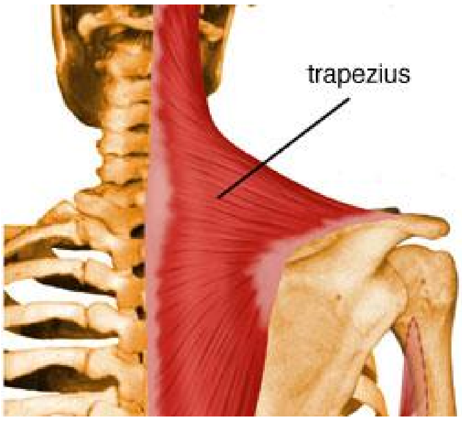
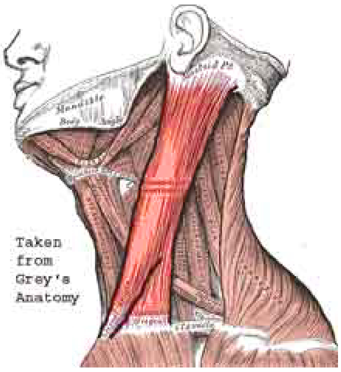


Figure 2.16: Trapezius muscle

In 1997, Tarng et al.(Tarng et al., 1997) presented a myographic signal controlled human-computer interface for quadriplegic users with C4 levels of injury or below. In this system, five electrodes are bilaterally placed on and between the upper trapezius (Figure 2.16) and sternocleidomastoid (Figure 2.17): for each pair of two electrodes, one is located over the sternocleidomastoid and the other over the upper trapezius; the ground electrode is located near the right earlobe. The subject is free to select five motions of head and shoulders and their recognition ratio is around 90%. With this system the user is able to control the mouse pointer (four directions and double-click) although the feature space and several parameters need to be adjusted before achieving a good classification ratio. The great advantage is that the user is able to select the motions to map with the actions. This was still preliminary work but a good motivation for several following EMG mouse pointer control interfaces.



Taken
from
Grey's
Anatomy

Figure 2.17: Sternocleidomastoid muscle

Park et al. (Park et al., 1999) suggested a single-switch EMG-based communication for disabled users with severe motor and speech impairments. The users operate this system by chewing with the masseter muscle achieving communication using morse-code through dots and lines, according to the contraction (chew) duration. The major limitation pointed out by the authors is the speed of the system, as disabled users sometimes are not able to chew and pause fast.

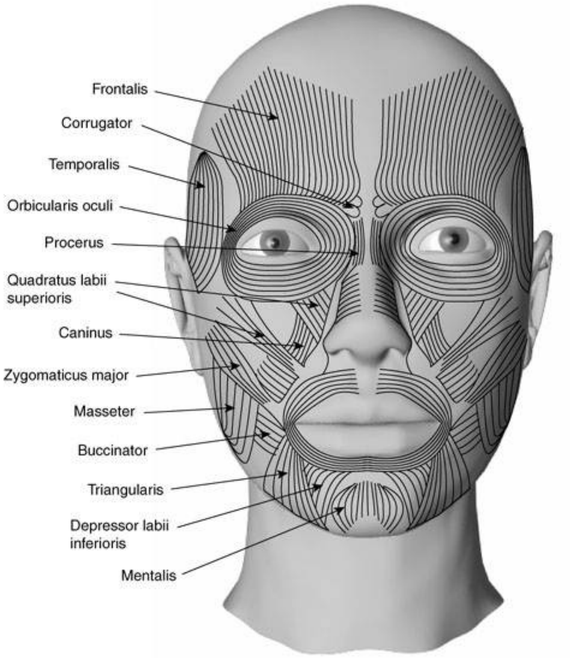


Figure 2.18: Face muscles

Aiming higher, Jeong et al. (Jeong et al., 2005) presented an EMG-based mouse control method for tetraplegics to operate computers by clenching teeth. Clenching actions were chosen due to the ease of acquiring relevant signal patterns and due to teeth clenching subtleness, considering social acceptance. The signal is acquired on the *temporalis* muscle (Figure 2.18) attaching electrodes to an headband (Figure 2.19) or a cap. The system requires a training stage where a Fuzzy Min-Max Neural Network is feeded with the Difference Absolute Mean Value at each channel. Two channels are recorded and four states are trained and further recognized with 95% accuracy: rest, left-teeth clenching, right teeth-clenching and all-teeth clenching.

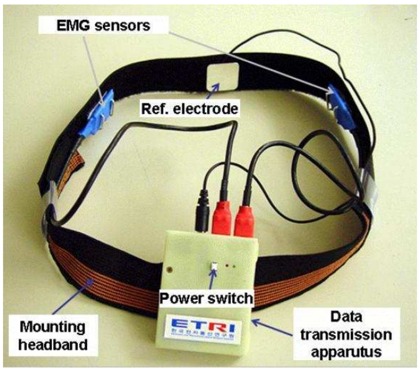


Figure 2.19: Jeong System Head Band

This system makes it possible for users to control the mouse pointer with this restricted set of clenching actions by using left-teeth (Figure 2.20 - [2]) and right-teeth clenching to adjust direction and using all-teeth clenching for moving the cursor in the selected direction and stoping (Figure 2.20 - [3 and 4]). Selecting a target (i.e. clicking on an icon) can be realized through double left-teeth clenching (Figure 2.20).

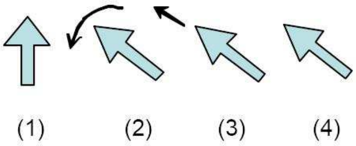


Figure 2.20: Jeong System Cursor Control Schema

The system can be used without disrupting the surrounding environment and without a large number of wires and electrodes.

HaMCos (Felzer and Freisleben, 2002a; Felzer and Nordmann, 2005; Felzer et al., 2005) follows the same principles focusing on EMG signals to control the mouse pointer. The system, although simpler and not so robust, is capable of detecting muscle contractions at any voluntarily contracted muscle group. Hence, HaMCos uses only one electrode and one muscle activation to issue commands, aiming at severe injured patients where other muscles could be out of control reach. The mouse pointer control relies on sequently wandering through the several possible states (left, right, up, down) and subsequently returning to STOP state. The user selects an action by contracting the monitored muscle when the system is at the desired state. Although more inefficient than other EMG approaches, it requires only one muscle group control aiming at a wider scope of users.

Felzer and Freisleben, HaMCos authors, developed a similar system but instead of using electromyography they used electroencephalography and instead of trying to decode the brain waves, they tried to capture movement-related bursts in the EEG signal (Felzer and Freisleben, 2002c). If EMG has greater amplitudes and signal to noise ratio than brain waves, why not just use it instead? - The authors rely on this rhetoric question.

Huang et al. (Huang et al., 2006) present an EMG human-computer interface focusing only on facial muscles (Figure 2.18): the facial mouse. Four electrodes are placed on face voluntarily contracted muscles and 7 mouse functions (left; up, right, down, single right click, single left click and double left click) are recognized. To detect the muscle activations this work adopts continuous wavelet transformation with a onset recognition rate greater than 80%. Each facial muscle activity maps a specific direction and the other actions are triggered with monitorized muscles activity combinations.

Wheelchair Guidance

The HaWCoS (Felzer and Freisleben, 2002b) project relies on the same principles as HaMCoS, applied to wheelchair guidance. With a single monitored muscle, the user can toggle between a set of events (left, right, straight and halt) and therefore control an electrically powered wheelchair. The system is presented, through user evaluations, as imposing an overhead of less than 50% when compared with a traditional joystick.

Han et al. (Han et al., 2003) also developed an EMG-based human-machine interface for wheelchair control focusing on spinal cord injured individuals, particularly with C4 lesions. Upon user tests the sternocleidomastoid muscle was chosen as the monitored muscle and actions are triggered by moving right shoulder up (right movement), left shoulder up (left movement) or both shoulders up (forward). Two modes were tested: in mode 1 the wheelchair goes forward while the user keeps the both shoulders up; in mode 2, "both shoulders up" action acts like a toggle which makes the wheelchair go forward or stop. Users preferred the toggle mode as it is less tiring

Moon et al. (Moon et al., 2004) present an interface for the above-elbow amputee or the lower extremities paralysis by C4 ou C5 spinal cord injury. Although they present several interaction prototypes including cursor control, their main concern is wheelchair guidance (Moon et al., 2005). The interaction basically consists of four commands also generated by three different shoulder elevation motions (left, right, both shoulders). EMG signals are collected in the Levator Scapulae muscles (Figure 2.21 - visible at upper right, at the neck), processed and onset detection is tested with predetermined double threshold values. The authors show, through user evaluation that electromyographic wheelchair guidance is feasible for wheelchair control. However the system still lacks robustness due to predetermined double thresholds not suitable for different individuals and different usage conditions.

Environmental Control

Chen et al. (Chen et al., 2002) developed an EMG-controlled telephone interface for people with disabilities by using row-column scanning and an EMG-based trigger pulse. The users can trigger a selection with a neck contraction. Although the system is very simple it is also adaptable for almost any spinal cord injured individual restricted only for those who aren't able to contract their neck muscles (above C3 lesions).

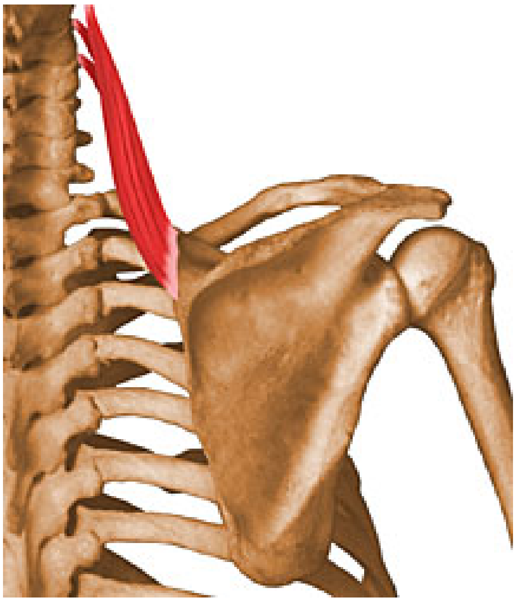


Figure 2.21: Levator Scapulae - Back view

Song et al. (Song et al., 2005) presented a system based on EMG signals to control the *Intelligent Sweet Home* which was developed to aid the living of the elderly and the disabled. It makes possible for users to control home-installed electronic devices using myographic signals with six wrist motions. In contrast to other projects reported in this document this system aims at users with wider range of control as they must be able to control their wrist consistently. Although powerful considering the scope of interaction and devices controlled this system restrings the target population.

Discussion on Electromyography

Although EMG-based interaction systems are not commercially available to the common user, we can verify its mature use in several medicine related areas. The major drawback on electromyographic interaction is the complex setup required. On the other hand, using surface electromyography it is possible to detect muscle onset and therefore associate events with pre-determined contractions or movements. As for evaluation criteria, we can summarize as follows:

Potential users range The number of voluntarily contracted muscles is large creating several acquisition scenarios, including cases where the impairments are enormous. The electrodes are placed accordingly to the lesion: the neck, jaw and temporal areas are presented as good choices. Therefore, there are several input sources that can be explored allowing higher degrees of control when several muscles are available but also to explore just one single muscle in the most severe cases, when no other input sources are available.

Dimensionality and Input Speed Considering myographic interaction, the dimensionality depends on the voluntarily contracted muscles set. Therefore, if one can control several muscle groups, we can argue that EMG has high dimensionality. On the other hand, for the most severe impairments, the dimensionality is also severely reduced. Moreover, although we have control on several muscle groups it would be difficult to interact with a keyboard with a EMG direct selection interface. EMG-based interfaces generally rely on a small set (from 1 to 4) monitored muscles.

Accuracy, Robustness and Repeatability An EMG-based solution is independent from ambient noise or surrounding movement in contrast to electroencephalography and voice based approaches. Also, when compared to other physiological signals, myographic signal presents the best signal-to-noise ratio and higher amplitudes, which eases its processing and makes it a good candidate to voluntary device control. The main problem in EMG-based interfaces relates to involuntary movements. This is even a greater problem when considering spasticity [2], a common collateral issue within the target population.

Ease of use Generally, from the user side, EMG-based applications are easy to use. Also, although some approaches rely on pattern recognition algorithms and therefore face a training phase, most of the surveyed approaches are based on simple signal processing techniques. On the other hand, and one of the reasons for its unavailability in the market, EMG interfaces require some attention on the electrodes mounting. This problem is a current research issue (Jeong et al., 2005).

Aesthetics, Hygiene and Acceptance The electrodes placement and the wires are a big inconvenience that can make the users uncomfortable. User and social acceptance issues also arise as considering some muscles it is difficult to hide the mounting apparatus.

Mobility Adequacy The independence from a display creates the possibility to use EMG interfaces in a mobility scenario. Moreover, the signal characteristics are also adaptable and robust to a mobile scheme.

2.2.5. Brain-Computer Interfaces

A brain-computer interface is a communication system that does not depend on the brain's normal output pathways of peripheral nerves and muscles (Wolpaw, 2000). A BCI consists on monitoring, through a brain-imaging technology, brain activity and detecting characteristic brain patterns associated with a certain action therefore achieving communication with

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[2] Spasticity is a type of hypertonia, that is common on tetraplegia situations, and consists of an increase in tone that affects different muscle groups to different extents

Figure 2.22: Brain-Computer Interface

the outside world. This technology creates a new interaction channel independent from muscle contractions suitable for severely disabled people who cannot use other assistive technologies that somehow rely on a given physical ability. Particularly, for locked-in patients, the brain can be the only available communication channel. In these cases, the patients are completely paralyzed and unable to speak, but cognitively intact and alert. This condition can be caused by amyotrophic lateral sclerosis (ALS), brain stem stroke or high level spinal cord injure.

There are several techniques that can monitor brain activity: Magnetoencephalography (MEG), Magnetic Resonance Imaging (fMRI), Single Photon Emission Computer Tomography (SPECT), Positron Emission Tomography (PET) and Electroencephalography (EEG). However, EEG is the only practical brain imaging technology for the following reasons: inexpensive, ease of acquisition, high temporal resolution, real-time implementation and direct correlation of functional brain activity with EEG recordings (Wolpaw et al., 2002; Smith, 2004). Electroencephalography (EEG) is a method used in measuring the electrical activity of the brain. This activity is generated by billions of nerve cells, called neurons. Each neuron is connected to thousands of other neurons and their combined electrical activity can be measured with scalp EEG. Although the temporal resolution of EEG is very good (better than millisecond), the spatial resolution is poor as the number of electrodes that can be placed in the scalp collect signals from large areas.

BCI Types

There are several groups worldwide researching brain-computer interfaces separated in different categories, according to the type of EEG properties used. Visual Evoked Potentials (VEP) are dependent BCIs because they depend on the gaze direction; those who use Slow Cortical Potentials, P300 Evoked Potentials, mu and beta rhythms are believed to be independent BCIs.

Visual Evoked Potentials. Jacques Vidal developed the first dependent BCI (Vidal, 1973) which consisted on determining eye gaze direction using VEP recorded from the scalp over visual cortex. The system was able to determine the direction the user wanted to move the cursor. The Brain Response Interface (Sutter, 1992) also used VEPs recorded from the scalp over visual cortex to accomplish word processing tasks. The user selects a letter from a 8*8 matrix (64 symbols) by looking at the symbol he wants to select. Subgroups of these 64 symbols undergo an equiluminant red/green alternation or a fine red/green check pattern alternation 40/70 times/sec. Each symbol is included in several subgroups, and the entire set of subgroups is presented several times. Each subgroup's VEP amplitude about 100 ms after the stimulus is computed and compared to a template already established for the user determining the symbol that the user is looking at. Users were able to achieve a 10-12 words/min ratio. VEP-based BCI systems have the same function as gaze-tracking systems as they determine gaze direction.

Slow Cortical Potentials (SCP). SCPs are slow non-movement potential changes generated by the user which appear among the lowest frequency features of the scalp recorded EEG (Fatourechi et al., 2007; Wolpaw et al., 2002). These alterations can last from 300 ms to up to 10 seconds and several studies showed that it is possible to learn SCP control. The Thought Translation Device (TTD) is a BCI system where the user can control the movement of an object on a computer screen through its SCPs manipulation (Birbaumer et al., 1999). Birbaumer and his team also used the TTD with a language support program to provide word processing capabilities and Internet access to disabled users, allowing selection of up to 3 letters/min (Birbaumer et al., 2000). The program enables the user to select a letter by a series of two-choices selection (from chunks to letters) and it's usable 24h/day as it provides a stand-by mode controlled by the user (through a combination of positive and negative SCPs).

P300 Evoked Potentials. P300 is a positive peak in the EEG at about 300 ms after a particularly significant auditory, visual or somatosensory stimuli which appears among frequent or routine stimuli (Fatourechi et al., 2007; Farwell and Donchin, 1988). Donchin et al. (Farwell and Donchin, 1988; Donchin et al., 2000) presented a word processing application of a P300-based BCI: the user is presented with a 6*6 matrix containing the alphabet letters. One row or column is randomly intensified every 125 ms, flashing all rows and columns, in an overall of 12 flashes. The system is based in an oddball paradigm as the user has to focus in a relevant cell, which constitutes 16,7% of the intensifications (2 in 12), eliciting the P300 (Donchin et al., 2000; Wolpaw et al., 2002; Lehtonen, 2002). Piccione et al. (Piccione et al., 2006; Hoffmann et al., 2007) showed that the P300 could also be used to control a 2D cursor using a 4 choice paradigm (four arrows), each of the arrows flashing every 2.5s in a random order in the peripheral area of the screen. Although the disabled could operate the cursor with the developed system, the average communication speed is very low. Other P300 based BCIs have been developed to improve disabled users' communication capabilities (Sellers et al., 2006; Hoffmann et al., 2007) with similar approaches.

Mu and Beta rhythms. The human brain waves present different rhythmic activity according to the level of consciousness and are affected by different actions and thoughts. The EEG is divided into several frequency ranges which are named after Greek letters (delta, theta, alpha, beta, gamma) although other brain rhythms have been proposed in the EEG literature. One of them is the mu rhythm which frequency is around 10 Hz and although similar in frequency and amplitude to the alpha rhythm, mu rhythm is topologically and physiologically different. mu stands for motor and this rhythm is strongly related to motor cortex function and somatosensory cortex (Lehtonen, 2002). Some beta rhythms are harmonics of mu rhythms but some are separable and thus are different EEG features. Several mu and beta rhythm-based BCIs have been developed since the mid-1980s as these rhythms association with cortical areas most directly connected to movement or preparation of movement are believed to be good signal features for EEG-based communication (Wolpaw et al., 2002).

With the Wadsworth BCI (Wolpaw and McFarland, 2004; Wolpaw et al., 2002), disabled users learn to control mu or beta rhythm amplitudes and therefore control the cursor in one or two dimensions. In the early stages users tend do employ motor imagery to control the cursor but over the training sessions, the imagery relevance decreases and users move the cursor like they perform conventional motor actions. Users achieved information transfer rates up to 20-25 bits/min (Wolpaw and McFarland, 2004). Their studies also included answer to yes/no questions where a 95% accuracy was achieved.

The Graz-BCI is focused on distinguishing between the imagination of different simple motor actions, such as left or right foot or hand movement (Pfurtscheller et al., 2000). The system also enables a tetraplegic patient to control a mechanical hand-orthosis (Figure 2.23) using two types of motor imagery (Pfurtscheller et al., 2003).

Regardless of the approach, a current BCI-system can offer locked-in patients the ability to communicate at transfer rates of up to 25 bits/min easing several applications' control (Answer simple questions, Word Processing, Control neuroprosthesis (Muller-Putz et al., 2005), Control the environment (Aloise et al., 2006; Cincotti et al., 2006, ASPICE Project), Navigate within virtual and augmented reality environments (Navarro, 2004; Pfurtscheller et al., 2006), Control an Electric Wheelchair (Tanaka et al., 2005).

Discussion on Brain-Computer Interfaces

Brain-computer interface technology is the less mature among those surveyed in this document. Although research in this area has been evolving in the last few years, is generally agreed that a long path is still to come. Nevertheless, it is an interesting technology as the brain can be the only output path to communication. Therefore, the main advantage on brain-compute interfaces is its suitability to a wide range of users.

Figure 2.23: Neuroprosthesis Control

Potential users range Although interfaces based on eye-gaze or EMG are more efficient than any of the BCIs available for severely disabled persons, a BCI can be the only communication tool for people suffering from locked-in syndrome, when no other output channel is available (Lehtonen, 2002; Wolpaw, 2007).

Dimensionality and Input Speed The communication is still very slow (around 25 bits/min). Also, the selection set must be very limited to achieve good recognition results. Considering the actual research panorama, it is hard to evaluate the future of Brain-Computer Interfaces as opinions differ widely.

Accuracy, Robustness and Repeatability On the other hand, BCI development is still in its earliest stages and current systems are still very limited, embrionary and error prone. Although recognition rates reported are high, BCI-based systems have not gone out of the laboratory and therefore these results are still highly constrained and obtained within restricted conditions, free of distractions and highly supervised. Also, the results achieved are still very variable within sessions and days even with prolonged practice. The EEG signal is highly sensitive to noise with a low signal to noise ratio, has low amplitudes and it is extremely fragile to artifact contamination (EMG and EOG artifacts due to blinks or facial movement as well as other external interferences).

Ease of use Operating a BCI system still demands high attention and cognitive loads which makes it difficult to use in noisy and distractive environments restricting the interaction scenarios. Also, the mounting still requires some specialist attention and can hardly be used by a normal user within his daily scenario.

Aesthetics, Hygiene and Acceptance The need to use a somehow awkward helmet and a set of wires around the head may be an obstacle to some users due to social acceptance issues.

Figure 2.24: Sip and Puff switch

Mobility Adequacy Nowadays, we can already find BCI solutions for mobile scenarios. There are approaches to wheelchair guidance as well as EEG-monitoring systems for mobile devices (PDA). However, the BCI use hardly copes with a mobile scenario as the interferences to the system and the distractions to the user are enormous.

2.2.6. Breath-Based Interfaces

One of the most common assistive technologies for communication and control is the Sip'N Puff switch (Figure 2.24), a binary action pneumatic device capable of sensing airflow direction through an easy accessible piece of tubing similar to a drinking straw (Kitto, 1993)[reviewed in (Surdilovic and Zhang, 2006)]. This kind of switches requires little or no movement and offers an easy and unobtrusive way to operate a device. On the other hand, these types of devices cannot sense airflow intensity, restricting the interaction to a yes/no paradigm (Kitto, 1993; Kitto and Harris, 1994b). This type of switch is needed for individuals who do not have the motor skills to reliably produce a mechanical, repetitive movement.

Searching for a higher degree of control, Kitto et al. (Kitto and Harris, 1994a), developed a synergy between a sip and puff switch and a chin joystick, creating the Sip and Puff Mouse. The important feature of this design is that the extended joystick is controlled by chin motion of the individual whose chin cup is custom molded (vacuum molded). A tube from the sip and puff circuit rests in the mouth of the individual to replace the mechanical button. Sip represents the left or right mouse bottom. Puff then represents the other mouse button. Since the circuit has individual adjustments for sip and puff, the device suits a wide range of individuals. Double clicking is easily accomplished by double sipping and double puffing. The device can be attached to the computer table or to a table attached to the wheelchair of the user.

The *"Breath-Joystick"* (Grigori and Tatiana, 2000) is a device highly sensitive to the human respiration flow. The setup consists on six thermo transducers located in front of the user's mouth, selecting necessary components of directed air stream. While four transducers emulate the X and Y coordinates, the other two emulate left and right buttons. The thermo transducers work at a temperature above 40°C, which removes undesirable water vapor influence. Although using a mouse's micro-controller and serial port, the device operates like a joystick, with a *deadband* where no movement occurs. Cursor moves when the air stream is outside of this deadband (above defined threshold). Therefore, when a user desires to move the cursor in a certain direction, he must send the air flow between respective thermo-transducers and must keep the air pressure until the cursor reaches the desired location. This system is an alternative to regular sip-puff switches and augments the scope of interaction as several input channels are present (four directions and two buttons). However, the authors do not present enough results to declare it as an advantage to others. Users still need to have an awkward mechanism in front of their mouse and it is not clear how users can distinguish the different actions.

Michel and Rancour (Michel, 2004) propose the use of thermal imaging to detect breath patterns. The main advantage is that the person does not need *to be precisely aimed at the infrared sensor because the thermal pattern is "visible" over a wide range of angles*. Recently, (Patel and Abowd, 2007) presented an approach (BLUI) where the user blows at the laptop or computer screen to control interactive applications. In order to locate the blowing, the authors rely solely on a microphone, similar to those embedded in standard laptops. It is important to notice that the system relies on the airflow created and not on the sound, so the interaction can be made without disrupting the environment. The authors present a set of actions which the user is able to operate like selection, scrolling and dragging.

Shorrock et al. (Shorrock et al., 2004) present another technique to communicate by breath alone. *A belt-mounted breath-mouse, delivering a signal related to lung volume, enables a user to communicate by breath alone*. Basically, an optical mouse is attached to a piece of wood, to which a belt is also attached. When the user breathes his/her diaphragm moves, making the optical mouse to slide on the piece of wood and generating pointer movement. The system is specially designed to work with Dasher (Ward et al., 2000), in one-Dimensional mode. Although interesting for text-entry and persons with total breath capabilities, the system is limited to other applications.

Discussion on Breath Interfaces

The sip and puff switch is the most known breath-based approach, it is commercially available and used by a large number of disabled individuals. However, this device restrictions are huge and other breath-based interfaces were studied to overcome those limitations. Overall, breath-based interfaces are advantageous as they are available to a wide users scope but still have a slow input speed and questionable ease of use.

Figure 2.25: Breath Mouse

Potential users range The ability to control diaphragmatic function, which is required to breath, is compromised when the impairment is high (above C3). Therefore, not all the users have fine breath control, requiring ventilation. Overall, the presented breath-based interfaces are unavailable to that particular user scope. On the other hand, users with impairments below C4 are likely to have fine breath control and are therefore possible users, whether considering sip-puff switches, whether considering approaches where higher head control is required (i.e., BLUI where the user needs to face a target when blowing).

Dimensionality and Input Speed The sip and puff switches are the breath-based most used interfaces. There are several problems with sip and puff switches that limit their use. One is the low bandwidth which reduces the interaction speed as well as the interaction scenarios. Other breath-based approaches enlarge the selection set and increase the dimensionality and therefore the input speed. However, the interaction speed is still limited and these approaches are only aimed at mouse pointer emulation. Nevertheless, recent research (BLUI) presents motivating results that are prone to improve breath-based interaction as the selection set is already appreciable.

Accuracy, Robustness and Repeatability The sip and puff switches are normally accurate. Other presented Breath-based interfaces, although aiming at solving some of the sip and puff switch problems are still embrionary and no clear results have been presented. Also, it is not clear how these systems will behave in open air where several flows can be present. Therefore, their robustness and repeatability is questionable.

Ease of use For those who have good breath control, sip and puff switches are not difficult to operate and require little adaptation phases. Other breath-based approaches, although increasing the selection set, are based on the same functions and appear to be easy to use. However, some of the approaches require a classification stage, increasing the usage setup time and installation dialogues. Another downside on breath-based approaches is the inability to control the device and talk at the same time (Vanderheiden and Smith, 1989).

Aesthetics, Hygiene and Acceptance Considering sip and puff switches, one can argue that it is rather inconvenient to use and presents some hygiene and ergonomics issues therefore limiting user and social acceptance. The other breath-based interfaces overcome this issue and face no aesthetics or hygiene problem as no contact is required between the mouth and the device.

Mobility Adequacy In opposite to the other evaluation characteristics, the contact requirement offers sip and puff switches the required stability and robustness to face a mobile scenario. Actually, there are several electronic wheelchair guided by sip and puff switches. On the other hand, non-contact breath interfaces use the air flow from the user's mouth to control the device but we have no results showing that these interfaces will perform well within an outdoor scenario where several air flows may be present (wind, other people,...).

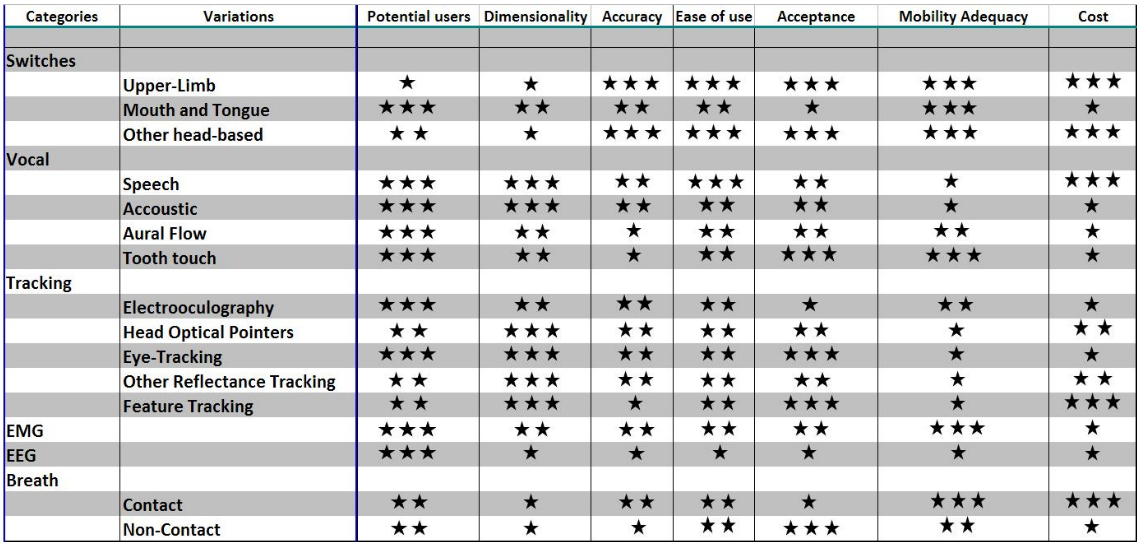
2.2.7. Overall Discussion

Along this chapter, we surveyed each technology group, presenting relevant projects and analyzed them taking several evaluation criteria into account. The technology characteristics and technology use within a certain scenario (that define a selection set and method) give us the necessary data to assess technological capabilities and limitations.

In this chapter, we will now compare the surveyed technologies following a criteria-based approach for the evaluation points previously defined. The overall comparison is presented in Table 2.2. Each of the evaluation characteristics is discussed below.

Potential users range

As seen in the chapter, there are approaches focused at a specific and limited user group while others have a wider scope of possible users. It is therefore relevant to analyze the availability of a certain assistive technology to the various target populations. The potential users of each assistive technology group is presented in Table 2.3. Although the most severely injuries can eventually impair speech and mouth-related functions, we consider all face-based approaches as extensive. Therefore, all the approaches that are able to measure any kind of input from the eye (EOG, Eye-Tracking), mouth (tongue and vocal) or face muscles are included in this group. Considering spinal cord injuries, these technologies are prone to be available to the most severe injured patients (even above C3). Breath-approaches are not included in this group as breathing capabilities may be damaged in most severe lesions. In a second technology group, we include all the approaches available to the users that are able to move their head and detain breath



Categories	Variations	Potential users	Dimensionality	Accuracy	Ease of use	Acceptance	Mobility Adequacy	Cost
Switches								
	Upper-Limb	★	★	★★★	★★★	★★★	★★★	★★★
	Mouth and Tongue	★★★	★★	★★	★★	★	★★★	★
	Other head-based	★★	★	★★★	★★★	★★★	★★★	★★★
Vocal								
	Speech	★★★	★★★	★★	★★★	★★	★	★★★
	Accoustic	★★★	★★★	★★	★★	★★	★	★
	Aural Flow	★★★	★★	★	★★	★★	★★	★
	Tooth touch	★★★	★★	★	★★	★★★	★★★	★
Tracking								
	Electrooculography	★★★	★★	★★	★★	★	★★	★
	Head Optical Pointers	★★	★★★	★★	★★	★★	★	★★
	Eye-Tracking	★★★	★★★	★★	★★	★★★	★	★
	Other Reflectance Tracking	★★	★★★	★★	★★	★★	★	★★
	Feature Tracking	★★	★★★	★	★★	★★★	★	★★★
EMG		★★★	★★	★★	★★	★★	★★★	★
EEG		★★★	★	★	★	★	★	★
Breath								
	Contact	★★	★	★★	★★	★	★★★	★★★
	Non-Contact	★★	★	★	★★	★★★	★★	★

Table 2.2: Overall Evaluation

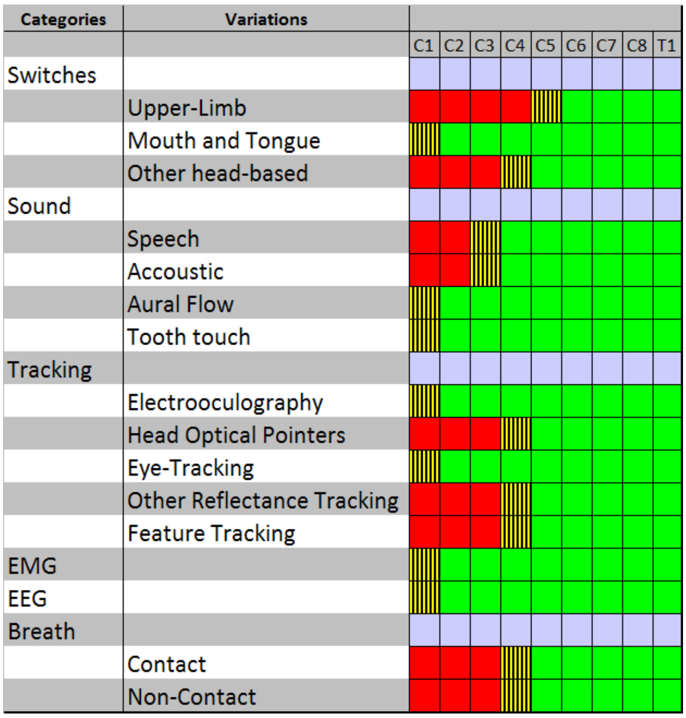
and intelligible speech capabilities. This group includes C3-C5 impaired users. Impaired below C5 users detain some upper-limb control and are therefore able to control switches, joysticks or other similar approaches (Arm EMG).

Figure 2.3 presents the matching map between the assistive technologies surveyed and the different motor capabilities and corresponding motor map. Although the assistive categories cover a wide group of technologies we point out for each of them the most probable acquired capability (i.e., to use an arm switch the user must have necessary motor skills to move the arm (C4)). There are some situations where users with lesions above the pointed vertebrae can control a device within the group but that control is very limited. Also, individuals with a partial injury may present motor abilities that offer the possibility to control above lesion pointed devices but generally the classification can be followed.

Dimensionality and Input Speed

Dimensionality is highly related with the possible interfacing schemes achieved with each technology, considering several scenarios, including those where the selection set is large. The high dimensionality approaches are those which are able to offer direct selection even when the selection set is considerable. The approaches included in this group are voice-based (speech and acoustic) as the vocabulary can be defined accordingly to the selection set and eye-based approaches that, through the adequate interface, can achieve selection set completeness (i.e., direct selection on an on-screen keyboard).

While some approaches are not able to offer direct selection for large selection sets, there are ones that suit that selection method with limited (but considerable) input set cardinality (EMG, EOG, Aural Flow, Tooth touch, Tongue and Mouth switches) or can be used



Categories	Variations									
		C1	C2	C3	C4	C5	C6	C7	C8	T1
Switches										
	Upper-Limb	🟥	🟥	🟥	🟥	▥	🟩	🟩	🟩	🟩
	Mouth and Tongue	▥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Other head-based	🟥	🟥	🟥	▥	🟩	🟩	🟩	🟩	🟩
Sound										
	Speech	🟥	🟥	▥	🟩	🟩	🟩	🟩	🟩	🟩
	Accoustic	🟥	🟥	▥	🟩	🟩	🟩	🟩	🟩	🟩
	Aural Flow	▥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Tooth touch	▥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Tracking										
	Electrooculography	▥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Head Optical Pointers	🟥	🟥	🟥	▥	🟩	🟩	🟩	🟩	🟩
	Eye-Tracking	▥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Other Reflectance Tracking	🟥	🟥	🟥	▥	🟩	🟩	🟩	🟩	🟩
	Feature Tracking	🟥	🟥	🟥	▥	🟩	🟩	🟩	🟩	🟩
EMG		▥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
EEG		▥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Breath										
	Contact	🟥	🟥	🟥	▥	🟩	🟩	🟩	🟩	🟩
	Non-Contact	🟥	🟥	🟥	▥	🟩	🟩	🟩	🟩	🟩

Table 2.3: Assistive Technologies Matching map

within an encoding scheme.

Other approaches highly restrict the cardinality of the input set and are normally used with an auxiliary scanning interface. User performance is highly damaged.

Accuracy, Robustness and Repeatability

The most accurate approaches are those that are independent from a recognition algorithm and are independent from the surrounding environment (Touch switches). On the other hand, the less accurate are those still embrionary considering recognition and/or are highly sensitive to the environment (Aural Flow, Feature Tracking, Heat Flow, EEG). In the middle, we considered all the approaches that suffer from one of those problems. Speech research can be argued to have surpassed the recognition issue but this is not true in noisy environments while all the computer vision approaches are still vulnerable to artifacts and interferences from the surrounding environment. This is also true for electrophysiological approaches.

Ease of use

The most difficult technology to use is the brain-computer interface due to the setup apparatus and the large training required. If a commercial product is delivered, training must be offered both to the users and caretakers. Although with a reduced complexity almost all the approaches require some training, habituation or some montage apparatus that can difficult its use. Speech and touch switches are the ones that offer no obstacles to the user, even at first use.

Aesthetics, Hygiene and Acceptance

All the approaches that entail visible fixtures in the user's body are prone to be rejected due to social acceptance issues. Also, some approaches imply some discomfort and can even harm the user. Vocal approaches that can somehow disrupt the surrounding environment and can break the user's privacy while interacting with the system in public are also reject prone. On the other hand, there are approaches that need no extra hardware on the user's body and can be used subtly (i.e., Touch switches, EMG, Tooth touch, Tracking and Non-Contact breath).

Mobility Adequacy

A mobile approach must offer independence from a computer screen and must not be disruptive to other user tasks. While within a mobile scenario (i.e., driving a wheelchair in a public space) the user must be aware of his surroundings and should be able to simultaneously perform a task in his mobile device. Also, mobile approaches must be immune to movement, noise and electromechanical interferences.

3

Mobile Device Control

In the last 15 to 20 years there has been major growth in the application of technology in ameliorating the problems of persons with disabilities (Cook and Hussey, 2002). Particularly, as discussed in Chapter 2, we have witnessed the appearance of several assistive devices and systems that try to bridge the gap between tetraplegic persons and computers to improve their communication and control skills and therefore, their overall autonomy. Although still an active research area, the majority of tetraplegic users can already control a personal computer (PC), drive a wheelchair or even control appliances in their home from the PC or wheelchair.

On the other hand, the access to mobile devices and their effective use has not been provided with the same quality nor quantity. Indeed, for a high level tetraplegic, it has not been provided at all. Although mobile device graphical user interfaces are somehow similar to those of desktop computers, the interaction is highly constrained both by the device characteristics and the interaction goals and scenarios. A mobile device is characterized by a relatively small screen and a input set with reduced size keys. While the assistive technologies that rely on gaze information can hardly cope with screen dimensions, physical aids to enhance keypad interaction would affect a small target group. Although the keypad and screen dimensions have been changing in the last few years, the overall size of the device is still reduced and limitations exist in the generality of the layouts.

Moreover, mobile devices have the purpose to be always available for the user to interact with but also for the user to be prompted for interaction. The reduced dimensions, portability, anywhere and anytime availability are the great advantages and the reason for their success and huge social acceptance. Considering impaired users, it is important not only to offer constant communication capabilities but also, if possible, to augment that capability (i.e., emergency sensors). Once again, the assistive technologies and systems presented in Chapter 2 are fragmentary and do not present the required versatility and adaptation to the variety of possible scenarios.

Our approach tries to tackle the above mentioned problems by studying tetraplegic users, their capabilities, accommodations and needs, as well as the tasks to be fulfilled. Following a user-centered design approach, we were able to identify common capacities among the target population and design interaction profiles that cover the several scenarios the users face along the day. Therefore, besides researching and identifying a suitable technique to bridge the physical gap, we studied the interaction processes that maximize performance within several scenarios, facing different restrictions. To provide real mobile accessibility, the designed approach copes with several degrees of impairment as well as several different interaction contexts. Both the impairment degree and the interaction context implicate a change in the dialogues between the user and the device and limit the human-device communication bandwidth. We selected Electromyography as the input mechanism to guarantee maximum adaptability both on impairment degree and possible scenarios. The preliminary studies with the target population as well as the main implications for design retrieved from those are presented in this chapter.

3.1. Preliminary studies

Although the study on assistive technologies panorama and common sense can lead us to point out some flaws on computer access, and in particular mobile device control, for tetraplegics, it is extremely important that the target users are included in the process, both to identify the existing problems and limitations but also to ensure a proper and suitable design.

3.1.1. User Centered Design

To guarantee quality, the users are included in all the design process stages. Indeed, *the start of any interaction design exercise must be the intended user or users* (Dix et al., 2004). As a comment, we believe that this is one the main contributions in this dissertation: the design was made from the human-out, trying to gather as much information from the user and his surroundings as possible. Therefore, following the user-centered design principles (Rubin and Hudson, 1994) we early started focusing on the users, trying to gather structured information, and maintaining the focus along the design process iteratively testing and modifying the prototypes according to the results and user feedback.

Therefore, the studies presented in this dissertation started with the gather of representative elements of the target population. It is important to observe that a user centered approach may be harder to follow when dealing with disabled users. Besides the health problems that individuals face, their lives are highly restricted by caretakers availability. Moreover, it is a hard task to gather a user group as the persons are normally less active in the society, with less communication capabilities and visibility, far and unreachable to and from the outside world. The impairment degree also influences this distance.

During the studies presented in this dissertation, we studied several users. Although some were available during all the process, others were not able to do so. Whenever we believed it to be adequate, non-disabled users were introduced in the design process to augment the user sample. All user-related evaluations are deeply covered in this document and the type of users (disabled or not) described.

3.1.2. User and Task Analysis

To assess the target population capabilities and restrictions as well as the actual panorama on computer interaction we conducted questionnaires and, whenever possible, observed tetraplegic users performing specific tasks. Due to the difficulties mentioned above (Section 3.1.1), the sample is composed of six tetraplegic persons. However, this set can offer us a good characterization of the existent problems as each individual represents a certain group of limitations detaining some sort of control over technologic devices. On the other hand, the inability to control some devices in certain circumstances points out limitations to be analyzed and if possible generalized as a problem of the target population.

In the first stage of the preliminary studies we performed questionnaires to the target users, trying to capture an overall idea on the user's impairments, limitations, technological acquaintance, interaction capabilities as well as understanding their daily scenarios and synergies with their surroundings and caretakers. The questionnaire is available in Annex A1.1. Whenever possible, and to better understand the processes, we asked the users to illustrate their answers by performing a determined task. In the following sections we will present and discuss the main results that were extracted from these studies.

Subject Characterization

We conducted questionnaires and observed five tetraplegic individuals, all male, with ages between 25 and 36 years. At the time of the analysis, three of the subjects were unemployed. One of the subjects was finishing a degree and another one worked as a salesman (Table 3.1). While the gathered data cannot give us an overall panorama on the occupation and unemployment statistics among tetraplegic users, other studies reveal low employment rates and support our results (McKinley, 2004).

Initials	Sex	Age	Academic qualifications	Profession
LP	Male	36	12th Grade	Unemployed
PF	Male	30	12th Grade	Unemployed
SA	Male	25	Economics Degree (Finalist)	Student
NC	Male	32	12th Grade	Unemployed
BM	Male	29	6th Grade	Salesman

Table 3.1: Interviewed users characterization

Impairment and residual function

In terms of the cause of the tetraplegia, all the users in the sample suffered a traumatic spinal cord injury. The presented impairment causes (car accidents, diving and falling) represent a great percentage of the overall tetraplegia situations (more than 50%) (Kotzé et al., 2004). All the users in the sample present the impairment for at least four years. The injury level and totality varies and goes from a C3 incomplete to a C6 complete lesion (Table 3.2).

Initials	Injury level	Injury Type	Cause	Age of injury
LP	C4	Complete	Car Accident	24 (12 years ago)
PF	C5	Incomplete	Dive	26 (4 years ago)
SA	C3	Incomplete	Car Accident	16 (9 years ago)
NC	C6	Complete	Fall	25 (7 years ago)
BM	C6	Complete	Dive	12 (17 years ago)

Table 3.2: User injury details

Nevertheless, it is important to stress that the level of lesion for itself does not define the motor control detained. Indeed, the most severe motor impairment of the user sample is LP, which presents a C4 injury, and not SA, which presents a C3 injury, but incomplete. Table 3.3 presents some of the most important muscles that provide upper body motor control. For each of the muscle, its main function is presented as well as the percentage of users in the sample that detain control. Figure 3.1 presents an overall view on the human body muscle composition. All the observed users present total motor control of the facial and neck muscles. Contrarily, no user detains finger or wrist motor capacities. Two of the users (BM and NC) have full biceps and triceps control and can therefore voluntarily move the arm and forearm.

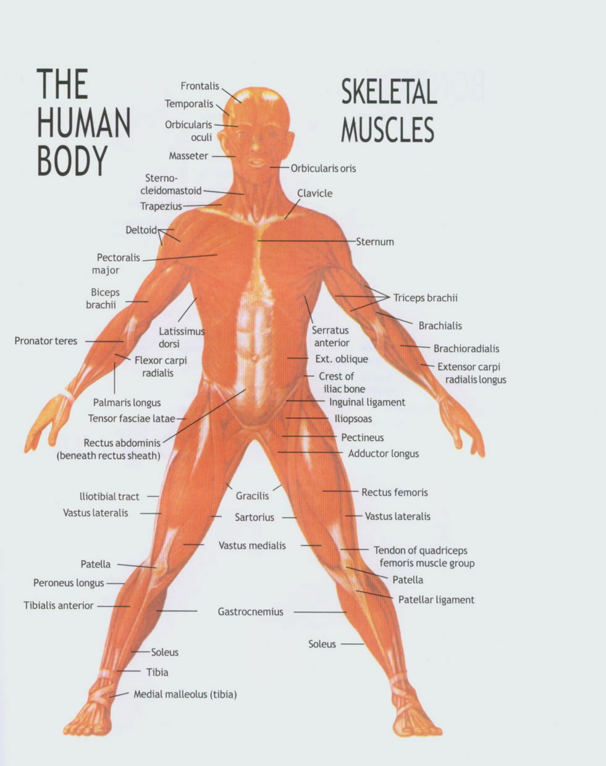


Figure 3.1: Human Body Muscles - Front View

Material and Interaction

Considering electronic devices, all the participants have at least one personal computer and one cellular telephone. All of them stated that they use these devices, with some limitations. Concerning personal computers, all the users can somehow manage to interact: C5/C6 users have some residual arm function and can through it (in some cases with the help of a stick attached to the hand - Figure 3.2) interact with the keyboard and the pointing device (in one of the cases emulated with the keyboard directional keys); C3-C4 individuals interact with the computer using eye tracking devices (Table 3.4).

However, although control is achieved, it must follow certain requirements. It is important to notice that the interaction must occur in front of the computer and only two users stated to have this interaction available while standing in the bed (with an eye-tracker).

Furthermore, the users are transferred from/to bed at specific schedules and have limited time to operate a computer.

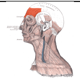
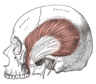
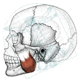
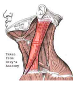
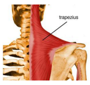
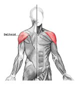
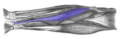
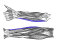
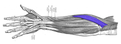
Muscle	Figure	Main Function	Users
Frontalis		Wrinkle brow	100%
Temporalis		Elevate and Retract mandible	100%
Masseter		Close mouth	100%
Sternocleidomastoid		Tilt head	100%
Trapezius		Retraction of Scapula	100%
Deltoid		Abduct Shoulder	60 % (3/5)
Biceps brachii		Flex elbow	60% (3/5)
Triceps brachii		Extend forearm	40% (2/5)
Flexor Carpi Radialis		Flex and abduct the hand	0%
Flexor carpi ulnaris		Flex wrist	0%
Flexor digitorum profundus		Flex fingers	0%
Extensor Carpi Radialislongus		Abduct the hand at the wrist	0%

Table 3.3: User Motor Control

Even those who are capable to operate the PC in bed, can only do so if they are sitting and obviously they cannot change their position without the help of another person. The interaction with mobile devices is also limited although these devices can be always near the user. While three users can press the keypad (similarly to the keyboard), the others (2 users) mobile interaction is limited to receiving calls using a bluetooth earpiece (the system is configured to automatically accept the call after a predetermined time). Considering the cases where there is arm function, the users are likely to be able to dial numbers and write messages (although stated to be slow), but they can only do it while they are sitting. Going back to the bed scenario, where the users are for at least 60% of the day (estimated value retrieved from the questionnaires), the interaction is minimal or non existing. If we consider more severe situations, with no below-neck function, voluntarily mobile interaction is absent.

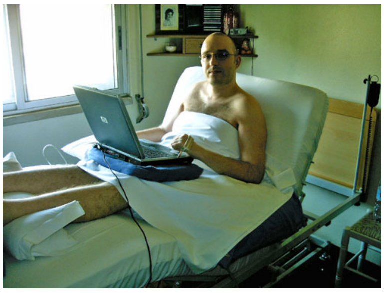


Figure 3.2: User (PF) using a stick to operate the keyboard

Initials	Computer	Place Computers	Interaction mean
LP	Yes (1)	Near bed	Eye-Tracking
PF	Yes (2)	Living room/Bedroom	Arm stick
SA	Yes (2)	Living room/Bedroom	Eye-Tracking
NC	Yes (1)	Office	Control Enhancers
BM	Yes (2)	Living room/Portable PC	Control Enhancers

Table 3.4: User material and interaction details

3.1.3. Implications for Design

It is clear from our preliminary analysis that tetraplegic persons face great difficulties to operate a mobile device. Although these devices are portable, lightweight and can be placed near the user, there are no suitable interaction mechanisms that cope with the difficulties arisen by motor deficits. Moreover, the possible mobile device interaction inherits problems that this population still faces while interacting with static devices. Tetraplegics are normally dependent on caretakers to perform daily tasks and to change accommodation. The interaction with computers is often restricted by these accommodation and therefore dependent on other persons availability and willingness.

The fact that a mobile device can be placed within the user's reach augments its possibilities if the user is able to press the buttons even if it occurs with difficulties and slowly. However, this interaction is only possible in certain conditions and a slight position shift can disable the interaction opportunity.

Taking into account the observed limitations and needs we designed a set of guidelines for mobile device control for tetraplegics. These guidelines are to be followed if one wants a mobile interface that copes with the user's capacities and needs but also with several interaction restrictions caused by particular interaction sites and positions.

Liquid Design

The concept *Liquid design* is used in the Web Design context. It is a design technique that automatically expands and contracts a web site to best fit the viewer's browser. The term "liquid" implies that a website flows smoothly into whatever space it is given. Overall, the user has a better experience as the design is molded to better fit the display characteristics.

An effective and accessible mobile device interaction system should apply Liquid Design. However, in this scope, the term "liquid" should be applied to all the interaction processes. Thus the system must be adaptable and deal with both the user's differences (i.e., different physical capacities) but also with the different interaction scenarios (i.e., sitted and facing the device screen; lay down in bed with no physical access to the device and no visual feedback).

As to resolution in web pages, the input and output characteristics must be molded by the system, and/or the user when adequate. As for information, the input and output sets should be maintained, giving the user the same opportunities a non-disabled has, whenever that is possible.

Communicate through available channels

As already observed, motor disabilities together with the accommodation shifts, can lead to the inability to reach a keypad or even to receive feedback from it. However, to ensure a daily and non-fragmentary communication, users must be able to input information to the device and receive feedback. All the information traditionally offered visually must be communicated through alternative channels, if the mobile device is not in the user's line of sight. On the other hand, the user must be able to communicate with the device independently from his accommodation, position and relative location of the device.

Although coping with small screens and keypads, mobile device interaction is largely focused on visual feedback. The mobile device output is given by the screen but the input is also highly constrained and dependent on visual information considering letter and function displacement on the keypad. Moreover, the keypad layout and key size increases the access difficulties, even for those whose residual capacities allow computer keyboard interaction.

Be extensive but also exhaustive

Among tetraplegic users, the impairments are diverse. One user can present reliable shoulder and neck motion and another can present higher limitations that disable him from moving any body part, except the face muscles. An accessible mobile device solution should be designed to be able to cope with the different capacities. Although the high scope of possible users can restrict the solution to be designed, it should be as exhaustive as possible, offering the less severe situations to have better performance with less restrictive interaction schemes.

Adapt the interaction processes to the user

We can use small mobile devices with colorful screens, stylish designs and featuring an extensive list of functionalities such as an agenda, calendar, mp3 player or web browser. The conjunction of recent powerful multi-task systems with a small device with limited input capabilities, has distanced mobile interaction and physically impaired people. Also, mobile device interaction is highly based on the visual feedback provided but with increased difficulty arisen from the multi-functionality and extra capabilities available. Thus, we can easily find complex forms where the user fills in the blanks which maximizes non-visual interaction difficulties as no clues concerning the layout are provided (i.e., write an e-mail where the destination and body fields are presented within the same screen with distinguished selection color patterns). Once again, an overall transformation and adaptation to the target group is required. The interaction scheme must consider the user limitations and present the information in an understandable and structured format.

Minimize stress scenarios

Although a simple process for a physically capable individual, error recurrence moves the user from device applications and overall capabilities. It is therefore important to reduce error situations and provide aid mechanisms during the processes that can help early recognition and recovery of erroneous commands. The user must be in control and feel that he can easily make corrections if necessary.

Allow and stimulate performance improvement

Even if a mobile phone confident and successful use is an important milestone, we must not define it as our final goal. It is important to provide mechanisms that ease learning and continuous improvement of user performance. Therefore, besides special acceleration mechanisms, it is also necessary to offer several degrees of personalization making no hard restrictions and stimulating the continuous improvement.

Grant social and user acceptance

One important factor for the effectiveness of any user interface is user acceptance. Although severely impaired users can be more tolerant considering the aesthetics and apparatus of a certain technology, that should not be taken as granted. Moreover, considering a mobile technology trying to cope with different environments, interaction in public must be considered.

(Petersen et al., 2004) suggested that interfaces should be designed considering social and cultural backgrounds, link the mind and body and take in account the instrumentality of the interaction. If some of these issues are carefully studied when designing interaction, it is possible that success is achieved and become a generally accepted technology. Besides, the chance of personalization also opens the door to an interface with better user acceptance.

3.2. Mobile Device Control for Tetraplegics

In the previous section we defined a set of implications for design, taking into account the users characteristics. Although those guidelines were built within the mobile device control for tetraplegics context, they can be applied across several other contexts. However, in this dissertation we focus our attention on mobile device control and its requirements. In this section, we straighten the scope of interaction focusing on the scenarios and tasks to be fulfilled, instantiating the aforementioned guidelines.

3.2.1. Use Scenarios

The proposed approach aims at mobile device control for tetraplegics. However, it also tries to cope with different accommodations through the day, without the need for constant caretakers assistance. Therefore, besides being able to adapt to several scenarios, it is also feasible that a user changes his accommodation, location or position and is still able to control the device, even though a new interaction scheme may be needed. To better understand the possibilities of the proposed approach, we present two different scenarios contemplating several different interaction schemes.

In the wheelchair

Lewis is a tetraplegic person with a C4 complete spinal cord injury. He is able to control the face muscles, his neck and lift the shoulders. Luis moves around in his electric chin-controlled wheelchair where he stays for about 4 hours a day (Figure 3.3).

As Christmas is approaching, Lewis goes to the mall with his friend James looking for some presents for their common friends. Lewis is using his mobile accessibility system with three monitored positions (one in *frontalis* and two electrodes in the *temporalis*). The mobile device his placed in the special wheelchair support plate and facing Lewis.

While James is looking in a bookstore for a new issue of his favorite comics, Lewis takes the time to check his task list in the device to assure that he does not forget any of the presents he had thought of. With his three-input configuration he is able to navigate the menus by blinking one eye and achieves selection by frowning.

Continuing their journey, Lewis and James enter a very busy and noisy store. While talking to the employee, Lewis receives a call from his sister. Lewis chooses to reject the call as the ambient is noisy and he is in the middle of a purchase. Nevertheless, as soon as he bought the present, he sent a message to his sister: ”I am at the mall. Call you in 5 minutes”.

Figure 3.3: User Sitting in the wheelchair

Lying in bed

Peter his a tetraplegic user with a C3 spinal cord injury. He is able to control his face muscles.

Peter is lying in bed facing up (Figure 3.4) and is controlling the system with his *temporalis*. As he is alone at the moment, he is taking the time to send some Christmas messages to his family and friends. As the mobile device is not in his line of sight he takes some time to write the desired messages as he is using a scanning method to enter text. However, he is still awake and having difficulties to sleep. To be able to control the device, he is also wearing a earplug, receiving voice feedback from the system.

One hour later, Peter is getting sleepy as his mother enters the room. She helps him change position and face to the side as Peter prefers to sleep in that position. As Peter expects a call early in the morning he wants to keep the system mounted. However, as he is lying to the side his mother takes out one of the electrodes. The system quickly notices the setup change and warns Peter that he is now featuring one-input control mode. Some minutes later, Peter falls asleep.

After some minutes, his friend Lewis calls him. However, as the system warns Peter about the incoming call from Lewis, Peter quickly rejects the call by blinking his eye three times.

Figure 3.4: User lying in bed

3.2.2. Task Requirements

Looking at actual mobile devices, we can state that, although the graphical user interface is similar to the one present in desktop computers, the interaction is much more restricted. Comparing with desktop computers, the input is much more limited and the visual feedback is also enormously reduced. Also, although recent operating systems present an icon-based view similar to the desktop metaphor, the operations within the environment are not as expressive as one can achieve in a personal computer (PC). Most mobile devices do not provide direct selection capabilities, which leads to the creation of multiple menus and difficulties when a specific task is intended. Touch screens support direct selection but represent a two-handed and visually demanding interaction that is naturally not considered taking into account the scenario versatileness that we aim to achieve.

Basically, when looking at mobile device interaction, three different group of tasks can be identified: *keypad direct interaction*, *menu navigation and selection* and *event reception*.

Figure 3.5: Mobile device keypad

We call *keypad direct interaction* to the insertion of information through the keypad (Figure 3.5). This interaction includes common text-entry interfaces (i.e., Multi-tap) and number dialing.

Menu navigation and selection has some differences between devices but it generally con-

(a) Icon Navigation (b) Text Navigation (c) Touch Navigation

Figure 3.6: Mobile Device Menu Interaction

sists on using a joystick, or keys on the device simulating a joystick, to navigate between options (Figure 3.6). This navigation can have one or two degrees of freedom. As an exception, touch screen devices, besides navigation, add direct selection capabilities to menu items. However, as already mentioned, they are much more restrictive considering user/device position, location and even attention.

Event Reception is related with the interface adaptation when an incoming event occurs. Indeed, when a message or a call is received, the interface changes to permit the quick user response to that specific event. In the message scenario, the user is normally given the opportunity to see the message at a one-click distance, while when receiving a call the user can also at one-click distance, accept or reject it.

Overall, there is a restricted set of actions that is built upon the keypad (numbers and letters), the joystick and the screen (menu navigation) and shortcut keys and the screen (event reaction). If a mobile device control for tetraplegics is to be achieved, the same functions should be possible. However, the direct physical impairments are likely to disable the ability to interact with the keypad and can also indirectly disable the capacity to have visual feedback from the screen.

Therefore, menu navigation, event reception and data insertion must be achieved featuring a higher set of restrictions in this case. Besides an input technique that copes with the physical impairments and creates a communication channel between the device, a redesign on the interaction is required.

3.2.3. Approach Requirements

To achieve the desired goals, besides traditional usability requirements, some requisites should be fulfilled. As we have already stressed, the main requirement is that the user is able to control mobile device functionalities and achieve this independently from his accommodation limitations. To develop our system we took into account these main considerations:

Adaptability

One important issue to guarantee the success of our approach is the extensibility of the solution. The system should be usable by a low-level injured individual but also by a high level injured one, even though the interaction mechanisms are different as well as usage performance. This adaptability is related to the user but also to the scenarios a single user faces in his daily life. Indeed, to provide a system that takes advantage of a mobile device and its capabilities, transversal use through several scenarios should be achieved. Considering the scenarios that make a tetraplegic user daily life and his dependence on caretakers, we must consider that, besides the input capabilities, the communication between the device and the person may also be compromised. Alternative feedback should be considered.

Different capabilities, scenarios and communication mean and bandwidth influence the interaction therefore the dialogues for each situation must be considered to maximize performance in each context.

Usability and Mounting

Another important issue to consider is that the caretakers are not myography experts and they may not have any knowledge or training on electromyography and the designed system. Therefore, besides the need to be easily mounted, the system must deal with the mounting inaccuracies that are likely to take place. Also, to ease the mounting process, the system should consider default locations and usage templates that can be followed and easily or automatically configured.

Although the system, to guarantee scenario and user adaptability, must permit widely variable setups, a set of default wearable templates may be studied and provided. Those should consider the possible interaction mechanisms but also other aspects that influence system usage (electrodes locations and aesthetics). As an example, a pair of glasses can be instrumented to have two differential electrodes placed near the *temporalis* muscle (one on each stem).

Robustness and Independence

Considering the limitations of the target population, it is important that the system acts accordingly to what is expected. Although this is always true for any system, in this particular situation, where the user capacities are limited, erroneous commands can be difficult to recover from. If these situations occur recurrently, they can lead the users to give up.

Moreover, besides the myographic activity processing and interference detection and removal, the system should be able to deal with spasticity (involuntary movements). As this cannot be achieved automatically, the interaction processes should consider dialogues that enable their elimination. Overall, the system should be able to detect, within possible, involuntary actions and system flaws.

Ease of use

The system is required to be easy to use and minimize the user's effort. Indeed, fatigue should be considered and the interaction should demand few effort from the user while still maintaining control on his side. Moreover, the system should fit the user, adapted to his capacities, habits and needs.

Lightweight

While putting our approach into practice we cannot forget that we are aiming at mobile devices (cellular telephones, Personal Digital Assistants, ...). Although component miniaturization has enabled these devices memory and processing capabilities improvement, they are still limited when compared with desktop computers. The proposed solution and its development must consider this issue and provide a solution that meets the user requirements both with accuracy and without unexpected delays.

3.2.4. Approach Overview

As previously brought up, the human/technology interface is more than just a piece of hardware. It is composed by the control interface, selection set and the selection method [reviewed in(Cook and Hussey, 2002)]. To achieve an effective human/technology interface, we must be aware that these components are interrelated and that each one of them deserves proper attention.

In the context of mobile device accessibility, we have already stated that tetraplegics are likely to be incapable to operate a mobile device through traditional control interfaces, whether keypads or touch screens). Moreover, the overall interaction with mobile devices is designed to interconnect with those input interfaces. Thus, to provide mobile accessibility for tetraplegics, we focus our attention in a suitable control interface but also how it interrelates with the selection set through adequate selection methods.

Furthermore, we believe that higher adaptability should be provided to achieve a non-fragmentary solution. Not only the control interface should deal with different capabilities but also the selection methods must be appropriate to the user's capabilities and interaction scenarios. Thus, we propose a solution that features Electromyography as the Control Interface, taking advantage of the users' residual capabilities to enable communication with the device, and an adaptive interaction approach that is able to deal with different selection methods depending on the input set and users' preferences (Figure 3.7). This adaptability also depends on shifting information organization and information presentation (including feedback). However, the selection set is maintained, when possible.

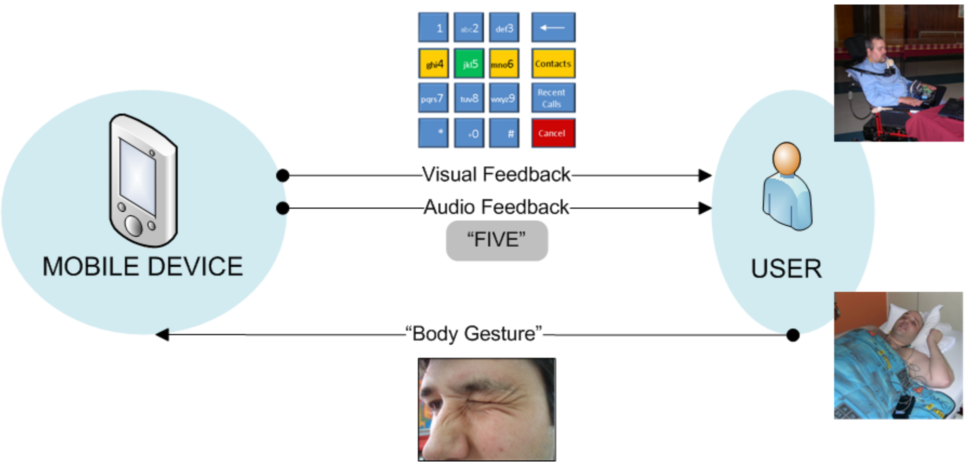
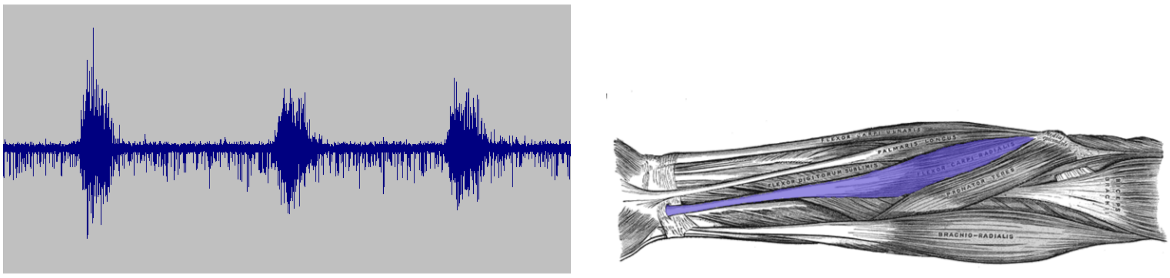


Figure 3.7: Approach Overview

In the next section, we look into Electromyography, its use in Human-Computer Interaction and present its advantages as well as issues to be approached. Also, and the most important, we justify why we have selected electromyography to bridge the gap between the user and the device. In section 3.2.6 we define the remainder of our approach, focusing on information presentation, adapting the device to the user's scenarios and preferences.

3.2.5. Electromyography

Electromyography is defined as the study of the muscular function through the analysis of the electrical signals generated by muscle activity. Therefore, it is the muscle activity graphical representation (Figure 3.8).



(a) Raw EMG Signal (b) *Flexor Carpi Radialis*

Figure 3.8: Sample of monitored muscle with three contractions

Physiological Background

Muscle contractions are preceded by electroquimic currents that go through the fiber membranes, creating a potential difference between active and inactive zones. This electrical potential difference can be captured, due to the conductive properties of biological tissue, at the surface of the human body via electrodes. However, the signals detected have low amplitude and must be amplified before being registered (De Luca, 1997; Correia et al., 1992).

There are actually two different ways to collect EMG signals: at the surface of the skin (surface EMG) or using needle electrodes in direct contact with muscle fibers. These two different setups are used with different goals. Needle electrodes have the advantage of capturing the signal from a muscle without interferences and no *cross-talk* from the surrounding fibers. However, they are intrusive and prevent the user from executing free gestures. On the other hand, surface EMG collects, at the surface of the skin, the sum of the activity of all the active muscle fibers in the detection area (Correia et al., 1992).

The surface electrode is a sensor composed by two different parts: detection surfaces, normally metallic (silver is commonly used as it presents a stable polarization), that are placed in contact with the skin and capture the myographic signal, and all the structure that supports it (Figure 3.9). The area of the detection surface influences the impedance and the volume of the detection. The larger the area, the smaller the impedance and bigger the detection volume (Correia et al., 1992).

The amplitude of the EMG signal is stochastic (random) in nature and can be reasonably represented by a Gaussian distribution function. The amplitude of the signal can range from 0 to 10 mV (peak-to-peak) or 0 to 1.5 mV (rms). The usable energy of the signal is limited to the 0 to 500 Hz frequency range, with the dominant energy being in the 50-150 Hz range (DeL, 2002).

The collected EMG signal depends largely on the mounting apparatus. Indeed, the electrode influences the signal in a way that it is difficult to improve the signal quality after the acquisition. One important factor on the signal-to-noise ratio and signal fidelity is

Figure 3.9: Different surface electrodes

the technique to collect and amplify the sample. There are two different techniques to acquire surface electromyography: monopolar and bipolar. In a monopolar configuration, only one electrode is placed on the skin over the muscle to investigate and the electrical potential is detected relatively to a reference electrode placed in a *neutral* zone (a place not affected by the activity being generated). This approach presents weak spatial resolution as it collects all the potential difference between the detection and reference electrodes, gathering activity from several motor units.

To achieve a better spatial resolution and increase noise rejection, a bipolar configuration is normally used. This differential amplification technique is shown schematically in Figure 3.10 and it consists on detecting the signal at two sites, subtracting the two signals and amplifying the difference. Therefore, all the signals that are common to both detection sites will be removed and the difference will be amplified. The rejection will include signals originated in other muscles but also distant power line signals as they will be common to both detection surfaces. This procedure relies on a high accurate *subtractor* whose accuracy is measured by the Common Mode Rejection Ratio (CMRR). A perfect subtractor would have a CMRR of infinity. A CMRR of 32,000 or 90 dB is generally sufficient to suppress extraneous electrical noises.

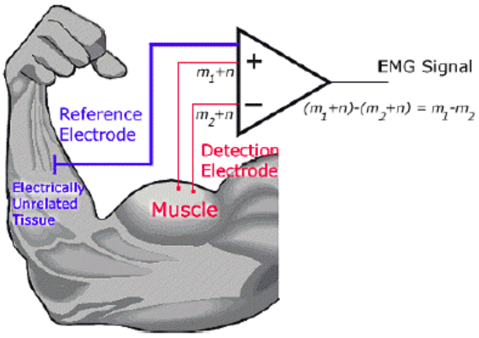


Figure 3.10: Differential Amplification Scheme

Electromyography and Human-Computer Interaction

The recurrent and increasing electromyography study in medicine related areas led to a great scientific investment to improve the myographic signal acquisition and analysis process. These advances culminate with the possibility to use portable electromyographic devices that communicate via wireless with a processing system. Portability makes it possible for any individual to carry and use an EMG device with great social acceptance (Costanza et al., 2004). EMG devices portability and reduced size easily lead to its use in HCI with work carried through in the area of Accessibility, Robotics, Affective Computing, among others. In the next sections, we present some of the myography-related research areas and point out some relevant projects. With this overview we intend to present the capabilities of electromyography as an interaction mechanism but also show the research lines followed.

Rehabilitation

Besides the projects and research lines presented in section 2.2.4, myographic activity is also used as an input mechanism within other accessibility scopes. As an example, (Coleman, 2001) studied EMG to improve and induce movement in the elderly. By including EMG biofeedback in the system they allow patients retaining muscle contraction capability to participate in practicing motor control activities, regardless of their ability to generate joint movement. The system detects muscle contractions and provides information to the users in a form of feedback that induces the patients to contract their muscles in a specific way. The author chooses to use entertainment capabilities to provide the feedback *to get the patients going*.

Gesture Recognition

Several researchers have leaned over gesture recognition using electromyography. The majority of the projects target at a arm operated joystick or arm-operated mouse. The Biofeedback pointer (Rosenberg, 1998) is an example of this kind of systems and enables the user to control the mouse pointer by wrist motion. The system monitors the user's commands with four electrodes placed in the forearm (Figure 3.11).

In the same scope, Wheeler et al. (Wheeler and Jorgensen, 2003) presented Neuroelectric Joysticks and Keyboards, recognizing up to 9 wrist and hand motions (keypad) with a forearm band (Figure 3.12). Besides developing an EMG-joystick controlled flight simulator, the authors also presented a system that detects *typing keypad numbers on the knee*. While the first system involves 4 electrodes, typing requires 8 electrodes and a complex

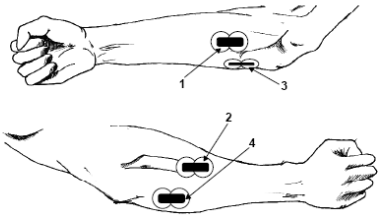


Figure 3.11: Biofeedback Pointer (Rosenberg, 1998)

recognition system (11 Hidden Markov Models).

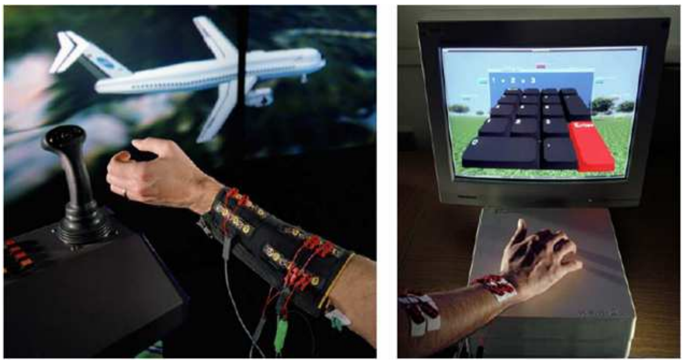


Figure 3.12: EMG Arm Joystick (Wheeler and Jorgensen, 2003)

Mobile Computing

(Costanza et al., 2004; Costanza et al., 2005) presented electromyography as a subtle and intimate interface for mobile interaction. They argue that a system composed by a simple electrode, that can be used without no one noticing, is perfect for event reaction while on the move. Indeed, the user is able to respond to system *questions* without disrupting the environment.

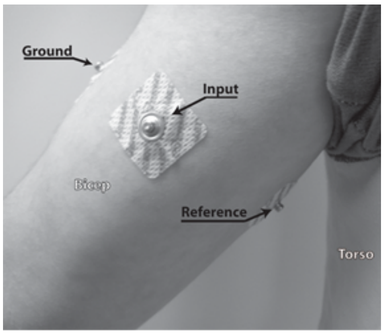


Figure 3.13: Subtle input interface (Costanza et al., 2005)

Prosthetics Control

Another interesting research area is prosthesis control. The majority of the projects in this area try to enhance the control of mechanical prosthesis using myographical signals as input. Considering a hand-amputee, if movement intentions can be identified and they can be reproduced mechanically (enhanced mechanical prosthesis) then the users will be able to have a functional hand prosthesis (Eriksson et al., 1998; AO and AB, 2001; Soares et al., 2003). Indeed, these movement intentions can also be used with function electrical stimulation grasping systems (Saxena et al., 1995).

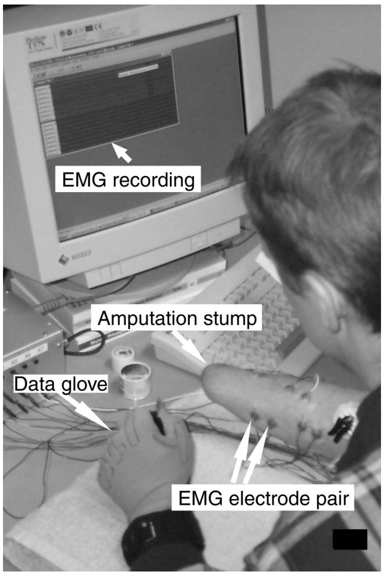


Figure 3.14: Prosthesis Control (Eriksson et al., 1998)

Affective Computing

In the last few years, the study of users' emotional behavior in the Human- Computer Interaction (HCI) field has received increasing attention (Picard et al., 2001; van den Broek et al., 2006). Emotion recognition is used to perceive usability problems but also to enhance interactive experiences. As an example, (Branco et al., 2005) focus on the relationship between user emotions and perceived usability problems. The authors propose to observe users' spontaneous facial expressions, by monitoring three muscles groups (corrugator, frontalis, zygomatic), as a method to identify adverse-event occurrences at the user interface level (Figure 3.15).

Sub-Vocal Voice Recognition

Figure 3.15: Facial Emotion Recognition (Branco et al., 2005)

It is worth noting that even sub-vocal recognition systems are currently under development. They use wearable myographic sensors to collect nerve signals transmitted from the brain to the vocal cords when the subject ”reads silently to himself”. The sensors detect the nerve signals that generate this sub-vocal speech and relay them to a computer program (Figure 3.16). Applications of this technology include improved voice recognition systems, systems allowing the transmission of vocal commands in noisy environments (Manabe et al., 2003; Jorgensen and Binsted, 2005).

Figure 3.16: Subvocal Voice Recognition (Jorgensen and Binsted, 2005)

Why Electromyography?

We selected electromyography as the input technology because it gathers the required characteristics for a mobile solution that is available during the day, through several scenarios, ambient shifts, and by different users.

Adaptability As the number of voluntarily contracted muscles is large, several acquisition scenarios are possible, including cases where the impairments are enormous. While a C5 impaired user can control his shoulder and neck muscles and those sites are presented as possible monitored inputs, a C1 user, which is totally paralyzed from his neck down, can control an interface by blinking his eyes. Electromyography offers us the user adaptability required to deal with the different user’s and their capabilities.

Another one of our goals is to provide scenario adaptability. Electromyography also provides it as the same or different setups can be used to control the interface. The important requirement is that the user and the system are aware of the input set being used at any given time.

Exhaustiveness Electromyography covers a wide scope of users as the only requirement is to have a voluntarily contracted muscle that can be monitored. But, one important issue is performance. A more capable user should be able to use a wider input set and possibly a more sophisticated interfacing scheme. Indeed, if the user controls several muscle groups, those can be monitored to issue different commands and the cardinality is only limited by user's memory limitations. Normally, no more than four muscle groups are monitored.

Screen Independence The independence from a display creates the possibility to use EMG in a mobility scenario. It also makes possible to interact when the users are lay down with no visual feedback, as long as alternative feedback is provided. While the majority of the techniques require some sort of position or screen dependance, electromyography can be used without any accommodation or position restrictions.

Ambient Independence An EMG-based solution is independent from lightning conditions, sound or surrounding movement in contrast to EEG, tracking and voice based approaches. Also, when compared to other physiological signals, myographic signal presents the best signal-to-noise ratio and higher amplitudes, which eases its processing and makes it a good candidate to voluntary device control.

Electromyography Drawbacks and Issues

Although suitable to address the requirements of the proposed approach and offer tetraplegic users a suitable input mechanism independently of the lesion severity and accommodation, electromyography faces some issues and drawbacks that need to be addressed.

Setup Apparatus The major drawback with an electromyographic solution is the awkward setup required. Indeed, the dependance for a set of wires and the necessary electrodes attached to the person's skin are incommodative. Moreover, if we consider a setup with several monitored muscles, the apparatus increases and the solution is likely to be rejected. Not only, the solution may have aesthetic issues but also, the mounting requirement time may lead to drop out. Moreover, to achieve accurate repeatability, the mounting should be made exactly within the same conditions. This process is hardly achieved by a regular user (caretaker).

Interferences Although with a relatively high signal to noise ratio, the electromyographic signal is likely to be contaminated by noise. The noise may be provenient from the electronics components in the recording equipment as every electronic equipment generates noise.

The signal is also likely to suffer interferences from the ambient, such as radio and television transmission, electrical-power wires,...*The dominant concern for the ambient noise arises from the 60 Hz (or 50 Hz) radiation from power sources. The ambient noise signal may have an amplitude that is one to three orders of magnitude greater than the EMG signal* (DeL, 2002).

The signal can also present motion artifacts that can be due to the motion between the electrode and the skin or due to cable movement. *These artifacts have most of their energy in the frequency range from 0 to 20 Hz. Also, the amplitude of the EMG signal is quasi-random in nature. The frequency components between 0 and 20 Hz are particularly unstable because they are affected by the quasi-random nature of the firing rate of the motor units which, in most conditions, fire in this frequency region* (DeL, 2002).

Involuntary Movements We monitor muscle contractions to permit interface control. However, these muscles can be contracted without the intention to operate the device. Considering the target population, we must take into account *spasticity*. The involuntary contractions and subsequent movements can lead to involuntary commands.

3.2.6. Interaction Profiles

Our approach uses electromyography as the communication channel between the user and the device and features a set of interaction profiles that deal with the different possible situations. To that extent we had to explore alternative interfacing schemes, that enable interface control through a more reduced input set. However, the interfacing selection must be done considering the tasks to be fulfilled that feature a high cardinality variability in the selection set and looking at the several possible scenarios and users.

To offer mobile accessibility to a wide group of users and scenarios, and as regularly used when the capacities are reduced, scanning solutions are provided. *Scanning selection involves presenting items until the user indicated that the desired item has been reached, therefore requiring far less motor skills than the direct selection technique. Items in the selection set are displayed through a predetermined or user-triggered item-selection process. The user has the* *option to either accept or decline the item presented by the facilitator* (Surdilovic and Zhang, 2006). To assure the extensibility of the solution as well as the performance, different interaction approaches should be provided. The studied approaches are diverse and are presented in Table 3.5.

Method	Minimal Input Set Cardinality	Navigation	Selection
Automatic Scanning	One	Dwell	Input 1
Inverse Scanning	One	Input 1	Dwell
Directed Scanning	Two	Input 1 and 2	Dwell
Coded Access	One	-	Input 1

Table 3.5: Possible interfacing methods and minimal requirements

With Automatic Scanning, groups or items are automatically highlighted or scanned in sequence. The highlight pauses at each group/item for a pre-set time (dwell). The user may select a group or item when that group or item is highlighted. The user must be able to make the selection within the dwell time, therefore this scanning interval must be configured and adapted to the user. If the user is able to issue other commands, those can be used to Cancel or Accelerate Scanning, for example.

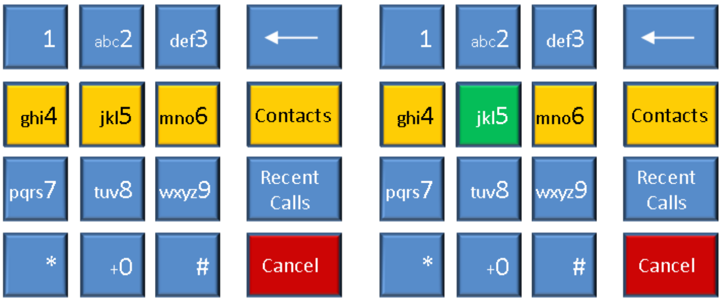
Inverse scanning augments the control on the user side and increases performance by exchanging the function of the input and pause times. With inverse scanning you advance the highlight by issuing a command. This scanning can be continuous (the highlight pauses at each item for a certain time but continues the ”navigation” while the command is being issued) or discrete (when the command is issued the selection advances one item). The advantage of inverse/step scanning is that timing is not as critical as with automatic scanning and you have greater overall control. If an extra input command is available, selection can be added and the user gathers overall interface control.

Directed Scanning is similar to inverse scanning but offers the user higher control degrees. Input commands act like a joystick and enable directional navigation. Selection can be made with an extra command or by dwelling for some period.

Coded Access regards item selection through input encoding. We feature this encoding method as options can be offered as numbered items. The user is able to select an option by issuing the selection command the number of times required to select the desired item. Although it is only feasible for a limited number of options, it offers the user higher control with only one input command. Fatigue as well as comprehensive feedback should be provided.

As for scanning solutions are concerned, different navigation options can be provided:

Row-column. Rows of items are highlighted from the top down one at a time. A selected row is then highlighted column-by-column (item-by-item) until the desired item



(a) Row Selection (b) Item Selection

Figure 3.17: Row-Column Scanning

is reached and selected (Figure 3.17). The highlighting returns to the first row after a selection. Column-Row highlighting is also possible although it is not so commonly used.

Group-item. Groups of items are highlighted until a group containing the desired item is selected. Then items within that group are highlighted until the desired item is reached and selected. The highlighting returns to the first group after a selection.

Item scanning. The items are highlighted one at a time, usually from left-to-right and top-to-bottom until an item is selected. After a selection, highlighting begins again with the first item and repeats scanning (Shein et al., 2003).

It is important to notice that for a specific scenario there are some available options and the user may be able to show a preference. However, some users and scenarios highly restrict the interaction scheme. Besides input capabilities, the feedback from the device is also very important and the type of feedback can also influence the interaction profile.

Non-Visual Scanning

As we have already stated, the physical impairments associated with a severe neuromuscular disorder are likely to disable the individual to have access to a mobile device but also to receive visual feedback from it. Furthermore, mobile interaction is still highly visually demanding. However, to provide a mobile device control interface for tetraplegics we had to consider both interaction channels as, to achieve success, the gap must be bridged both ways. Looking back to mobile interaction and using menu navigation as an example, it is clear that having control over the device and maintaining the device within reach is essential both to interact with the keypad (or touch screen) but also to see the selected application, the status of the device. One common solution to overcome visual inabilities is replacing the information traditionally offered visually with auditory cues. Indeed, considering the scenario where the device is not in the user's line of sight, we may consider the user as being interaction-blind. Although the user may be visually capable, in this scenario, he faces similar difficulties as a blind user might and the audio channel is a good candidate to circumvent the temporary communication requirements.

However, and considering the aforementioned scanning solutions, some navigation scenarios are not suitable with a non-visual scanning solution. Looking back to menu selection, if a row-column scanning method is employed, it is difficult to succeed as no auditory cues are offered to surpass the lack of visual feedback. Considering Item Scanning, or even Group Scanning, where there is a semantical meaning connected with each scanned group, the only requirement is to read the actual selection to the user. In a Row-Column Scanning, sometimes this could be difficult to achieve as a row may not have items that can be grouped or described easily.

Once again, we can learn from the interaction a blind user has with the computer, particularly web navigation. Actually, for a blind user to read a web page it needs to be carefully created as all content-related items must be clearly identified. One concept that is also used, is the aggregation of items, which can also be labeled to improve comprehension. Therefore, aiming at higher performance levels, it is important to offer the capacity to navigate using the same aforementioned scenarios.

3.3. Concept Preliminary Evaluation

A tetraplegic user with severe motor limitations is unable to operate a mobile device in several different conditions. Our approach to enable mobile device control by a diverse set of users within a diverse set of accommodations takes advantage of the users' physical residual capabilities (i.e., eye movements, neck movements, chin movements,...) to bridge the gap between the user and the device. On the other hand, as the input command cardinality is likely to be reduced we also redesign the interaction between the user and the device, adapting the input requirements to the user's momentary capabilities.

One aspect that is important to consider is device feedback. As previously underlined, the users are likely to feature accommodations where no visual feedback with the device is guaranteed. Thus, and to guarantee the dialogue between the device and the user (and vice-versa) we enriched the communication with audio feedback.

Although the tasks are maintained, there are several differences between our approach and the traditional way to operate and interact with a mobile device. It was therefore important to evaluate the approach effectiveness and if the users were able to achieve the desired results. The following sections present our preliminary user evaluation on the presented approach.

3.3.1. Motivation

We performed this preliminary evaluation to assess with the users the validity of our approach. One important feature to be evaluated was the suitability of the body residual movements as input commands. Also, and equally important was to verify if our interaction profiles dealt with the user's scenarios and covered the possible divergent situations. In this evaluation we were also interested in assessing the user's preferences considering monitored locations, input cardinality and input mode (i.e., type of scanning).

The research questions to be answered with this evaluation are available in Annex A2.3.3.

3.3.2. Procedure

The evaluation was composed by a set of tasks to be fulfilled with the mobile device. This tasks had to be accomplished in two different scenarios (with and without visual feedback) featuring, within each scenario, two different interaction profiles (automatic and inverse scanning with one and two input commands respectively). The evaluation plan is available in Annex A2.3.

Each session starts with the introductory remarks, users filling a background questionnaire (Annex A2.2) and signing a consent form.

The evaluation is composed by four different task scenarios (Annex A2.4) which gather some of the main operations performed in a mobile device (Calls, Messages and Navigation). To answer the proposed research questions, we chose to employ a Wizard-of-Oz technique. The Wizard-of-Oz (Dix et al., 2004) is a simulation technique that does not require much computer supporter functionality because it features human intervention to replace the missing functionalities. The prototype for this evaluation included all the feedback (visual and audio) as well as all the mobile device navigation features and functionalities. However, all the interaction between the user and the device was simulated. At this point, we intended to evaluate the interaction and the effectiveness of the approach (residual body movement/contraction) but do it independently from the method used to capture those events. Moreover, we wanted to collect information from this setup to serve as a baseline to a more instrumented and full-featured prototype.

To capture the several possible scenarios we ask the users to perform each task four times, two with visual feedback and another two times with only audio feedback. In both scenarios, each of the trials were performed one time with only one input command (featuring automatic scanning) and three input commands (featuring directed scanning). To avoid the results to be biased, we have switched the order of the tasks between users. Also, in the different executions (different schemes) of the same task, we have also changed the items positions (only the *Back/Exit* item was always presented last). However, as the number of users is limited, there can be some results that are affected by previous learning in some tasks. Meanwhile, as this exploratory evaluation meant to evaluate the approach as a whole, we have concluded that it was not an issue if we were not going to evaluate or compare the results between tasks with different variables. Indeed, what we aim to find in this evaluation is if the overall approach suits the user needs in all the scenarios and not if it is faster in a condition than another. Also, we desire to find possible errors and improvements to be made and get the first user impressions on the approach.

Concerning automatic scanning, we have set up a pre-determined timeout of 3.5 seconds. This time window is large enough to offer the users with the required confidence to control the application. However, it can be considered slow and augment the time to complete the tasks. Once again, this is not our main concern in this preliminary evaluation.

For each setup, the user was offered a set of movements (depending on his capacities). The selection was made from face and neck locations: temporalis (blinking eyes), frontalis (frowning), mentalis (putting lip down), masseter (clenching teeth), sternocleidomastoid (neck movement).

To guarantee a suitable analysis, we recorded video and audio of the entire session and performed a semi-structured interview to collect the user's opinions. The guidelines for the interview are available in Annex .

3.3.3. Software Tools

This evaluation includes a functional mobile device prototype featuring the main mobile device tasks (Making, Receiving and Managing Calls; Writing, Sending, Receiving and Managing Messages; Menu Navigation). This prototype can be operated through the keypad and, to enable the wizard to operate it without interfering with the user's interaction, it features network control.

3.3.4. The Users

The evaluation was performed with 4 users, 2 tetraplegic and 2 able-bodied users (Annex A2.2) with ages between 21 and 31. All the users are used to work with mobile devices and usually have the mobile devices near them. All of them perform tasks with the mobile device in a daily basis.

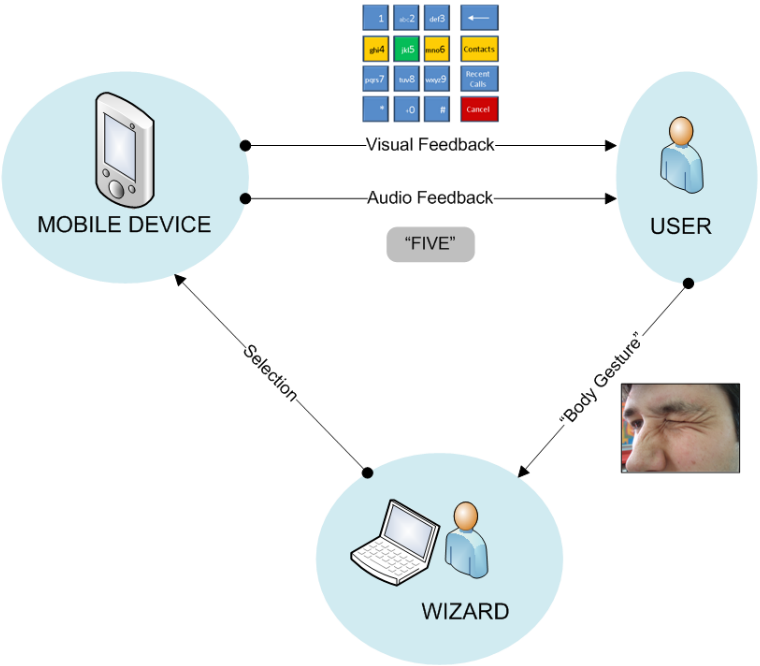


Figure 3.18: Preliminary Evaluation Setup

3.3.5. Results

The first result worth mentioning in this evaluation appears even before the tasks have started, in the process of body sites selection. It is interesting to observe that the users selected body sites that are good candidates and rejected the most problematic pairs (i.e., masseter). However, three of the users were also evaluated in the Input Recognition Evaluation and that is likely to have influenced their choice. For Automatic Scanning with only one-input command, the users have selected the temporalis on the right side of the face (50%) and the frontalis (50%). As for Directed Scanning with 3 commands, the users have all selected the temporalis (2 sites) and the Mentalis (75%) or the Frontalis (25%).

Concerning the tasks, all the users were able to successfully complete the trials. This evaluation raw results are available in Annex A2.7. The presented times include the initialization time (starts at idle state) and must be analyzed having in mind the 3.5 seconds timeout. Indeed, this timeout has high impact when the user is featuring only audio feedback as, for example, for a row description the user is likely to have to hear the all sentence before issuing a command. This happens even when Directed Scanning is being used as the user still needs do hear the description before navigating further. On the contrary, when the user has visual feedback, he can quickly navigate to the desired position. The results reflect these differences but are generally close to the expected values for a error-free navigation (Figure 3.19). That can be confirmed with the low number of errors detected.

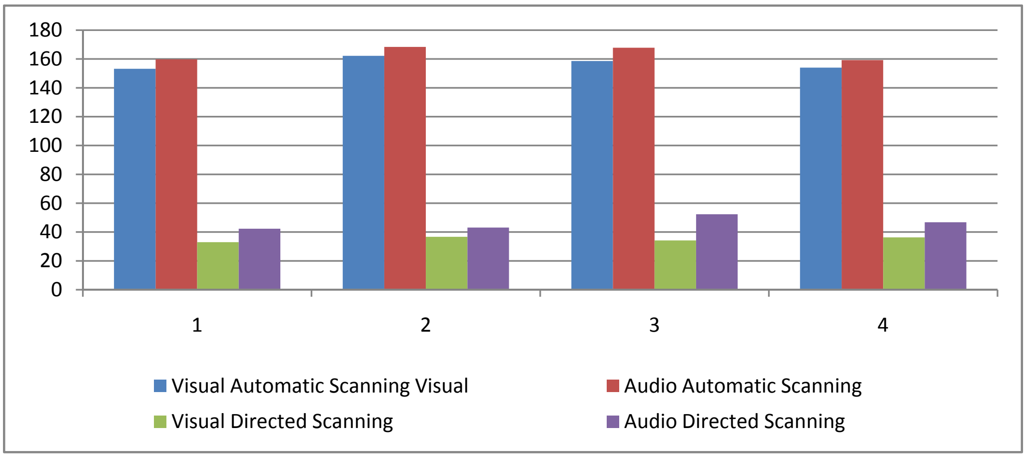


Figure 3.19: Task 3 - "Write Message" Completion times

Excepting one error related with the selected body sites (the user made the wrong gesture and entered a row instead of navigating to the next row) and one error due to user distraction (user forgot the status of the sentence to write), all the other errors appeared in the Audio Feedback scenarios. Those errors were caused due to late selection of the desired item (the selection was already in the next item). Indeed, we found that the prototype featured a flaw that influenced the results and created most of the errors: the timeout was being started before reading the description. For large sentences like a row description (i.e., items in a menu row), the users had not 3.5 seconds to perform a selection but, in some cases, 0.5 seconds. The solution was to start the timer after reading the description which makes sense as the timeout is related with the user decision time window.

The users were generally satisfied with the system and showed positive about controlling the device with body contractions. However, some of the users stated that they would do it only with a subtle interface that others would not identify. Full capable users agreed that using the system to react to events while walking or driving would be interesting and tetraplegic users stated that the system would offer the opportunity to be always connected to the world. Also, one of the users enlarged the scope of the approach and suggested that the system could be used as an unique communication and control unit. Considering the monitored locations, the users varied as full-capable individuals would select locations that are covered with clothes (mostly biceps and triceps) while tetraplegic users restrained themselves to our suggestions (temporalis, frontalis, mentalis) with the exception of sternocleidomastoid and trapezius muscles (shoulder and neck movements).

Overall, we believe that the approach is valid and well accepted by the users. Specifically, we can now answer the research questions for this evaluation:

Are the users able to associate "body gestures" with actions? Yes. The results showed that the users had no difficulty in associating a contraction with a certain action and use it to control the mobile device. Moreover, the users were able to do it in the context of several tasks.

Are the users able to operate the device within different accommodations? Yes. Not only the users can control the device independently from the accommodation as the evaluation showed that the users can do it even if no visual feedback is offered.

Does performance reflect accommodation and feedback type? Yes. As expected, the need to hear an item description makes the interaction and item selection a little slower. This difference between feedback type performance is even more accentuated when the user has higher control degrees (i.e., Directed Scanning).

Do users require help during interaction? No. The users were generally confident and able to complete the tasks successfully.

Are there any main/universal collection point candidates? We believe so. However, the fact that most of the users were already influenced by previous evaluations does not allow us to conclude the universality from their selection.

How does the number of input commands influence performance? If the user has higher input cardinality and an adequate interfacing scheme, the performance is likely to increase. This was verified in the performed evaluations.

How does the number of input commands influence confusion? The users stated to be more confident with less input commands although they have performed better with higher cardinality. In a first approach a high number of commands increases confusion.

Are the users comfortable with the interaction profiles? Yes. The users stated to be comfortable and confident on the system.

How do the users react to interfacing schemes shift? In this evaluation we have only performed one shift. The users asked questions before using the system with the new interfacing scheme but had no visible problems while interacting with the system.

Does the interaction time cause frustration or errors? In timeout-based scanning solutions, and considering a *generous* timeout and a wide selection set (i.e., text-entry), the users can become a little frustrated. Although, we believe that when they become more experienced, the timeout can be reduced and the scanning experience will be improved. However, this frustration was only stated by full-capable individuals as tetraplegic users are used to deal with scanning solutions.

User Suggestions One problem that some users found was related with erroneous commands: when a user entered an undesired level of selection (i.e., selecting a row) it had to wait for a significant amount of time for the system to recover and bring the user back to the previous navigation level. One user suggested that, at the end of each line, a *Back* item should be available. The users would then be able to undo a mistake just by navigating in the selected row. We believe that this suggestion goes a little further. Indeed, in solutions with reduced control (i.e., automatic scanning with one input command), the basic system functions should always be available in another way. Thus, if no Cancel/Back input command is provided, one should consider to enable its selection at any navigation level.

Other suggestion also related with scanning and erroneous selections was on the visual feedback. One user suggested that, like a semaphore, the selected item smoothly changed color from green to red, until the selection changes. By doing so, the user would have more information on the selection status and it would be easier to decide to or not to input a command. The users mentioned that this could also be applied to audio feedback with some kind of pattern that can be identified (i.e., sound volume).

4

The Myographic Mobile System

Chapter 3 define on the guidelines and basic concepts of our approach. Indeed, we believe to have focused limitations on the general assistive technologies panorama and particularly, present the lack of solutions considering mobile interaction for the severely motor disabled. We also delineated the basic foundations of our approach, instantiating the implications for design and presenting how electromyography fits with the interaction requirements. To properly evaluate the proposed approach, real users must use the designed system within real life scenarios. To accomplish this, we implemented a system for tetraplegics to control mobile devices using myographic activity.

4.1. System Architecture

We have defined an approach to mobile device control based on a new control interface but also featuring internal data reorganization to allow versatility and adaptation to the several possible interaction scenarios. With that end in mind, we have designed our prototype with three different modules that allow the separation between the control interface, data and service management and information presentation modules. The architecture of our prototype is depicted in Figure 4.1.

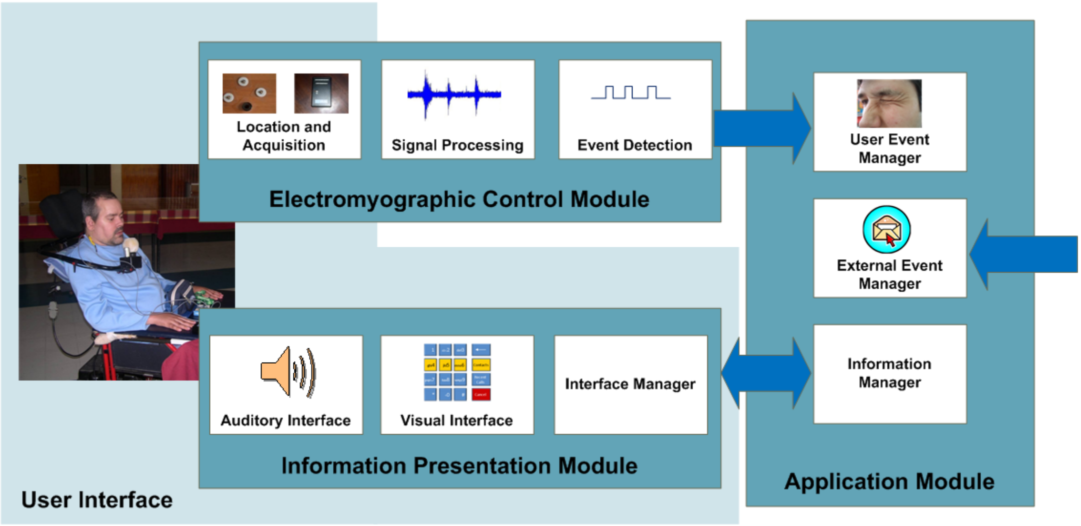


Figure 4.1: System Architecture

The **Electromyographic Control Module** features all the components related to the user myographic activity. Thus, this module is responsible to interpret the user's intentions and output an event to be processed by the Application. It features three different components, signal acquisition, signal processing and event detection. *Signal acquisition* relates to the signal collection at the surface of the user's skin and a set of processing steps that must occur near the collecting surface. This component outputs the raw myographic signal that must be processed to be readable and understandable. The *Signal Processing* component is responsible for this signal transformation and outputs muscle energy in a way that the computer can more easily identify onset and offset times. The Event Detection component is able to output meaningful events like muscle onset, offset and cable disconnecting by analyzing the processed signal.

The **Application Module** relates to the core of the application, the mobile device, its behavior and services. Besides the services already offered by traditional mobile devices, it features components to deal with the user (input commands) and external (i.e., incoming messages and calls) events. The *Information Manager* gathers the user's preferences and manages the application state. Besides translating the received events in meaningful mobile device application events, it also manages the internal application state so that the interface with the user can be performed accordingly.

The **Information Presentation Module** is directly connected to the information presented to the user. This information depends on the application state. In our prototype two types of feedback can be presented: auditory and visual. This module and the Signal Acquisition are the ones that compound the User Interface. They are interdependent in an interaction loop adapted to the user's needs and capabilities.

In the next sections, we offer further detail on each of our prototype's modules, presenting our options to guarantee a suitable dialogue with the user. We give special attention to the Electromyographic Control Module and, in general, the User Interface.

4.2. Working Material

The aim of our research is to bridge the gap between the tetraplegic user and a common mobile device. We believe that a common mobile device is one that features a screen, a keypad (or touch screen), and cellular communication functionalities. Looking at the actual panorama, bluetooth communication capabilities are also likely to be available.

Our prototype is designed and developed aiming at a mobile device with those common characteristics so the solution can be aligned with the panorama that user's face today and in a near future. The prototype was developed in C# for the Windows Mobile 5.0 platform. All the results presented in this document were gathered using a HTC Oxygen S310 smartphone (Figure 4.2).

Figure 4.2: Mobile Device - HTC Oxygen S310

4.2.1. Electromyography Portable Device

Our electromyography device collects samples at a 1000Hz sampling rate in 5 independent channels. It has a 110dB CMRR amplifier and a band pass filter between 25 and 500 Hz with gain 1000. It is a relatively small device (14cm * 8cm * 4cm) that can be carried in a belt or pocket (Figure 4.3).

It is a portable device which communicates by a Bluetooth interface with a 100 meters range. To collect the signals we use surface differential electrodes, with 1.5 cm radius (Gamboa et al., 2004).

Figure 4.3: EMG Portable Device

4.3. Electromyographic Control Interface

Understanding the muscle activity and interpreting accurately the generated myographic signal make us able to produce a system that is controlled by the user and his muscle contractions. However, to build such a system, several phases must be considered, from the signal acquisition to its processing and muscle onset detection. Also, as brought up before, the electromyographic signal presents several interferences that must be removed. To achieve the required accuracy, we developed a system that needs careful attention on its several phases: signal acquisition, signal processing and onset detection.

4.3.1. Signal Acquisition

The first phase in any myographic interface is signal acquisition. Besides the material to be used, we must consider the mounting sites as well as the hardware pre-processing steps. Both these aspects greatly influence the fidelity of the collected signal. As already presented, the electromyographic device includes processing components that improve the signal quality, removing interferences and noise (i.e., 25-500 Hz band-pass filter).

In order to get useful information concerning the muscular activity it is necessary to carefully analyze some aspects, from technical details of the electrode placement in the surface of the human body to the points where this placement must be done. Several aspects influence signal quality: skin preparation, electrodes placement position, electrodes fixation, electrodes distance and outside interferences (De Luca, 1997).

We have discarded all the skin preparation techniques as we do not think they are appropriate to an user interface. Besides, after several tests we observed good signal quality with small interference. However, as an example, to reinforce the surface electrodes adherence we created an elastic band for the neck (Figure 4.4) and two elastic bands for the forearm. We have not focused our attention in this special purpose devices as one of the contributions of our system is the setup freedom. The users can select the locations to be monitored. However, we also believe that the approach can be complemented with a set of special components that ease interaction and maximize success.

Figure 4.4: Neck Elastic Band

We used a 2cm distance between electrodes which guarantees good acquisition results, collecting the signal of a significant portion of the muscle and restricting, simultaneously, undesired signals to insignificant values (De Luca, 1997).

Basically, the electrodes can monitor any voluntarily contracted muscle. However, the signal frequencies and amplitudes are somehow different from muscle to muscle. Figure 4.5 presents the electrodes position options in a frontal view. It shows surface electrodes placement positions in the right side and deeper needle electrodes positions in the left side. Obviously, we only use surface electrodes as we are studying a wearable daily interface and want to keep users far from pain / discomfort.

The electrodes should not be placed in the motor point where it verifies a damping of the signal low frequency components. Besides electrodes placement position it is also important to see to the orientation of the electrodes in relation to muscular fibres. The imaginary line that joins the two surfaces (two surface electrodes as we are using a differential setup) should be parallel to the muscular fibres orientation. In our scenario it is not expected that caretakers are electromyographic experts nor that they have special attention when performing the system setup. Therefore, one of our goals is to provide a solution that deals with slight position and orientation shifts. Thus, the system is able to detect the user's intentions even if the setup is performed with slight position and orientation shifts as well as no skin preparation techniques.

Considering the target population and aiming at a wider number of possible users, there are some face muscles that can be selected as probable monitored locations. Moreover, some body gestures (i.e., blinking an eye) can be monitored in a particular muscle and isolated (from other muscle action potentials). If the user detains higher control of his body, the possible locations also increase. Movement of the neck, shoulders and arms can also be monitored and used to input commands to the system. The number of input commands is limited by the number of controlled muscle groups the user presents.

Figure 4.6 presents electromyographic signal samples collected in the *masseter*, *temporalis* and *frontalis* respectively associated with the actions of clenching teeth, blinking eye and

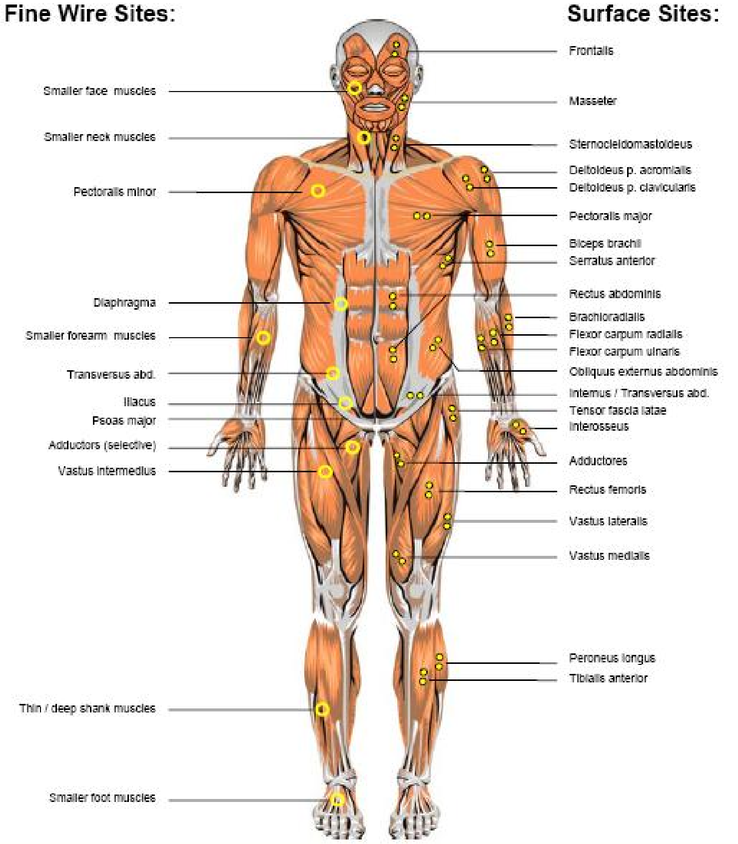


Figure 4.5: Electrodes frontal possible positions

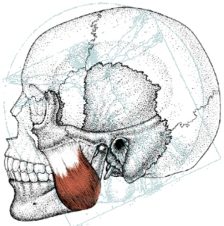
frowning eyebrows. In this example, we can observe the raw electromyographic signal (received from the device) and the same signal after signal processing (reviewed in next section).

4.3.2. Signal Processing

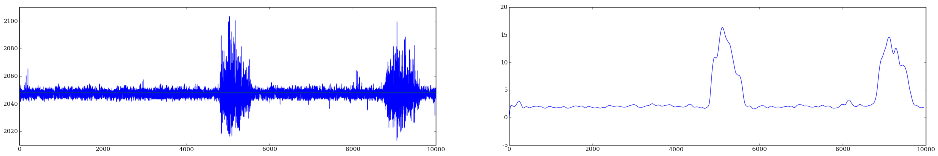
In order to extract useful information from the signal we need to process it. This processing phase transforms the signal into a more meaningful indicator and it includes components to gather a digital signal representation, amplify it to enable analysis, improve the signal quality and represent it in a transformed yet more comprehendible form.

The outcome of this module is a signal representation that is aligned with the system's purpose. Thus, the goal of the signal processing module is to transform the signal so we can identify muscle contractions, independently from the monitored muscle and with no previous information.

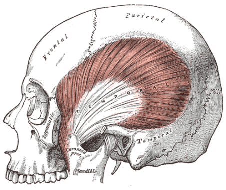
Some of the projects mentioned in the area of electromyographic human-computer interaction (Chapter 2.2.4) have strong pattern classification algorithms that offer them great reliability. However, the drawback is that, besides the need for long training sessions for



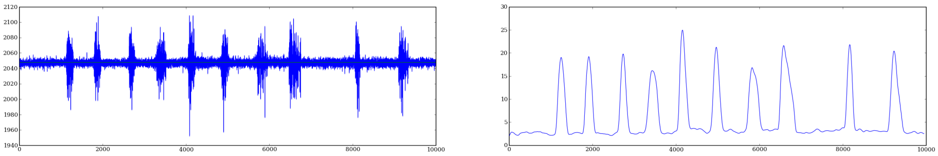
(a) *Masseter*



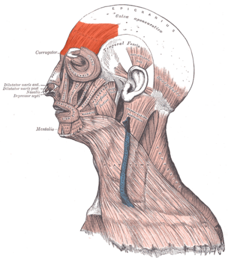
(b) Raw Sample (c) Processed Sample



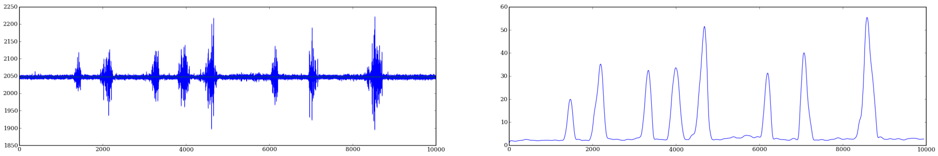
(d) *Temporalis*



(e) Raw Sample (f) Processed Sample



(g) *Frontalis*



(h) Raw Sample (i) Processed Sample

Figure 4.6: EMG Samples

each user, the systems require that the mounting sites and ”body gestures” remain constant. As we require high versatibility and adaptability, a feature-based algorithm is not usable. In our work we try to make a simpler approach adaptable to every user with no training required. Thus, we have developed a signal processing based approach.

Our signal processing module is composed by a hardware pre-processing and a smoothing phase (Figure 4.7).

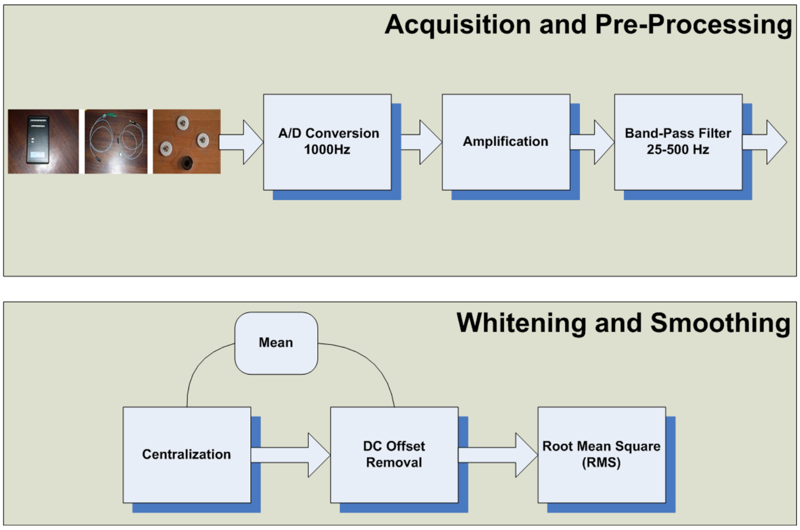


Figure 4.7: System Design

Hardware Pre-Processing

The electromyographic device, wires and electrodes gather the first component set in order to acquire and process the myographic activity. While some of these components are required in a system that aims at a digital signal analysis, other components relate to the signal quality improvement.

A/D Conversion

Analog signals are voltage signals that are analogous to the physical signal they represent. The amplitude of these signals typically vary continuously throughout their range. The analog-to-digital conversion process generates a sequence of numbers, each number representing the amplitude of the analog signal at a specific point in time. The resulting number sequence is called a digital signal, and the analog signal is said to be sampled (DeL, 2002, reviewed in).

One important technical item is the selection of the proper Sampling Frequency. To obtain a proper conversion of the complete frequency spectrum of a signal, the sampling rate must be at least twice as high as the maximum expected frequency of the signal. This relationship is described as the Nyquist sampling theorem (Nyquist, 2002) and it shows that sampling a signal at a low frequency results in aliasing effects. Considering electromyographic signals, almost all of the signal power is located between 25 and 250 Hz and scientific recommendations require a minimum band maximum of 500 Hz (Hermens et al., 1999; Freriks and Hermens,), which translates in a sampling frequency of at least 1000 Hz (Konrad, 2005, reviewed in,).

Our EMG device samples signals at a frequency of 1000 Hz.

Amplification

The EMG amplifiers used are differential amplifiers that subtract the value between two electrodes. This step of the process is essential to remove exterior interferences from the signal and to limit the motor units to be considered. Also, as EMG amplitudes are reduced, the amplifier augments the signal voltage so it can be analyzed afterwards.

Band-Pass Filter

Surface EMG, as a sum of several frequency waves, has its useful information located in a determined frequency band. Most researchers agree that the relevant information is between 25 and 250 Hz. The band-pass filter used in our system rejects below 25 Hz and above 500 Hz. This band-pass filter *cleans* several interference patterns that can reduce signal fidelity. For example, motion artifacts have most of their energy in the frequency range from 0 to 20 Hz. On the other hand, ambient noise is around 50/60Hz, a rich EMG frequency band, that can hardly be removed without reducing the signal significance.

Whitening and Smoothing

After the acquisition phase, we have a digitalized and amplified signal with a restricted frequency range. However this signal, called *raw* signal, although it has already been pre-processed, can hardly be interpreted by the computer if no further processing stages are executed. To allow an accurate signal interpretation we have to clean the signal and represent the muscle energy in a way that we can easily identify activation and deactivation times.

Centralization

The signal received from the electromyography device has a gamma of values between 0 and 4096, having this to be adjusted, since, really, the signal oscillates between negative and positive values. The centralization is a very basic operation and consists of deducting the base value (2048) from the signal.

DC Offset Removal

While most of the amplifiers work with an offset correction, it is possible that the signal baseline is shifted away from the true zero line. If this offset occurs and it is not corrected, all amplitude based calculations are invalid. This condition can by averaging the raw EMG signal (the mean value should be zero if no offset is present) (Konrad, 2005).

Thus, to remove the baseline offset, we add the samples to the set of received values already acquired and, with the average calculated on these, we calculate and remove this DC (direct current) offset, that can exist in the EMG signal:

$$y(t) = f(t) - m(t) \tag{4.1}$$

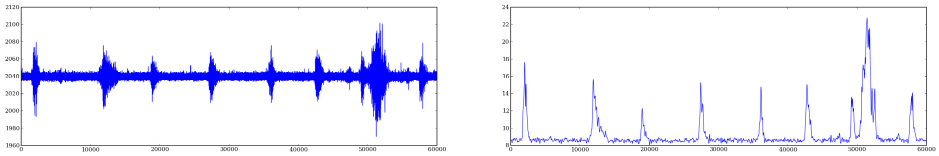
Linear Envelope

The interference pattern of EMG is of random nature. Indeed, the set of motor units changes within the diameter of available motor units and the way motor unit action potentials superpose is arbitrary. Thus, even if all the procedures are repeated exactly the same way, the raw EMG signal cannot be reproduced a second time by its precise shape (Konrad, 2005). This is true in medical and kinesiological studies and a greater issue in human computer interaction where we dismiss several preparation procedures and aim at a relaxed setup preparation. To overcome this problem, the non-reproducible part of the signal is minimized by applying digital smoothing algorithms that outline signal evolution during time. The steep pikes are discarded and the signal receives a *linear envelope*.

One common approach to envelope the signal is to apply a Moving Average algorithm. In this technique, based on a pre-defined time window, the window samples are averaged. The samples in the window are rectified before performing the average. Commonly, Full-Wave Rectification (the negative samples are reflected by the baseline) is applied as all the signal energy remains available, in contrast to Half-Wave Rectification, where the negative values are discarded (DeL, 2002). The signal averaging can be performed with a linear moving average but it can also be based on a Hanning, Hamming or Bartlett window. They are different in the way they weight the several samples in the window to be smoothed.

Another approach to signal smoothing is *Root Mean Square*. The root-mean-square (RMS) of a variate X, sometimes called the quadratic mean, is the square root of the mean squared value of X (Equation 4.2). The RMS reflects the mean power of the signal and is the preferred recommendation for smoothing (De Luca and Knaflitz, 1992). The RMS EMG is also applied to a moving window and time duration values between 50-100 ms are likely to work well as the real time impression is kept and the signal is smoother as

(a) C5 Tetraplegic User



(b) Raw Sample (c) Processed Sample

Figure 4.8: Tetraplegic person using the system (Two Input Commands)

desired.

In our prototype we applied the RMS algorithm value as it is a measure of the power of the signal, thus it has a clear physical meaning. Also, the application of the RMS translates in a signal with higher amplitudes and therefore, with easier recognizable onsets and offsets.

$$g(t) = \sqrt{\frac{\sum w(i)^2}{N}} \tag{4.2}$$

where N is the window dimension.

Figure 4.8 presents a tetraplegic user lying down operating the system using two input commands. It also presents one of the monitored samples (both raw and processed representations).

Onset Detection

Several clinical applications, like gait analysis and coordination studies, require the accurate detection of when and for how long the muscles are active. Therefore, several methods have been proposed for detecting the on and off timing of the muscle (Staude et al., 2001).

In clinical applications, the most common method for resolving motor-related events from EMG signal is still visual inspection by trained observers. However, as this method is unsuitable for the majority of the applications, other automatic solutions must be analyzed. *Single-threshold* methods, which compare the EMG signal with a fixed threshold, are the most common computer-based approaches of detecting the onset of muscle contraction. The accuracy of this detection depends on an appropriate threshold definition. The most popular approach to threshold definition calculates the baseline standard deviation (SD) (before muscle activity) and multiplies it with a pre-determined multiplication factor. Although a popular method, the standard deviation threshold definition can be difficult to set up for valid and repeatable results. The EMG signal varies between trials and subjects and the SD is likely to be largely different. This kind of method rely on criteria that are too heuristic.

To overcome the single threshold problems, other solutions have been proposed (Bonato et al., 1998; S. et al., 1998)(Staude et al., 2001, reviewed in). However, these approaches are too demanding and not suitable with our processing limitations and performance requirements.

Our system requires that muscle contractions are detected. Moreover, we are required to detect contractions from different muscles, from different muscles, at different times, with no manual identification. Also, as the user is able to select the monitored locations, the system has to deal with contractions that although aimed at firing a certain action, can affect more than one monitored muscle (i.e., if the user selects right and left masseter and clenches right side the left side is likely to be affected. However, there may be a difference and our goal is to identify it).

On the other hand, we are not required to detect the exact firing time as a delay of some milliseconds is tolerable. Also, most of the research on onset detection occurs in the clinical area where, as an example, the goal may be to identify problems in gait and coordination. The solutions surveyed analyze a signal independently from the other monitored locations.

We have developed two onset detection methods adapted to our requirements and goals, that take advantage of the characteristics and context of use. The first requires an initial Calibration Step while the second is similar to the standard deviation threshold-based solutions described above.

Calibration Mode

The calibration mode of our system tries to tackle the threshold definition problem for each signal collected by performing a preliminary calibration phase. This phase consists in asking the user to perform each of the monitored contractions, one at a time. With this procedure we aim to achieve two goals, define a user and situational threshold for each channel and use the information from the other channels to improve overall intention recognition. Moreover, with this calibration phase, we also desire to recognize erroneous situations (i.e., cable disconnecting, wire related interference,...).

In a multi-electrodes setup, one of the problems that may arise is the influence of a certain contraction in more than one monitored locations (even though that may not be expected by the user). Therefore, besides defining a threshold that suits a single channel configuration, we also intend to deliver a solution that is able to deal with this unexpected interferences. To achieve the aforementioned goal, we take advantage of the other monitored signals and time windows. Thus, we ask the users to make a contraction (a near-maximum voluntary contraction) in a determined time window. However, to define a threshold to the recalled location, in spite of analyzing its time window, we only analyze the remaining ones. With this approach, we define a threshold that deals with the worst case scenarios, when other muscles are being contracted. The threshold is defined as the maximum sum of the higher RMS value and a scale of the maximum standard deviation (calculated with inner 50-100ms samples), of those remaining time windows. Figure 4.9 presents the calibration step for the temporalis and frontalis setup. It is clear that the thresholds for right and left eye blink are easy to determine as during the remaining contractions the signal in that specific channel is almost stable. On the other hand, the frontalis presents contractions when the blinks are performed. Therefore, the threshold is higher and is near the High threshold value.

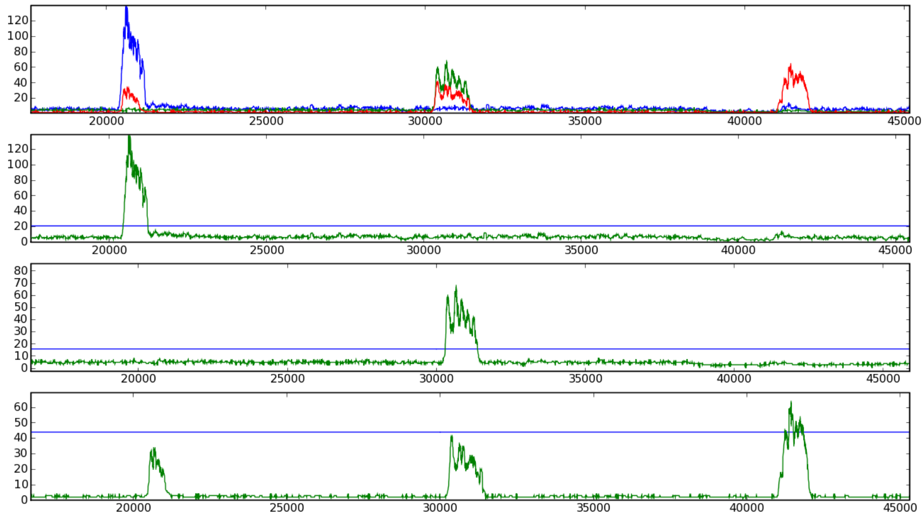


Figure 4.9: Calibration Step
The first chart presents the three signals. The other three charts represent the temporalis right, temporalis left and frontalis signals with the calculated low thresholds.

During the calibration process, in a time window referent to a certain contraction, we also collect the maximum voluntary contraction (MVC) as the RMS peak value of that window. This value summed with a scale of the maximum standard deviation value (calculated using 50-100ms inner time windows) is our high threshold.

This value enables us to detect abnormal situations and ignore erroneous commands. We only consider contractions that are quantified between the two thresholds. Moreover, this high threshold allows us to identify setups that are not feasible. Indeed, if the low threshold is higher, equal or even with a value too close (a scale of the maximum standard deviation referent to that contraction) to the high threshold, the monitored locations are discarded and the user can be warned. This detects setups that are not feasible but also situations where the user does not use a certain location (and does not perform its particular calibration). With this conditions the user is able to define an acceptable range of energy for each muscle contraction independently. It enables personalization and adaptability but also restricts the acceptable signals and therefore, reduces the probability of unexpected behaviors.

One particular situation occurs when only one signal is acquired: in this scenario the low threshold is defined using a window where no other contractions are performed. In this situation, and regarding the lower threshold, the two methods presented here are very similar. However, concerning high threshold, the single-location setup is equal to a multiple setup.

Although the signal is smoothed, single spontaneous spikes can easily exceed the threshold range and possibly be marked as a muscle contraction. To neglect this undesired commands, we define a minimum time (minimum subperiod duration) that the processed signal has to constantly stay between thresholds to be accepted as a muscle onset (i.e., 50 ms). Figure 4.10 present a set of recognized and unrecognized states. We can observe one false negative in the last chart. Also, we can observe two spikes that were correctly discarded. The correct choices are shaded in green while the uncorrect (one) is shaded in red.

Besides the aforementioned procedures, we have also included optional verification mechanisms that are able to improve recognition. Particularly, and although we believe our system to be accurate, it is still possible that a user performing a contraction still creates an acceptable contraction following the desired contraction. This can happen in the same location or even in one of the other monitored locations. As an example, we can observe neck lateral movement (leaning the head towards the shoulder) with both sternocleidomastoid sides being monitored. While leaning the head to one of the sides, is likely to be detected as a contraction in that side, finishing the motion and returning to normal position can also be detected as a contraction in the other monitored location. Although, this is not an expected behavior by the user, the contraction is probably being performed and it will not be differenced from the normal behavior.

Thus, if it is required and can be applied, we also define a mute window after a certain contraction (i.e., 100 ms). During that time window, after a detected action, the system

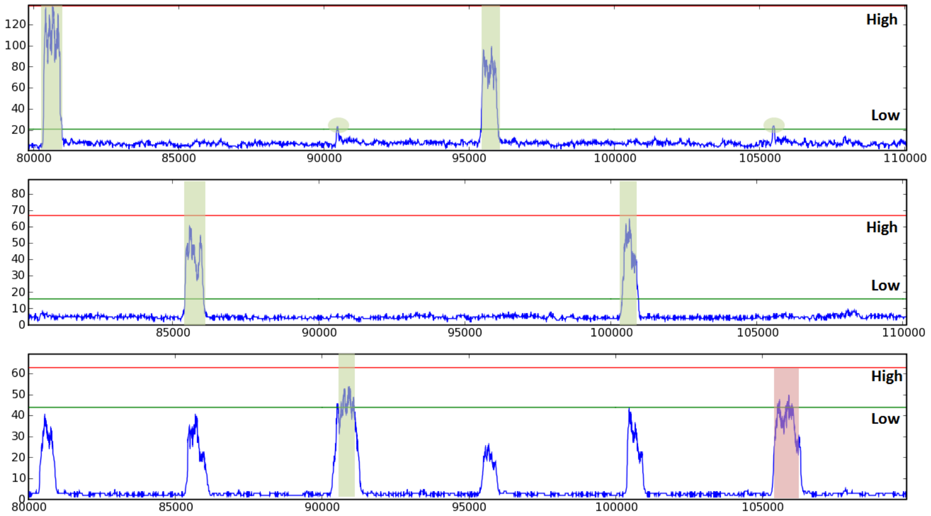


Figure 4.10: Recognition Procedure Illustration

will discard any possible actions.

One thing that is also possible is that two muscles are contracted in the same time window and the system detects both onsets. We believe that this can be a possible situation and useful for certain applications. Therefore, we have not included in the main recognition system, a component to analyze these situations. However, we have provided an optional component that can be used if the application requires. This component can eliminate this detections or decide between them. This decision is made according to the percentage of the contraction performed. This percentage is calculated in the range between the low and high thresholds. The signal with higher contraction percentage is selected. Thus, we select the contraction that is most likely to be the desired, as it reflects an higher intention considering the user initial calibration.

On the other hand, if the application permits, we output several detections from the recognition system.

The calibration mode allows us to detect and adapt the system to the user with a determined setup. If a shift is performed or a serious error situation is detected the user is able to request to calibrate the system again.

On-the-fly mode

On-the-Fly mode is very similar to the SD threshold algorithms described above. With this option, the user is able to use the system, with no previous calibration steps. The system detects muscle onset with an approach where threshold is estimated as a multiple h of standard deviations (Staude et al., 2001). Another "problem" with this mode is that modern EMG amplifiers are so noise free that the multiplication factor has to be increased to 8 times or higher to give reliable results. This situation can also be improved if the user is able to define a sensitivity feature that influences the multiplication factor.

To improve recognition, this mode also includes Minimum Onset Window and Offset Window procedures. This mode is not as accurate as the calibration mode but it can be used if the monitored locations are not likely to interfere with each other.

Some of the projects that use electromyography as a control interface have strong pattern classification algorithms that give them great reliability but the drawback is that they need long training sessions for each user. Our onset detection modes, although may require a calibration step , are not too long (5 seconds per monitored location) and can offer the user with an instant feedback on accurate calibration and recognition. Besides preparing the system to further interaction we believe that this step is important to make the user confident on using the system. We also believe that the advantages of the calibration step make it worth.

4.3.3. Experimental Evaluation on Input Recognition

To analyze and evaluate the extensibility and versatibility of the system we have performed a preliminary user evaluation. In this phase, we have focused our efforts in validating the electromyographic signal as a suitable control interface, evaluating contraction recall in several sites as well as possible setup collisions.

Motivation

The purpose of this study was to evaluate the electromyographic signal processing module. It is independent from any application and it does not feature any feedback component. From these studies, we aimed to validate the electromyographic signal as a suitable multi-command issuer while validating our signal processing module as robust, versatile and extensible. Furthermore, we aimed to identify possible preferred electrodes placement positions, setup collisions and compare the system recall when used by impaired and able-bodied users.

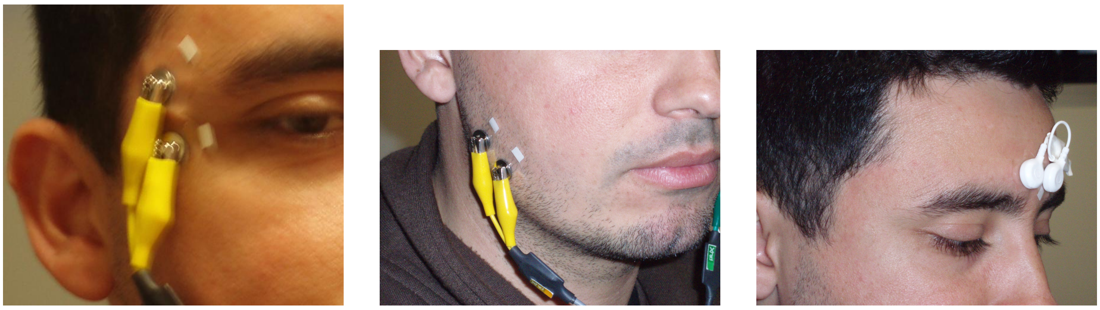
The research questions to be answered with this evaluation are available in Annex A3.3.3.

Procedure

To answer the proposed research questions, we performed an evaluation featuring several electrodes placement, varying the placement and number of monitored sites. To this purpose we have identified a set of voluntarily contracted muscles in the face. Each task featured the recall of a set of determined muscle contractions (the command order was issued by the evaluation monitor). Each task featured the recall of each site 5 times and each command is issued every 5 seconds.

The selected acquisition sites (Figure 4.11) were:

- Temporalis [Left and Right], Frontalis (3 sites, 15 commands)
- Frontalis and mentalis (2 sites, 10 commands)
- Masseter [Left and Right], frontalis (3 sites, 15 commands)



(a) Temporalis (b) Masseter (c) Frontalis

Figure 4.11: Evaluation electrodes locations

Although several other scenarios could have been tested, the performed evaluations gathered a meaningful set of placement sites. With the evaluated setups we aim to take conclusions on muscle contraction recall, collisions, good setup candidates and possible signal features difference between able-bodied and disabled users.

This evaluation session was composed by two phases. The evaluation methodology can be found in Annex A3.3. In a preliminary stage, the user was welcomed, informed about the session and filled a background questionnaire (Annex A3.2) as well as a consent form (Annex A3.1). The second phase was the evaluation itself. For each of the aforementioned electrodes placement, the user was asked to perform a maximum (but still comfortable) contraction for all the monitored muscles (Calibration step). Then the user was asked randomly to recall a muscle contraction, with a 5 seconds interval between commands. The order of the several possible placements was randomly selected for each user.

The electromyographic signal was collected with Ag/Acl surface electrodes connected to a BioPlux6 physiological system. The collected systems were transmitted via Bluetooth to a laptop computer (Toshiba Satellite A30), a Pentium 4 3.0 Ghz with a memory of 512 Mb. The evaluation sessions were performed mainly at IST-Tagus Park in a quiet room but also, when necessary, in the user's home (tetraplegic users). The sessions were consently recorded (video and audio) with a digital camcorder.

The Users

The evaluation was performed with 8 users, 2 tetraplegic (Figure 4.12) and 6 able-bodied users (Annex A3.2). Of the eight participants, 2 (25%) are female and 6 (75%) male. Their ages range from 21 to 53 years old and their education level goes from 12th Grade to Post-graduate degrees. Both the tetraplegic users have C5/C6 injuries and are dependent on caretakers. Both users detain full face, neck, shoulder and partial arm control.

While the set of users, and particularly tetraplegic users, is not large enough to guarantee statistical significance, we believe that an analysis can be performed and these preliminary results can provide us with the required validation on an electromyographic control interface and, in particular, our recognition system.

Moreover, we believe that if the monitored locations are above the injury level and body motion in the monitored part is not affected, the tetraplegic user will be as able to control de device as a fully capable individual. Thus, we have added a set of fully capable users to compare results with the target population but also to increase the overall user sample, if the results between user groups are similar.

Figure 4.12: Tetraplegic user during the evaluation

Software Tools

To perform this evaluation we have developed a simple signal recording application. With an initial parameterization, the application collects and records in a text file the collected signal. Besides the raw signal, the application computes, in real-time, the desired features (MVC, Standard Deviation, Mean Value, Moving Average, Root Mean Square) and outputs during the acquisition indicative values so that the monitor is aware of possible experiment errors and can promptly identify them. The text files are tagged with the user's identification, number of acquisition sites and their respective locations. These log files respect a pre-determined norm to ease further analysis.

Although we were able to collect several features in real-time, it was desired that we would be able to visualize the signal and observe it with different filters applied as well as being able to capture extra signal features. To be able to handle the collected signals we have developed a signal visualization platform (Figure 4.13) that is able to present the signal in real time, but also to read data from the produced text files. This application was enriched with a set of navigation, signal processing and feature extraction capabilities.

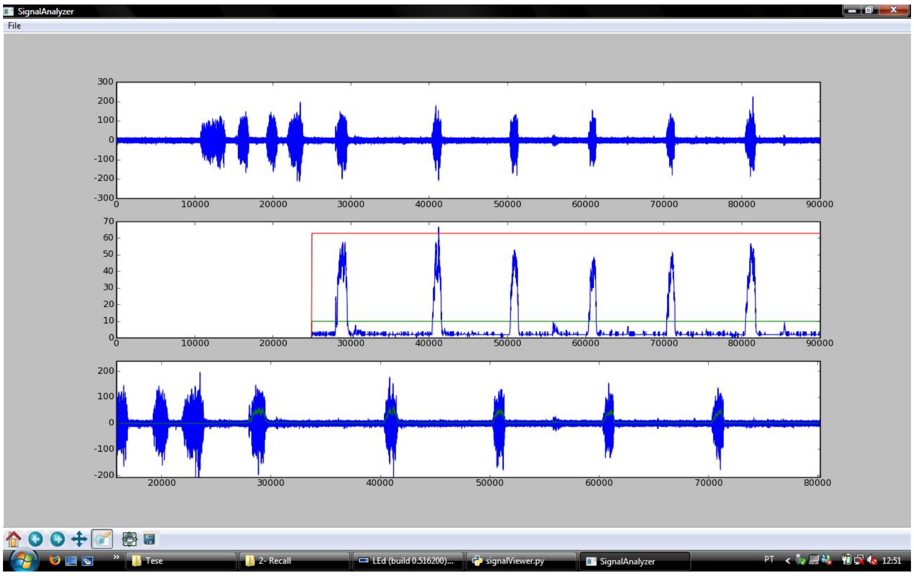


Figure 4.13: Signal Viewer Application

Results

The results analyzed in this section were recorded in log files during the evaluation sessions. We collected the raw signal, processed signal and threshold values for each of the monitored channels. Afterwards, we performed an offline analysis to evaluate the system precision and recall. The raw results for this evaluation are available in Annex A3.5.

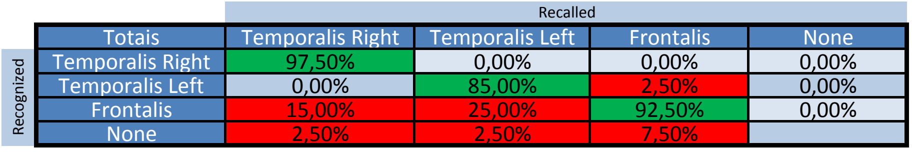
This evaluation was performed using the Calibration Mode with the following parameters:

- Root Mean Square Window - 75 ms
- Minimum Onset Window - 50 ms
- Offset Window - 150 ms
- Standard Deviation multiplication factor - 2

In a first analysis, we have not included the MVC Percentage method as we think that the system can also be used with simultaneous contractions to achieve a certain action. Also, in this evaluation we have not included components to detect errors in the calibration phase (i.e., difference between low and high thresholds).

Tables 4.1, 4.2 and 4.3 present the recognition results for the three performed setups. It may seem strange that the sum of the columns surpasses in some situations the maximum percentage (100). This is due to the possibility of multiple onset detections in one recall. Therefore, these results present the true positives and false negatives but also a set of false positives. However, none of the experiments revealed general false positives as some contractions lead to two detections but no detection occurred in ”silence” situations.

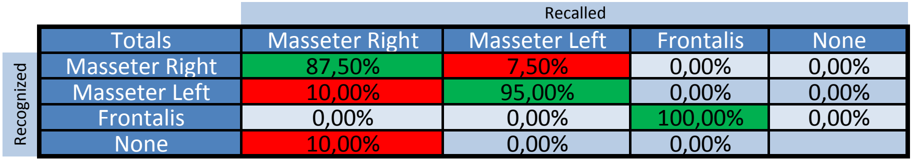
As it might be expected, the setup with the closest set of monitored positions (*temporalis* and *frontalis*) was the one that revealed a lower True Positive Classification (91.67%). The distinction between eye blinks (*temporalis*) is clear and this pair is presented as a good choice (Table 4.1). Some of the users had collisions between the *temporalis* and the *frontalis* as it was visible that frowning lead to eye blinks and vice-versa. However, we believe that this recognition could be improved if the user repeated the calibration as it was clear in the performed post-analysis that the detected collisions were due to unacceptable calibration procedures (i.e., low thresholds too close to high thresholds).



		Recalled			
	Totais	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	97,50%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	85,00%	2,50%	0,00%
	Frontalis	15,00%	25,00%	92,50%	0,00%
	None	2,50%	2,50%	7,50%	

Table 4.1: Recognition Evaluation Confusion Matrix (Temporalis and Frontalis)

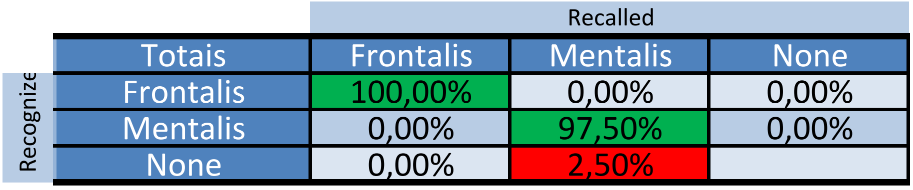
On the other hand, the *masseter* and *frontalis* presented frowning as a suitable action (Table 4.2). Moreover, in opposite to the *temporalis* pair, the masseter and the associated action (clenching teeth) are likely to lead to errors if the user is not able to perform clearly distinctive actions. It was clear during the evaluation and in the post-analysis that the most successful users used their lips to create different gestures. However, in general the system presented a good accuracy (94.17%).



		Recalled			
	Totals	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	87,50%	7,50%	0,00%	0,00%
	Masseter Left	10,00%	95,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	10,00%	0,00%	0,00%	

Table 4.2: Recognition Evaluation Confusion Matrix (Masseter and Frontalis)

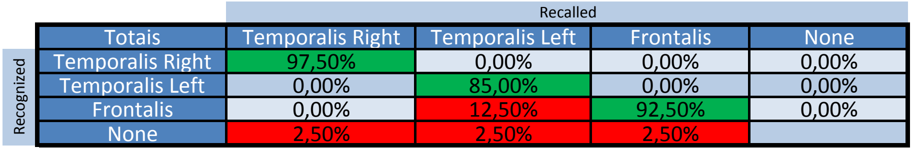
The *frontalis* and *mentalis* setup, as no collisions exist and both contractions are clearly marked (and show high amplitudes), presents a high recognition rate (98.75%).



		Recalled		
	Totais	Frontalis	Mentalis	None
Recognize	Frontalis	100,00%	0,00%	0,00%
	Mentalis	0,00%	97,50%	0,00%
	None	0,00%	2,50%	

Table 4.3: Recognition Evaluation Confusion Matrix (Frontalis and Mentalis)

The results for multi-detection are above 90% which seems a good result. Moreover, in the context of the particular system presented in this thesis, we only consider single detection per time window. Therefore, we performed a second offline analysis with the MVC Percentage decision component and improved the results. This improvement is only visible in the False Positives that were previously and simultaneously detected with the recalled True Positive. The results are presented below:



		Recalled			
	Totais	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	97,50%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	85,00%	0,00%	0,00%
	Frontalis	0,00%	12,50%	92,50%	0,00%
	None	2,50%	2,50%	2,50%	

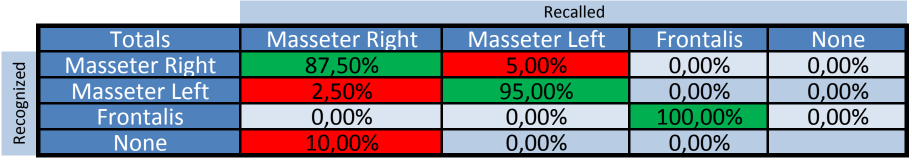
Table 4.4: Confusion Matrix with MVC Percentage method (Temporalis and Frontalis)

One aspect that is interesting to compare is the precision and recall from able and disabled users. Graphics 4.14, 4.15, 4.16 present the false negatives (erroneous), false positives and true positives results for the overall, tetraplegic and fully-capable populations respectively to the three performed setups.

The results are quite similar and it is difficult to assess any particular difference. It is interesting to notice that, in the temporalis and frontalis setup, the tetraplegic users performed even better than the fully-capable population.

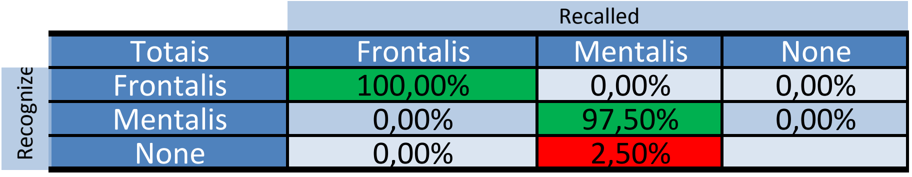
In general, the results achieved showed that the recognition system is accurate. With the achieved results we were able to answer the pre-determined research questions:

Can we accurately identify a ”body gesture”? The recognition rates are high and it is clear that a body gesture can be identified. The recognition accuracy improves



		Recalled			
	Totals	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	87,50%	5,00%	0,00%	0,00%
	Masseter Left	2,50%	95,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	10,00%	0,00%	0,00%	

Table 4.5: Confusion Matrix with MVC Percentage method (Masseter and Frontalis)



		Recalled		
	Totais	Frontalis	Mentalis	None
Recognize	Frontalis	100,00%	0,00%	0,00%
	Mentalis	0,00%	97,50%	0,00%
	None	0,00%	2,50%	

Table 4.6: Confusion Matrix with MVC Percentage method (Frontalis and Mentalis)

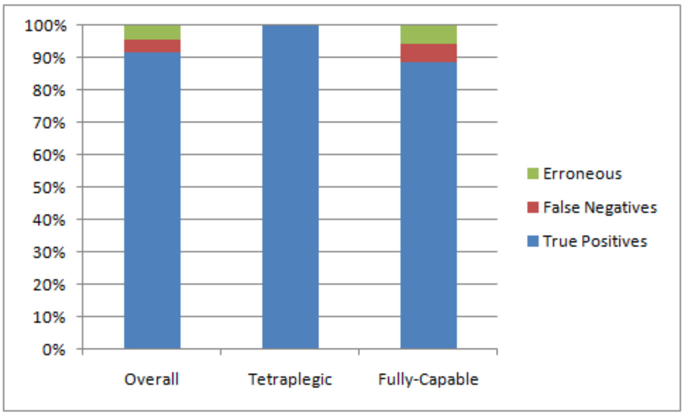


Figure 4.14: Comparison between able and disabled users (Temporalis and Frontalis)

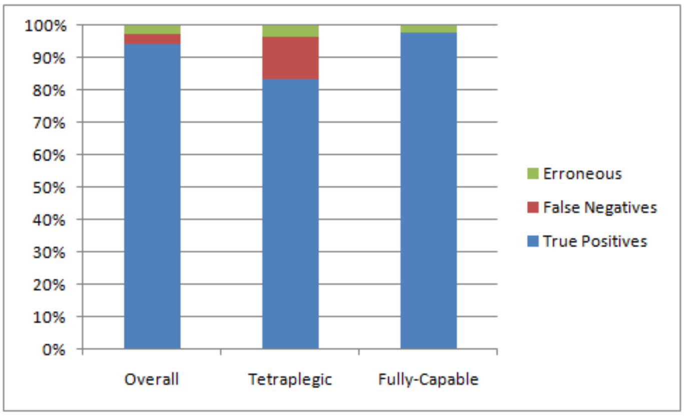


Figure 4.15: Comparison between able and disabled users (Masseter and Frontalis)

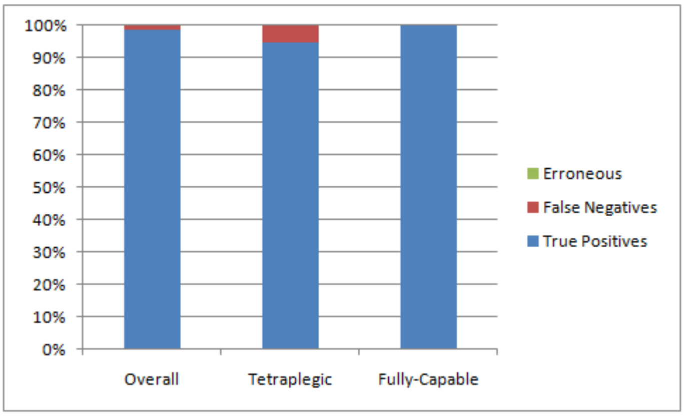


Figure 4.16: Comparison between able and disabled users (Frontalis and Mentalis)

when a single-detection method is employed.

Is the system able to cope with multi-electrodes setup? Yes. However, if the set of monitored locations is close, the recognition accuracy can decrease. Also, if the user is not able to clearly make different gestures/contractions, the accuracy could also be damaged. However, the results were still highly accurate and the errors were minimal.

Which are the most probable collisions? The collisions occur when the electrodes are too close (temporalis and frontalis) or if the user cannot make distinguishable contractions (cannot clench teeth independently).

Which are the best placement positions? The best placement positions are those with a clear associated body gesture (i.e., temporalis, frontalis, mentalis). If a multi-electrodes setup is applied, locations that have different motor actions associated are the best choices.

Which are the candidate locations for each impairment? As we only tested locations above the injury level we are not able to define the best candidates for a particular situation. However, we believe that the injury level does not influence the results if the locations are above it.

In similar mountings, is there a difference between impaired and non-impaired users? No. The results presented no clear difference and in some situations the tetraplegic users outperformed the able-bodied users.

4.4. Application and Information Organization

Nowadays, mobile devices include a wide set of functionalities. Moreover, the interfaces in those mobile devices have also evolved and we can find in the market both mobile devices with simple navigational interfaces to highly graphical interfaces that are similar to the desktop ones. However, although mobile devices are different and have divergent user interfaces, the flexibility on mobile interface design is low. Therefore, to accomplish our goals and implement our approach we have to enlarge the development scope to replace input interfaces, output interfaces but also the internal structures and mechanisms that deal with this interaction components. Indeed, to guarantee the desired flexibility and adaptability, our application hooks all the operating system events (keystrokes, reminders, messages received, incoming calls,...) and is responsible to perform actions accordingly to those events, preferences, configuration and internal application state. We can divide this Application component in two different parts: the Event Layer, that is responsible for enclosing the native mobile device logic; and the Information Manager Layer, that depending on the actual state and the events processed can change the state of the application.

4.4.1. Event Layer

As any computer, a mobile device is subject to several events whether from the user, communications or even operating system and applicational internal events. To deal with all the messages received from the various possible sources we have created an event layer that encapsulates the internal state machine of the application. Moreover, by intercepting all the desired events we are able to control the mobile device and provide the required extensibility. We can see this layer as the applicational core of our solution. It was created in the context of BloNo (Lagoá et al., 2007), a project to provide mobile accessibility for blind users, which I have actively worked in. As the goals were similar, and an overall paradigm shit was required, we have created a core that is able to intercept the registered events depending on the application configuration. This makes it possible for the application to be controlled with the keypad (i.e., blind users) or by an optional control interface (i.e., tetraplegic users).

4.4.2. Information Manager Layer

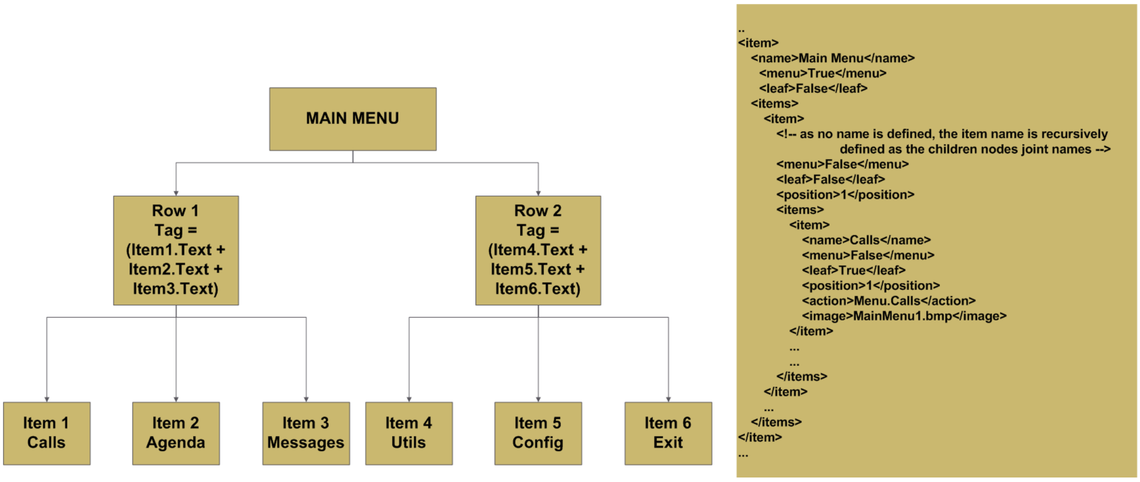
Our approach suggests that the user can control the device differently depending on the configuration being used. Actually, the user is able to use only one input command with an Automatic Scanning scheme but also to change to a Direct Scanning scheme featuring two or more input commands. Moreover, it is also desirable that the interface itself could be represented in a structured way so it can adapted to all the interfacing schemes and input commands cardinality. Once again, it is required that we provide the tools to extend and adapt the application to all the required scenarios.

The Information Manager is able to receive a message and depending on the application state and the actual Behavior, decide the next application state. The application features several Behaviors (and more can be added) which represent the different interfacing schemes to be used. These behaviors can also be configured. As an example, our prototype application features Directed Scanning Behavior, Automatic Scanning Behavior, Coded Access Behavior, Inverse Scanning Behavior.

One other aspect that is important is information organization. The interfacing schemes defined as Behaviors depend on the structure of the information connected with any interaction. As an example, Figure 4.17 represents a resumed hierarchical information configuration for a Menu from our prototype. With this representation, the system, depending on the selected Behavior, is able to group the items into rows and columns if a row-column scanning is selected and perform the desired action when a certain leaf item is selected. Each Behavior has its inherent functioning. It is worth mentioning that we have not focused our contribution on layouts. We defined one Menu Layout, one Keypad Layout, one Inbox Layout and one Text-Entry Layout to be able to evaluate our approach.

One important aspect on the information kept is the data related with each item. As it can be observed in Figure 4.17, for each leaf item, a bitmap and a text identifier are described. Those will enable audio and visual feedback. It is worth mentioning that in a hierarchical Behavior type, audio scanning is provided and it can be defined or, if no identifier is defined, the system will automatically tag it with the enumeration of its child text descriptions. In this way, at all the navigation steps, the system has accurate and descriptive information on the interaction state.

In sum, depending on the selected Behavior, the events and the information structure, the application is able to change states.



```
..
<item>
   <name>Main Menu</name>
     <menu>True</menu>
     <leaf>False</leaf>
   <items>
      <item>
         <!-- as no name is defined, the item name is recursively
                        defined as the children nodes joint names -->
         <menu>False</menu>
         <leaf>False</leaf>
         <position>1</position>
         <items>
            <item>
               <name>Calls</name>
               <menu>False</menu>
               <leaf>True</leaf>
               <position>1</position>
               <action>Menu.Calls</action>
               <image>MainMenu1.bmp</image>
            </item>
            ...
            ...
         </items>
      </item>
      ...
   </items>
</item>
...
```

Figure 4.17: Hierarchical Information Structure for a Menu

4.5. Information Presentation

The EMG system offers the user the capacity to input commands and therefore interact. However, as we argued before, it is important that the system enables the user to control the device with only one input command but also to enable a more capable user to take advantage of his capacities and provide a more complete set of input commands. Looking back to Chapter 3.2, we defined a set of interaction profiles that enable the user to interact with the device within several different interfacing schemes and input set cardinalities. This interaction depends on the control interface, but also on the information presented to the user at each interaction step. The aforementioned application layer gathers all the required processes to control the application state machine and it delivers to the presentation layer the structured state of the application. The presentation layer decides how to present that information, taking into account its context. In the next sections, we will present how this information is presented in our prototype to achieve the approach goals and requirements. We will focus on navigation and feedback presenting how the information can be presented in different scenarios, with different restrictions, and still bridging the gap between the user and the device, enabling information to be exchanged between the user and the device and vice-versa.

4.5.1. Navigation and Feedback

As reviewed in Section 3.2.2, there is a group of task types that encloses the majority of the interactions between the device and the user. These groups can be identified by their semantic but also by the way they are presented to the user. We have identified three task groups: menu navigation, that encloses all the navigation procedures that lead to some application and may be composed by a set of interaction steps (traditionally several screens); Event Reception, that includes not only incoming call and message screens but also reminders and alerts; and Keypad Direct Interaction, that in the scope of our approach we divide in Text-Entry (i.e., writing a message or contact name) and Keypad-Entry (i.e., entering a phone number).

It is important to mention that all the interaction screens can be created similarly. However, we will describe them separately as we believe that there are differences in the configuration that improve the interaction in each of the tasks being fulfilled. The differences are in the way the information is presented, whether auditory, whether visually.

Menu Navigation This is one of the most common tasks to be performed with a mobile device. Except Event Reception related tasks that leads us directly to the goal-related screen, all the other tasks performed depend on a navigation process that takes the user to the main task interaction dialogue.

Similarly to the actual mobile devices, our information organization allows that each menu element has a description, a picture and an action associated. Thus, we can have an interface that is similar to the one seen nowadays offering the opportunity to change the grid cardinality and consequently each icon size, although no further automatic layout is performed.

The structure defined for each screen allows the adaptation the preferred Behavior. The information presented to the user is the one reflected by the system state. At any given navigation step, the system has a selected item. That item is presented to the user. As an example, in a row-column scanning profile, the selected item can be a row or an item (Figure 4.18. The state shift is dependent on the interfacing scheme and number of input commands (i.e., Automatic Scanning, Directed Scanning, Coded Access,...).

(a) Menu Start Screen (b) Row Selected (c) Item Selected

Figure 4.18: Mobile Device Navigation Screenshots

Event Reception This set of tasks is particularly different as it consists in an interruption to the user. Indeed, this are the only interactions that begin ”from the device”, instead of the user. In this group, we include incoming calls and messages, but also reminders and alerts, whether prepared by the user (calendar reminders), whether created by the operating system (battery alert).

In this task group, the options available are (although one can define others) to give immediate attention to the interruption (i.e., accept call, read message, see reminder description), to reject the interruption (reject call, discard message/reminder) and to ignore (silence the ring tone, postpone the reminder/message).

We have decided to make this set of tasks as two-step interaction processes. When the phone rings, I probably do not want it to start reading the message or even reading the name of the caller of an incoming call. Thus, the first decision the user makes is to ignore or get more information on an incoming event (i.e., ”message from Tiago”) and only after he is able to accept, postpone or ignore the event.

Dialing Making a call is probably one of the most important, if not the most (with its counterpart, receiving a call), tasks to perform with a cell phone. To enable this task, the navigation procedure is similar to the one applied in Menu Navigation tasks. This group is presented as different mostly because of its semantic differences. Also, like menu navigation, we can find nowadays mobile devices with a keypad designed in the screen (touch screens) (Figure 4.19). The difference with our approach is the interfacing scheme. Besides direct access we also provide scanning and encoding solutions attached with the appropriate feedback (visually and auditory).

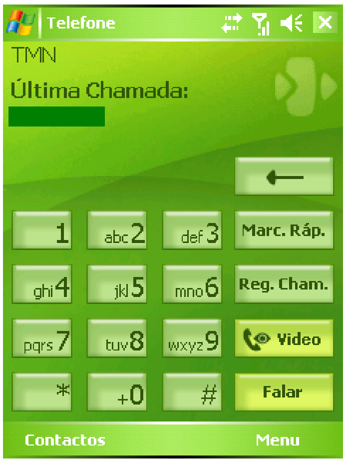


Figure 4.19: HTC P3600 Windows Mobile 5.0 Keypad Screen

Text-Entry Once again, text-entry navigation is similar to menu navigation and touch screen mobile devices also have on-screen keyboards. The main problem with text-entry and our approach requirements is that although items can be identified independently (item scanning), the number of items is large. In this scenario, a variation of group scanning is normally preferred when the input set is reduced (disabled users). However, and considering our approach goals, it is difficult to create comprehensible descriptions for a set of letters. The solution we applied in menu navigation is not feasible as a row of letters will have several items. On the other hand, if the number of rows increases (reducing row description length), the performance will also be below acceptable values.

To solve this problem, we once again merged our approach with the one developed in the scope of mobile accessibility to blind users. Indeed, the requirements on non-visual scanning are similar to both populations. The difference is on the control interface. Tetraplegic users face higher restrictions as they do not have physical contact with the mobile device and the keypad. Thus, we have analyzed NavTap (Guerreiro et al., 2008), a text-entry method for blind users, and made the required changes to include scanning possibilities.

NavTap text-entry method allows the user to navigate through the alphabet using the mobile phone keypad. The alphabet was divided in five lines, each starting with a different vowel as these are easy to remember. Using the mark on key '5' we can map a cursor on the keypad using the keys '2', '4', '6' and '8'. Keys '4' and '6' allow the user to navigate horizontally through the letters while keys '2' and '8' allow the user to jump between the vowels, turning them into key points in the alphabet. Both navigations (vertical and horizontal) are cyclical, which means that the user can go, for instance, from the letter 'z' to the letter 'a', and from the vowel 'u' to 'a' (Figure 4.20). Key '5' enters a space or other special characters and key '7' erases the last character entered. This method drastically reduces memorizing requirements, therefore reducing the cognitive load. In a worst case scenario, where the user does not have a good alphabet mental mapping, he can simply navigate straight forward until he hears the desired letter. There are no wrong buttons, just shorter paths.

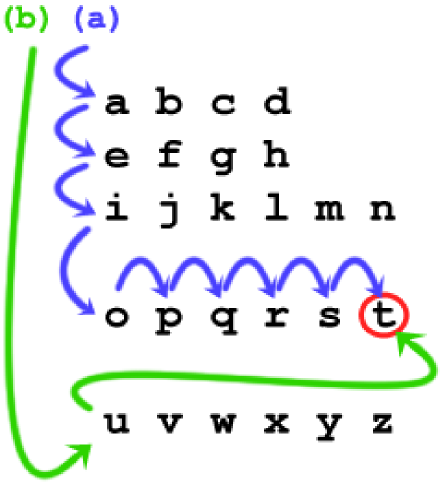


Figure 4.20: NavTap navigation scenarios to the letter 't'

The reason we have used the same approach in the text-entry tasks in the scope of this project was the letter organization. The vowels at the start of every line are used as reference points but, in our case, also as row descriptions. Thus, this solution enables visual scanning (as the rows are highlighted when selected) but also auditory scanning as the users (similarly to blind users) have the notion of their navigation status due to row descriptions. The main difference between the two methods (NavTap for blind users and NavScan for tetraplegics) is that if a group scanning is applied in the latter the navigation is not cyclical. It is worth mentioning that this solution implies a row-column scanning or in the worst case (with little gain) an item scanning. However even in the latter the user is always aware of his navigational status (as it is likely that the user has a good knowledge of the alphabet and its sequence) which would have been harder with other keyboard disposition (i.e., QWERTY).

One other important issue is that when we are writing a sentence there is much more to it than letters like punctuation or accentuation. Moreover, the NavTap system, besides the directional keys, featured special function keys to erase the last letter, accept the last word and obviously to finish and accept the message. As we do not want to augment the input command set (and are probably incapable of doing so due to user restrictions) this options are added to the interface as new navigation rows.

4.5.2. Interfacing Options

Our prototype offers the user a default set of interfacing schemes: Automatic Scanning, Inverse Scanning, Directed Scanning, Coded Access and Direct Access. The interaction configuration can be saved or can be set up at the calibration phase. In both situations, the user (or caretaker if desirable) is asked to pair a certain action with the desired body input command. To accomplish this we have defined a set of possible commands that include, besides keyboard and keypad items, navigational (i.e., UP, DOWN,...) and action (i.e, ACCEPT, CANCEL, FINISH...) items.

With this set of commands and behaviors and the matching interface actions we are able to achieve control with different setups. As an example, if we are calling a number and we have set up an automatic scanning scheme with one input command we can select the number by scanning the on-screen keypad with the selected scanning scheme (i.e, row-column scanning). However, although we are featuring automatic scanning, we can also add one input command that is directly related with the FINISH action. By this, we can navigate the keypad but finish the selection and make a call without having to navigate to the ”Call” ”key”. Taking it to an extreme, we can have all actions in the screen related with a certain input command: direct selection. In this scenario, and using the physical keypad as the control interface we can go back to the traditional control but this time with a configurable and adaptable approach.

There is one big difference between our daily mobile device usage and the one proposed in this thesis: the users will be monitored and wearing the system even when they are not interacting. And, even though we also carry our mobile devices, there is one important feature that we may use: to lock our mobile device keypad or to somehow be protected from inconvenient interactions (although several times this can also occur when one forgets to lock the keypad or receives a call and, as the mobile device unlocks the keypad, gets inconveniently accepted when pressed by something in the pocket, wall or purse).

To enable the user to have control on the control interface activation we have defined that the user has to perform a *dialogue* with the system. Therefore, when the system is in idle state and the user inputs a command, the system asks the user to perform a number of contractions in a defined time window (if more than one input commands are available the system will ask a sequence; if only one input command is available the system will ask a reduced number of commands within a reduced time window). If the dialogue is successful, the navigation process begins. Although this can also be used in the context of Event Reception tasks, we have made an exception out of this group due to the immediate response need. In this case, the only requirement is a contraction to get information on the incoming event and afterwards navigation is initialized. However, even in this scenario, two contractions are required to launch any type of action.

On the other hand, we were also required to think in the opposite scenario: how to lock the keypad. And this question is enlarged in the scenario where the user enters an undesired navigation level (entering an undesired row in row-column scanning with no "BACK" input command). To both cases we have applied a reset timeout. Basically the system returns one level at a time, after a pre-defined timeout, until the Main Menu is achieved and, after one more timeout, the system goes to *idle mode*. This procedure enables erroneous commands recuperation and also locking the system.

5

Results and Discussion

The preliminary user studies (task analysis) pointed out several restrictions on tetraplegic interaction with technology. While, we believe that the designed approach takes advantage of the users' capacities while still dealing with their restrictions, some research questions need to be answered. The preliminary evaluations presented our system as accurate considering muscle contractions detection and our approach as understandable and effective. In one hand, we have showed that we can detect the user's intention. On the other hand, we have shown that the users can relate *body gestures* with actions on their mobile devices and achieve proper control.

However, to fully validate our approach and stated contributions, further evaluation is required. The system must be evaluated as a whole, in real situations, assessing its usability. To this end, we have conducted task-oriented experiments. While the main purpose of our evaluation is to assess the mobile device accessibility, we have also conducted experiments in desktop-based scenarios.

The research questions to be answered in our final evaluation to state our approach as a success are:

Is electromyographic suitable as a real-time control interface? In Section 4.3.3, we have presented the results for the evaluation on contraction recall. It validated the detection of muscle contractions. However, those evaluations were performed focusing in a discrete control interface with no real concerns to the detection of the exact onset time, how long the muscle remained activated and the offset time. Thus, we still do not have an idea if the detection is performed in real-time (or if the user keeps that impression). Therefore, we need to evaluate if the system can respond in real-time, offering the accuracy and speed required for a continuous control interface.

Is the system wearable and robust to movement? Across the day, the user is likely to perform several position shifts as well as voluntary or involuntary movements. Therefore, besides a suitable dialogue that reduces the probability of erroneous command controls, it is required that the system is robust enough to filter the unwanted interferences. Moreover, it is also important that these possible movements do not damage the system and control is achieved afterwards.

Can users effectively operate the mobile device? Tetraplegic users with high level injuries are likely to have few or no mobile device control. We developed a system to enable mobile device control in the several scenarios that compound their daily life. We need to validate if the system fulfills the requirements and enables users to operate the mobile device while in the chair, bed and whether looking at the screen (visual feedback) or not (audio feedback).

The research questions are available, with higher granularity, in Annex A4.3.3.

5.1. Evaluating Accuracy and Speed

To evaluate the system response speed and accuracy we have performed an user evaluation on desktop control. The mouse cursor requires a high response rate to be properly controlled therefore this task seems appropriate to evaluate the system. However, cursor control or any kind of continuous control is not our goal. In this particular evaluation, the scenario itself evaluates the characteristics we aim to observe so we thought of it as a good candidate challenge. In this evaluation context we performed two evaluations: Target acquisition (point and click) and continuous control mode in a text-entry application.

5.1.1. Motivation

Evaluating the response speed and accuracy is important as some tasks require immediate attention. Moreover, if the system features scanning navigations, it is important that the application is synchronized with the user's actions to achieve the expected results. Therefore, although cursor control is not our goal, we believe that the implicit continuous set of tasks are highly demanding and thus, ideal to evaluate these particular characteristics: speed and accuracy.

5.1.2. The Users

This evaluation was performed with three full-capable users with 19, 24 and 51 years. All of them were used to deal with computers. Although none of the users is part of our target group, this evaluation is focused on the system response time and therefore we believe that the results are independent from the user physical condition. All the users performed both evaluations.

5.1.3. Point and Click Scenario

The first evaluation features target acquisition in a desktop environment and besides evaluating the time to acquire and click a certain target also evaluates the difficulties the users may have to hold the pointer steady over a target. With this approach we can easily collect the time to acquire targets, erroneous clicks and even compare our system with other approaches. As our goal is not cursor control we have not compared the performance with other solutions (i.e., trackball, mouse, eye-tracking,..). However, our test application is similar to the one used by (Barreto et al., 1999) and consists in a point and click timed exercise. Thus, we are able to compare our approach with one that is also EMG-based but also features EEG signals that work as a clutch (recognize user's attention) to improve recognition.

Procedure

The tests were carried through in a Pentium IV portable computer, with 512 MB RAM and a 17″ color monitor. To collect the real time signal we used the electromyographic device described in Section 4.2.1.

The setup is created with enough electrodes to emulate mouse moving directions and left-click. The users were equipped with two pairs of electrodes in each forearm (four directions) and another pair near one eye to detect blinking (click emulation).

Before the experiment the users got acquainted to the system for two minutes. Familiarization was a very fast task since the users understood the relation with the mouse movements normally executed.

The recognition system was set up to On-the-fly mode (RMS window = 75ms, SD Scale = 8), requiring no previous calibration. The users were able to adapt themselves to the system and observe the required strength to move the cursor in the desired direction.

The experiment consists in:

a) Clicking a Start Button, starting a timer;

b) Moving the cursor towards the Stop button, with any trajectory;

c) Clicking the Stop Button, the time is presented to the user and saved.

The Start Button dimensions are always 8,5 x 8,5mm but there are four Stop Button dimensions (8.5 x 8.5mm; 12.5 x 12.5mm; 17 x 17mm; 22 x 22mm). We made 80 evaluations, 20 of each for every Stop Button size. The Start Button changed between the four corners.

Software Tools

We developed a simple OpenGL application with a Start Button (presented in a corner position) and a Stop button presented in the middle of the screen (Figure 5.1.

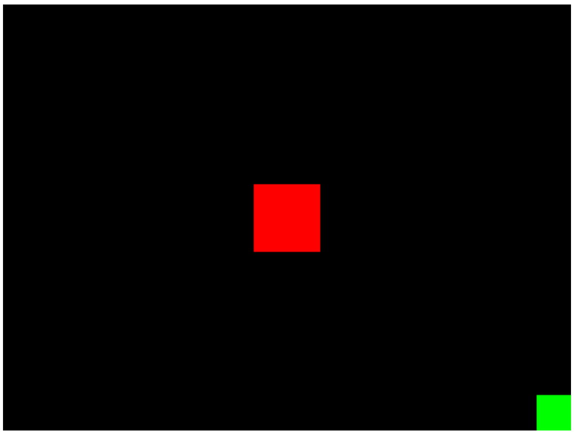


Figure 5.1: Speed and Accuracy Test Application

The application collects all the user interactions and logs the timestamp for all the application events. This enabled us to post-process the data and analyze the results.

Results

Figure 5.2 shows the average values taken for each subject to complete the 80 trials. The subjects required an average of 7.5 seconds to achieve the experience goal.

Although the acquisition times are slow compared to absolute pointing solutions (i.e., eye-trackers) the system is presented as accurate as no clicking errors were detected and the users easily achieved the targets. The acquisition times are conditioned by the relative navigation mode used, with no acceleration features. Our approach seems to be

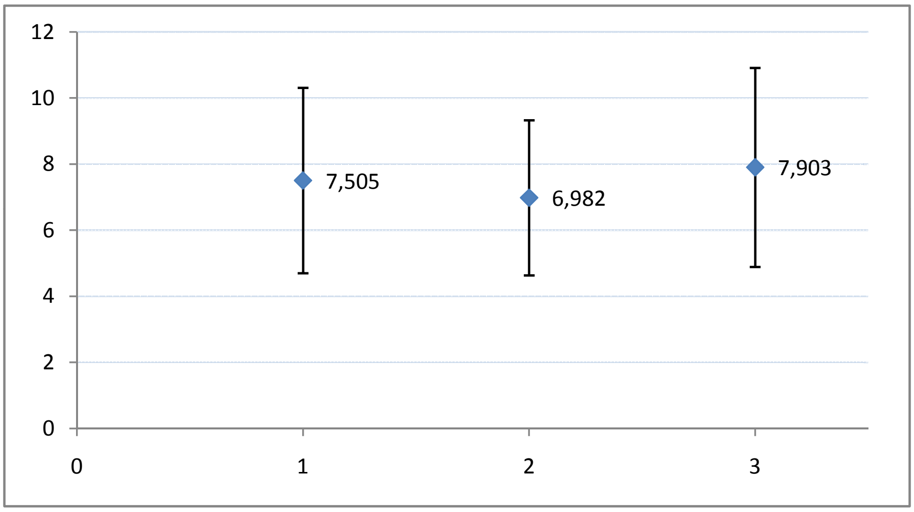


Figure 5.2: Speed and Accuracy Evaluation Results

quite efficient compared to others. We have duplicated an experiment already made by (Barreto et al., 1999) and the results are quite better. The subjects in our trials required around 7.5 seconds to move the cursor from the corner button to the center button and performing a Left-Click as Barreto had an average result of 16 seconds.

This experiment gave the users the necessary control of the device to complete further evaluations.

5.1.4. Text-Entry Scenario

In general, projects using EMG concentrate on a point and click approach, which is inappropriate to the writing activity (very slow). We propose a synergy between applications where a pointer is continuously controlled by myographic activity, which appears to be a faster and efficient approach. Although tested in a desktop environment, this applicational scenario can be transported to mobile device text-entry. The downside is that it is also a continuous control approach and it is difficult to use EMG as a continuous control interface as prolonged contractions become attenuated (and unrecognizable) and fatigue issues arise.

Procedure

The hardware used was similar to the previous evaluation scenarios (Section 5.1.3) .

The users were asked to write the sentence ”Dasher is a fine text entry interface and I enjoy it”. These evaluations were performed with the forearm setup (similar to the one described in Section 5.1.3) and neck setup with only two electrodes (one electrode in each side, monitoring the *sternocleidomastoid* muscle) as the application gives the one-dimensional control possibility. The text-entry applications used were Dasher that is described below (Section 5.1.4).

We also tested the forearm position setup and asked the users to write the sentences using Windows On-Screen Keyboard to compare our synergy navigation application with point and click approaches. We used the same goal sentence. The users alternatively started using whether onscreen keyboard, whether Dasher.

Software Tools

Dasher (Ward et al., 2000) is a text-entry interface based on a zooming technique. This application was developed considering situations or users associated with an incapability to write with the keyboard. The user basically navigates in a ”sea of letters” which appear accordingly to word prediction techniques. It allows two-dimensional and one-dimensional control.

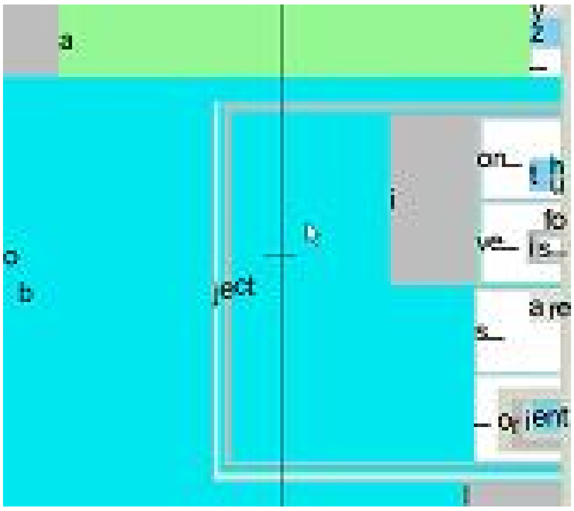


Figure 5.3: Dasher Application

In the context of another project from our research group (Visualization and Intelligent Multimodal Interfaces Group at INESC-ID, Lisbon, Portugal), we have developed a *framework to manage multimodal applications and interfaces in a reusable and extensible manner*(Fernandes et al., 2007). The main goal of our framework is to manage input modalities and applications separately allowing that each component can be reused and extended. We focus on inputs’ capabilities and applications’ interests offering at each moment the most suited input for a determined task in a specific application. For a given input, capabilities are the set of tokens or input data that can be offered by the input to any application, i.e., mouse commands, gesture tokens, tracking positioning or speech commands. Our framework provides the capacity to manage input modalities and capabilities accordingly with the application and user’s will.

To control the desktop independently from the control interface we have created an application that emulates operating system events. Therefore, using this application, our framework and any control interface we can set up a set of relations between input commands and application events. In this particular application we have related the four forearm detected motions and the eye blink with cursor events (four directions and single-click).

Results

The experiment results are presented in Table 5.1. In order to understand the evaluation we need to define exactly the meaning of every metric:

- Error: an error is detected when the user misses a letter and has to go back. Some of these errors may be users fault, i.e. skipping a letter or a space by distraction.
- Time: time until the user ends his sentence correctly.

Task	Errors	Time(s)
Dasher/Forearm	0.00	124
Dasher/Neck	0.33	200
On-Screen Keyboard/Forearm	0.33	480

Table 5.1: Average Text-entry trial results

All the users succeeded and were capable to write the entire message. The errors detected were related to user's distraction, i.e. skipping letters and having to go back in the writing. There were no errors in the forearm control + Dasher task. One of the users made an error in the neck control (missed a letter) but was capable to go back and complete the trial. We had one error in the On-Screen Keyboard (hitting between letters).

We presented a synergy between applications that outperforms the On-Screen Keyboard scenario: our approach averaged 124 seconds against 480 seconds in the keyboard. Both the Speed as the Dasher results are quite interesting and present electromyography as an auxiliary interface for impaired individuals. These tests included the writing through neck movements which were successful. Electromyographic interaction is an opportunity for tetraplegic individuals and we improve this opportunity with a faster and accurate approach. These results show that even though an electromyographic interface is slower than absolute positioning approaches, it can be improved if the interaction is designed accordingly. Also, and considering accuracy and speed, it was clear in this application scenario that the users were able to navigate through the "sea of letters" with a real time response and few, and always controlled, unexpected movements.

5.2. Evaluating Wearability

(Costanza et al., 2005) give relevance to EMG technology in the context of the mobile computation mentioning it as a subtle interface translated in a great social acceptance. They are based on the fact that individuals who use the system are able to interact privately without disrupting the environment that encircles them. This work is mentioned by the motivational ideals related to the use of EMG with mobile devices. It evaluates the EMG usability while walking and making contractions of different durations. However, (Costanza et al., 2005) use only one input channel for simple subtle intimate response events. In this evaluation, we try to assess if the electromyographic setup is robust, if it keeps its characteristics if used for some time and if the users feel comfortable when using it while on the move.

This experience intended to evaluate the system in standing and walking conditions while responding to voice impulses. The users were already familiarized with the system due to first evaluation trials (Section 5.1.2). To create an applicational scenario we have used the same framework used in the Text-Entry Evaluation, emulating cursor events (Section 5.1.4).

5.2.1. Procedure

Our evaluation method tries to validate EMG wearability and mobility,y but with a more complex prototype than previous works, where there are several monitorized input channels/muscles and several corresponding actions previously selected. The aim of this experiment was to evaluate if the system responds as it is expected even in standing and walking conditions.

To evaluate the system's correct response we designed a walking circuit (similar to (Costanza et al., 2005)) which the user has to follow as he responds to orders. Several variants were tested from the Walking with no contractions setup to the Walking with 5 contractions involved. The variations are:

- Walking with no contractions.
- Standing with stimulus response.
- Walking with stimulus response.

The users were equipped with two pairs of electrodes in each forearm (four directions) and another pair in the right *temporalis* (click by blinking). Another setup was created with one pair of electrodes in each side (two directions) of the neck (Figure 5.4).

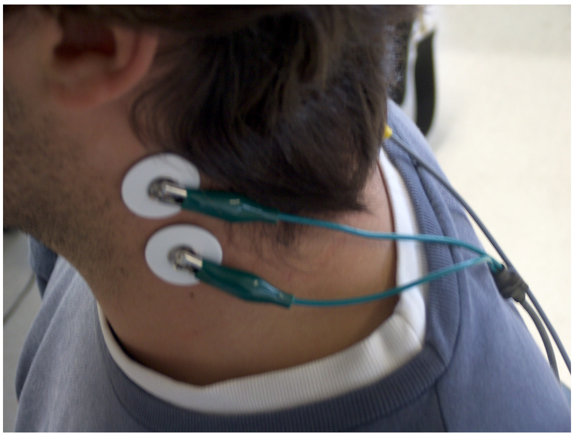


Figure 5.4: Electrodes placement

5.2.2. Results

One of the users had one false positive in the Walking with Stimulus Response task. The other two had no false positives. The false positive was due to wire misplacement. No false negatives were detected in any of the users' experiments.

While these results present the approach as robust, they are not sufficient to say anything about spasticity. The designed system is robust to movement but if the monitored muscle is contracted (voluntarily or not) an action will be performed. However, we believe that these results point out that small movements and other common possible interferences (i.e., wheelchair guidance) are not likely to create erroneous commands.

5.3. Evaluating Usability

The previous evaluations have shown that the technique and our application (recognition system) can accurately identify the user's intentions. Also, we have shown that the system can be used along the day without unexpected behaviors. Although those exploratory and assessment evaluations are essential in the development process, to really validate the whole system, evaluations with the final product that deal with the user reality and goals are also required. Only after putting the approach to the test within real life scenarios, we will be able to present it as valuable. To this end, we performed two different trial sets: evaluating setup usability and wearability; and evaluating the mobile device control usability. The former focus on the system mounting and it evaluates how the system will behave when operated by the system main stakeholders (users and caretakers) while the latter evaluates the system as a whole, testing the system's ease of use and effectiveness to fulfill the main mobile device tasks.

5.3.1. Setup Usability and Repeatability

One of the most important factors to achieve an effective interface is that the system is easy to use. This is important while the system is in use but also in the mounting and configuration stages. Thus, although we have already validated the recognition system, those evaluations were performed with an experienced helper which performed the electrodes placement and configuration. However, in a daily scenario that experienced helper is not present. Moreover, the electromyographic signal characteristics imply variations from day to day and signal repeatability is impossible to achieve.

Motivation

While designing our approach, the main focus and concerns go to the target user, a tetraplegic person. However, our approach influences and depends not only on the user, but also on the caretaker, at specific times. The mounting and initial system configuration is the most important step that both stakeholders (user and caretaker) are present. Thus, to state our approach as effective and usable, one question must be answered: can the user use the system and achieve good recognition results without the help of an experienced helper?

The Users

This evaluation was performed with a tetraplegic user, identified as User #8, in the Input Recognition Evaluation (Section 4.3.3). The user data can be found in Annex A3.2. It is also important to refer that the caretaker was a 24 years old female with no previous medical or electromyography related expertise. Her background is on housekeeping and she has completed the 6th grade.

Procedure

This evaluation was composed by three sessions performed in three different days (spaced by two days) with one tetraplegic user at his home. Each individual session was similar to the one described in the Input Recognition Evaluation (Section 4.3.3) with the difference that all the mounting procedure was performed by the caretaker. For the caretaker to be able to perform the task for the three recalled setups (both temporalis and frontalis, both masseter and frontalis, frontalis and mentalis) we presented pictures of the monitored areas. Also, a set of recommendations on electrodes placement and system configuration were handed to the caretaker. Between tasks both users were asked for any problem that might have occurred. The test monitor tried to keep the users comfortable.

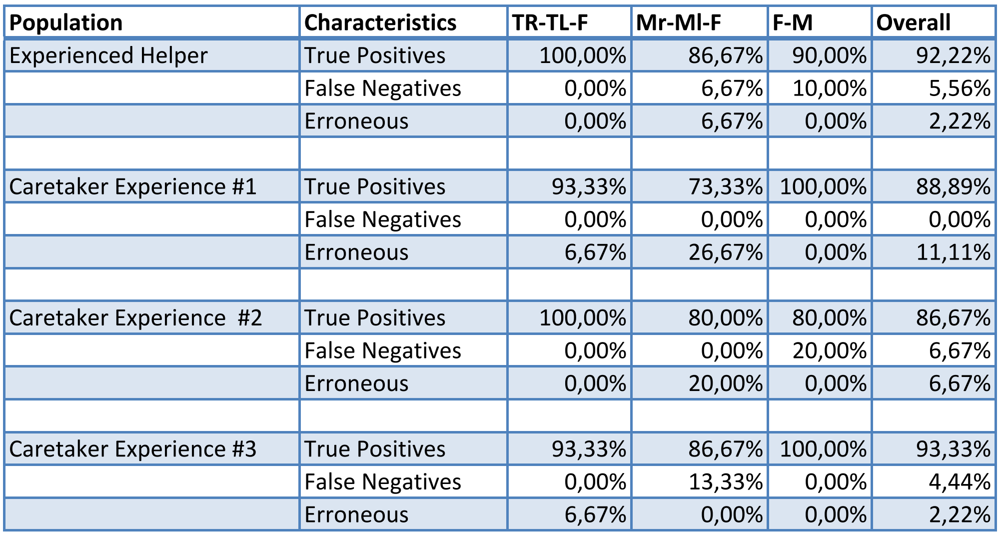
Software Tools

As in the Input Recognition Evaluation Section 4.3.3, we have used an application that recalls sequentially the configured body sites and saves the collected signal (raw and processed versions). The processing system and visualization application were also similar.

Results

The results obtained in this evaluation are available in Annex A4.6.1. Figure 5.5 presents the resumed results joined with the results from the same user in the Input Recognition Evaluation (Annex A3.5). Overall, the results are quite similar. In the first session, the number of errors is a little higher with the Caretaker placement than the Experienced Helper. However, by analyzing the electrodes placement and the signal afterwards, we concluded that there are not significant shifts in the placement but rather an evolution of the knowledge of the system by both stakeholders that adapted themselves to each other and to the application.

Another important analysis is on the error situations, which occurred in these evaluations, mostly in the first Caretaker experience. Most of the erroneous situations were created between right and left teeth clenching. This scenario, as stated before, is error prone as some users are unable to clearly clench teeth independently. User #8 showed difficulties with this scenario in all sessions. However, the results show that there was an improvement and we believe that it was related with both intervenient' performance. The resumed results for this evaluation are available in Table 5.2.



Population	Characteristics	TR-TL-F	Mr-Ml-F	F-M	Overall
Experienced Helper	True Positives	100,00%	86,67%	90,00%	92,22%
	False Negatives	0,00%	6,67%	10,00%	5,56%
	Erroneous	0,00%	6,67%	0,00%	2,22%
Caretaker Experience #1	True Positives	93,33%	73,33%	100,00%	88,89%
	False Negatives	0,00%	0,00%	0,00%	0,00%
	Erroneous	6,67%	26,67%	0,00%	11,11%
Caretaker Experience #2	True Positives	100,00%	80,00%	80,00%	86,67%
	False Negatives	0,00%	0,00%	20,00%	6,67%
	Erroneous	0,00%	20,00%	0,00%	6,67%
Caretaker Experience #3	True Positives	93,33%	86,67%	100,00%	93,33%
	False Negatives	0,00%	13,33%	0,00%	4,44%
	Erroneous	6,67%	0,00%	0,00%	2,22%

Table 5.2: Repeatability Resumed Results

Overall, the results are similar to the ones gathered in the Input Recognition Evaluation and present the system as usable even when no experienced user is involved. Moreover, we believe that both stakeholders can learn and get used to the system and improve performance. One important factor to mention is that the collection sites were established without the user intervention. These influences the results as some users are likely to dislike or be incapable of creating a distinct contraction. Once again, if the system is experienced for some sessions we believe that this would evolve and the users would achieve greater performances and accuracy rates.

Finally, the caretaker found the system easy to set up although she has showed a little discomfort in the beginning of the evaluation. The main problem that she mentioned was the "wire mess" that was all around the user. This is a problem as the wires used were too small to offer the required flexibility for a more comfortable setup. However, this problem is easy to solve as they can be replaced with longer and thicker wires.

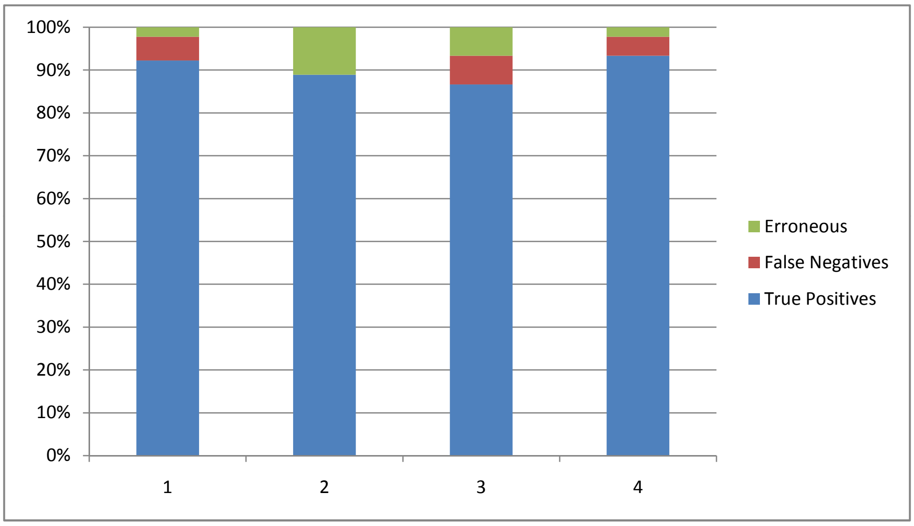


Figure 5.5: Comparison between system recognition sessions
The first bar represents the overall results for the System Recognition Evaluation already presented. The other three bars present the results for the sessions where all the process was conducted by the caretaker and the user.

5.3.2. Mobile Device Interaction Usability

The main goal of our approach is to offer tetraplegic users the capacity to perform the most common mobile device tasks. While we believe that the aforementioned results validate specific aspects of the approach, those are not sufficient to validate the solutions found as valuable to the target user, concerning the tasks to be fulfilled. Therefore, an evaluation on the overall usability of the system is required.

Motivation

We know that the system is able to recognize muscle contractions and can do it quickly and accurately. Also, preliminary evaluations show that the users understand the approach and can relate the selected body sites with commands to perform the desired tasks. However, we will not be able to present the approach as successful, if the prototype is not validated in a real scenario by the target users, while performing the most common and important tasks in a mobile device. Some questions still need to be answered. Can the users perform the tasks (make/receive calls, send messages, navigate menus)? Can the users do it while in a restrict position or accommodation (without visual feedback)? Can the users learn to use the system quickly? Do users like the system and are they willing and interested in using it?

The research questions to be answered in this evaluation are available in Annex A4.3.3.

Procedure

To validate the approach and answer the proposed research questions we performed an evaluation with two tetraplegic users featuring several tasks commonly performed with mobile devices. This evaluation was similar to the preliminary concept validation (Section 3.3) but this time with a fully-developed prototype and no external intervention. The users had to perform several tasks and do it with different limitations (with visual feedback and with only-audio feedback).

This evaluation session was composed by two phases. The evaluation methodology can be found in Annex A4.3. In a preliminary stage, the user was welcomed, informed about the session and filled a background questionnaire (Annex A4.7) as well as a consent form (Annex A4.2). The second phase was the evaluation itself. The task scenarios were the following:

Menu Navigation and Message Reading You are going to a dinner today but you don't remember the place's name. You do remember that George sent you a SMS with that information. Navigate to your inbox and read the message you have received from George. You are at the main menu.

Accepting and Rejecting a Call Before going to the dinner everyone is calling but you are not in the mood and want to have a little rest. Alexander calls you and as you know it is just to chat you cancel the incoming call. One minute later, you receive a call from the dinner organizer and you want to take it. The phone will ring. Just wait.

Writing a Message You regret to have canceled Alexander's call and you want to send him a message. You are at the start of the message (Write Message Screen). Input the text ″call later″.

Making a Call You still don′t know the place so you just decide to call George. His number is the 93 369 23 91 [randomly selected]. You start the task in the ″Making Call″ screen.

The users performed all the tasks with two different setups. We shifted the order of the tasks and the configuration order to avoid biased results.

The electromyographic signal was collected with Ag/Acl surface electrodes connected to a BioPlux6 physiological system. The collected systems were transmitted via Bluetooth to a mobile device, HTC S310. The evaluation sessions were performed in the user′s home (tetraplegic users). The sessions were consently recorded (video and audio) with a digital camcorder.

The Users

The evaluation was performed with 2 tetraplegic users, one female and one male with 28 and 31 years respectively (Annex A4.1). Both the tetraplegic users have C5/C6 injuries and are dependent on caretakers. Both users detain full face, neck, shoulder and partial arm control. Both users own and a mobile device and use it. However, the interaction scenarios and tasks are limited. The interaction is only possible when the mobile device is within reach and the users are in the wheelchair or in the bed turned to the side. The most common tasks are to receive calls and occasionally make calls.

Software Tools

This evaluation featured the prototype described in Chapter 4 composed by the electromyographic control interface and the interface with visual and audio feedback in the mobile device. We have also recorded the signal and performed a post-test signal analysis (with the Signal Viewer Application described in Section 4.3.3).

Results

The first relevant information to be analyzed in this evaluation is the configuration selected by each user, for each of the scenarios (with and without visual feedback). In the evaluations where visual feedback was available, both the users selected a Directed Scanning approach. However, they have selected different body locations and different cardinalities. User #1 selected only two input commands (frontalis and mentalis) and

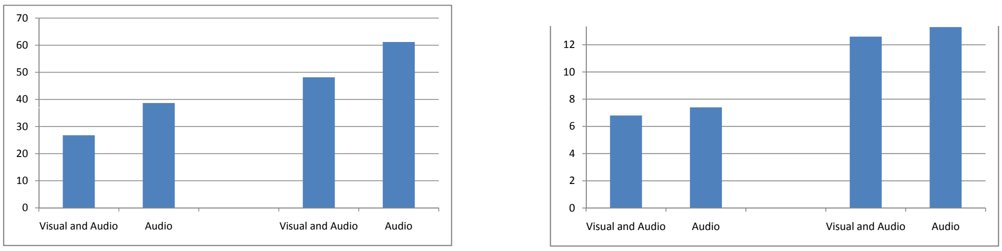
User #2 selected three (temporalis right and left and frontalis). User #1 maintained his selection through all the trials while User #2 changed to an Automatic Scanning with only one input command when visual information was not available. It is important to notice that both users had some experience with the system (from previous evaluations). As an example, User #1 selected only two commands as he believed that it would be enough to navigate forward (mentalis) and perform selections (frontalis).

This evaluation results are available in Annex A4.6.2. All the users were able to successfully complete all the tasks which is an excellent result and the main goal of our approach. However, depending on the selected body sites and interfacing schemes, the performance can be better. In respect to completion times, the difference between the Directed Scanning approaches and Automatic Scanning is well established. Also, once again, it is visible that when only Audio feedback is featured the performance decreases (Figure 5.6).

Comparing the results from this evaluation with the preliminary evaluation we can observe that the completion times are similar. The errors that appeared in the preliminary evaluation due to timeout early start (before the option was read) did not occur as we have corrected the configuration and, in this prototype, the timeout starts only when the audio feedback ends. However, although the error rate is small (0.25 errors /trial), they still occur.

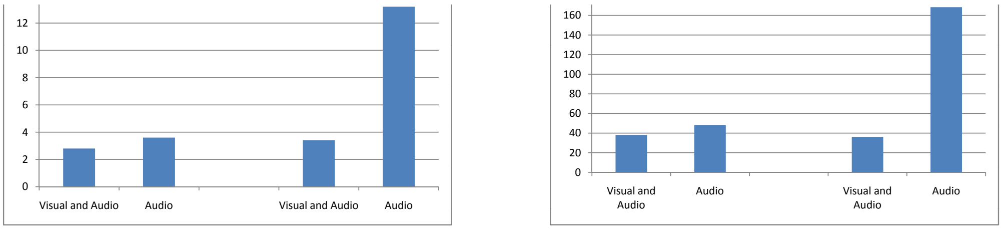
We have identified two types of errors: recognition errors are related with the recognition system and occur when the user intends to input a certain command and the system misrecognizes the user's intention; user errors are those where the user performs an erroneous action and is often related with distractions. User #1 had no recognition errors. The only error identified in the trials with this user occurred when the user was trying to navigate too fast and passed the desired option. We could have neglected this error but, as it influenced negatively the completion time, we choose to tag it as an error. On the other hand, User #2 faced some recognition errors. They were twofold: the user had one false negative while featuring Automatic Scanning with the temporalis muscle and two erroneous commands (confusion between frontalis and temporalis left). The users were able to recover from the errors and were able to complete the trials.

To assess the user's opinion, we have performed a questionnaire in the end of the evaluation. This questionnaire featured five questions to be classified in a 5-point Likert Scale (Rubin and Hudson, 1994). The questionnaire results are available in Figure 5.7 and are clear about the user's opinion on the system and overall likability.



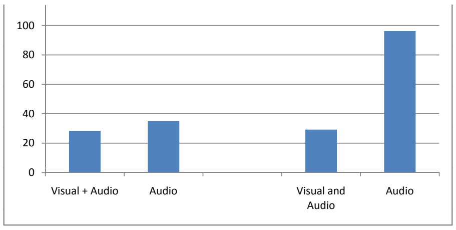
(a) Menu Navigation Completion Times

(b) Reject Call Completion Times



(c) Accept Call Completion Times

(d) Write Message Completion Times



(e) Make Call Completion Times

Figure 5.6: Tasks Completion Times (in seconds)

5.3.3. Discussion

With the results achieved, we are now able to discuss the approach usability. In this section, we analyze the results taking into account four factors, outlined by (Booth, 1989) and reviewed in (Rubin and Hudson, 1994): Usefulness, Effectiveness, Learnability and Likability.

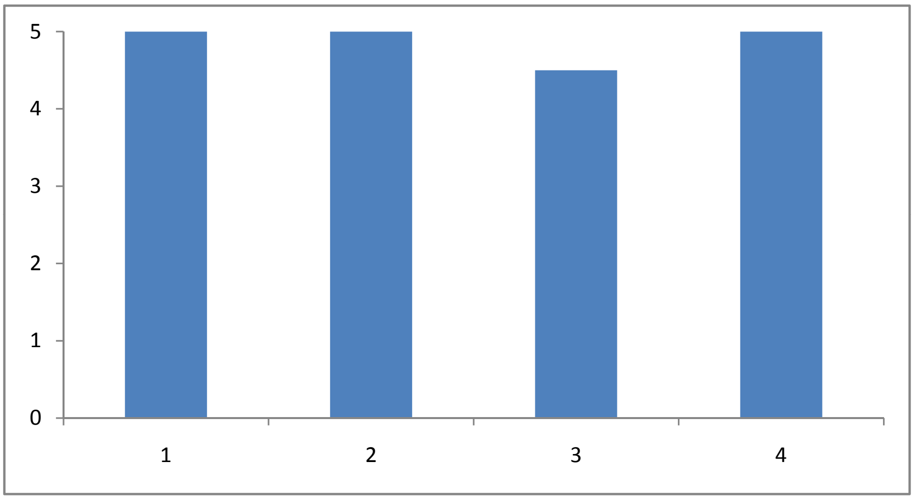


Figure 5.7: Post-Questionnaire Results

Usefulness

Usefulness is related with the degree to which a solution enables the user to achieve the goals. This is the most important factor as, if the user is not able to achieve his goals, no further factors need to be considered. This factor is related with the tasks and how the users are able to fulfill those tasks.

Our approach is useful. Indeed, the users are able to perform the main mobile device tasks. Moreover, they are able to do it in different situations, accommodations and locations. This is very important as some of the tasks performed with the system were not available to the target user before.

One important issue to analyze is the execution of those tasks in real life scenarios. Results show that the system can be used without the need for an experienced helper and that the recognition system requires no technical expertise, although improvements may be achieved with experience.

Effectiveness

Effectiveness, or ease of use, quantifies how the users are able to perform the tasks and how they improve their performance with experience. Indeed, concerning the first approach, all the users were able to complete the tasks accurately after a preliminary introduction. Considering ease of use, it is also important to look at the pair user-caretaker. Results showed that the caretaker was able to understand the concept and the user-caretaker achieved an overall 93,33% recognition rate, similarly to the result achieved by the pair user-experienced helper.

One must say that it is not possible to present a generalized quantification on the approach, from the achieved results. The target user sample is reduced to two users. However, results suggest that the tasks are easy to perform, both for the user and the caretaker. Once again, we are enabling mobile device control and offering access to tasks that were not available before. Both users achieved the desired goals within acceptable times, with none or few errors.

Learnability

Learnability has to do with how the users improve their performance and overall system usage after some predetermined training period. Our results are not clear enough about learnability. To assess the system's overall learnability, a more extense evaluation is required. However, there were some indicators that the users improved performance with training. Concerning system recognition, the recognition rate improved from the first to the last session which suggests that the pair user-caretaker improved their knowledge on the system and on their specific functions.

Likability

Likability refers to the user's opinions, what they think about the system, their satisfaction on the approach and application. Although some preliminary results could point that the users were not interested in using a somehow intrusive control interface, the final results show that they are satisfied with the final results and willing to use a product that reflects our prototype and the underlined approach.

6

Conclusions

The primary goal of our work was to provide tetraplegic users with an effective mobile device control interface. Moreover, and taking into consideration the preliminary user studies, not only it was required an interface that enabled device control, but also one that was able to cope with a large spectrum of situations. This variability goes from physical differences among individuals to accommodation shifts even for the same individual.

To accomplish the aforementioned goals, we designed a system that features user communication by voluntarily contracting muscles and an overall redesign on the interaction scheme. Indeed, the system was required to cope with the different possible solutions where the user may be restricted to one input command but can also face restrictions considering visual feedback (when lying down). On the other hand, the system was designed to be exhaustive and enable a more capable individual to take advantage of his condition and feature a better interaction scheme. Overall, our approach tries to offer higher degrees of independence by enabling users to interact with the system along the day, even if the initial mounting and accommodation conditions are changed. Caretakers assistance is still required as accommodation shifts are concerned but the system does not require any intervention when that occurs.

To evaluate our approach, we developed a prototype that instantiates the guidelines and requirements delineated in the preliminary user studies. This prototype enables the user to interact with the mobile device by contracting any voluntarily contracted muscle. This interaction features one-muscle control as any other N-muscle interaction. According to the task to be fulfilled and the cardinality of the input set (number of muscles monitorized), the interaction is redesigned. To cope with the different accommodations where visual feedback may be nonexistent, optional (voice) feedback was added.

Evaluation studies showed that a daily wearable myographic interface is feasible and that, with task and user-focused interaction schemes, a mobile device control interface for tetraplegics can be achieved. We verified that if the necessary adaptability is offered while still keeping the user in control, a wide scope of users is covered as well as the featured daily scenarios.

Moreover, considering the actual panorama on assistive technologies on computer access for tetraplegics, we believe that the work presented in this dissertation goes beyond mobile device interaction. Actually, the accommodation and location issues shifts are also restrictive for static interaction. Indeed, as seen in the user studies, the time frame for computer interaction is often restricted by caretakers availability as several requirements must be met.

6.1. Future Work

Although our goals were accomplished, we believe that the research undertook in this dissertation brought up further work to be developed.

Universal Remote Control

As stated above, we believe that the interaction issues regarding static computers and actual assistive technologies faces several restrictions and neglects the daily scenario variability. However, even for interaction with static computers, an interface for tetraplegics should be designed contemplating the differences between disabled and non-disabled users. Although it is true that full-capable individuals operate a computer if they are positioned near the interaction mechanisms, it is also true that those individuals can voluntarily assume that required location and position. It is clear that the presuppositions are different and therefore a different interaction must also be designed.

The research presented in this dissertation enables control regardless of the accommodation of the user as well as device location and user-device position relation. As actual mobile devices feature several communication capabilities, the presented interface can be augmented to communicate with any other device and function as a universal remote control maintaining the same interaction schemes presented but offering control of other devices besides the mobile device.

Hybrid Control

Electromyography was the technique selected to offer the users with the required interaction capabilities. We believe it to be suitable to all the requirements and delineated design guidelines. However, and specially considering home interaction, multimodality could be explored to augment one's performance and overall capacities. As an example, voice interaction, if a private and noise-free environment is considered (user's bedroom), with its high command dimensionality could augment the presented solution.

Text-Entry Performance

While this dissertation is mainly focused on offering a tetraplegic person the capability to control a mobile device, independently of his accommodation and physical capacities, there are several situations where a highly restrictive control is achieved. Even though the performance is suitable for less demanding tasks like accepting or rejecting a call, others like writing a message can be very time-consuming and even fatiguing. As new interaction scenarios were brought up by this dissertation, it would be interesting to study text-entry acceleration (prediction and abbreviation) mechanisms that could improve thee tasks while coping with the lack of visual feedback.

Setup Usability

While we believe the system can be used and prepared without the need for an expert, it still demands a big setup apparatus. The electromyographic mobile device controller implies that several wires are placed around the user's body and although we have found specific usability solutions for particular body sites, the extensibility of the solution (any voluntarily contracted muscle) reduces the ability to provide mechanisms to support easy electrode location. However, this problem could be minimized if wireless electrodes are provided which is possible due to component miniaturization. Also, this solution would probably improve the collected samples as it is less likely to be contaminable by interferences.

A1

Preliminary Population Analysis

A1.1. User Analysis Questionnaire

User Characterization

1) Name: ______________________________

2) E-mail: ______________________________

3) Telephone: ______________

4) Sex: Male ____
Female ____

5) Age: ______

6) Habilitations: 4th Grade ____
9th Grade ____
12th Grade ____
BsC ____
MsC ____
PhD ____

Clinical History

7) Level of cervical lesion: ____

8) Complete or Incomplete? ____

9) How many years have you become tetraplegic? ____

10) What was the cause for the impairment? ______________

11) Point out the controlled areas:

Area	**Left**	**Right**
Eyes	____	____
Face (i.e., jaw)	____	____
Neck	____	____
Shoulder	____	____
Arm	____	____
Forearm	____	____
Hand	____	____
Fingers	____	____

Static Technological Material

12) Do you have a computer: ____

13) How many? ____

14) Which brand(s) and operating system(s)? ____________________

15) Where are those computers located? ____________________

16) What are their main functions? ____________________

17) Can you control any home electronic device? Which ones? ____________________

Mobile Devices

18) Do you have a cell phone? ____

19) Do you have a PDA? ____

20) How many? ____

21) Which brand(s) and operating model(s)? ________________________

22) Which functions do you use? ________________________

Personal Computer Interaction

23) Can you interact with the computer? ____

24) If yes, How? ________________________

25) Which tasks can you accomplish? ________________________

26) Which tasks you often require help? ________________________

27) In which conditions can you operate the computer? ________________________

- Accommodations ________________________

- Position ________________________

- Other restrictions ________________________

Mobile Device Interaction

28) Can you interact with the device? ____

29) If yes, How? ____________________

30) Which tasks can you accomplish? ____________________

31) Which tasks you often require help? ____________________

32) In which conditions can you operate the computer? ____________________

- Accommodations ____________________

- Position ____________________

- Other restrictions ____________________

Movimentation

33) Do you have an electric wheelchair? ____

34) Can you move around alone? ____

35) If yes, How? ____________________

Daily Life and Independence

36) During a normal day, how many accommodations? ____

37) Schedule of the shifts: ____________________

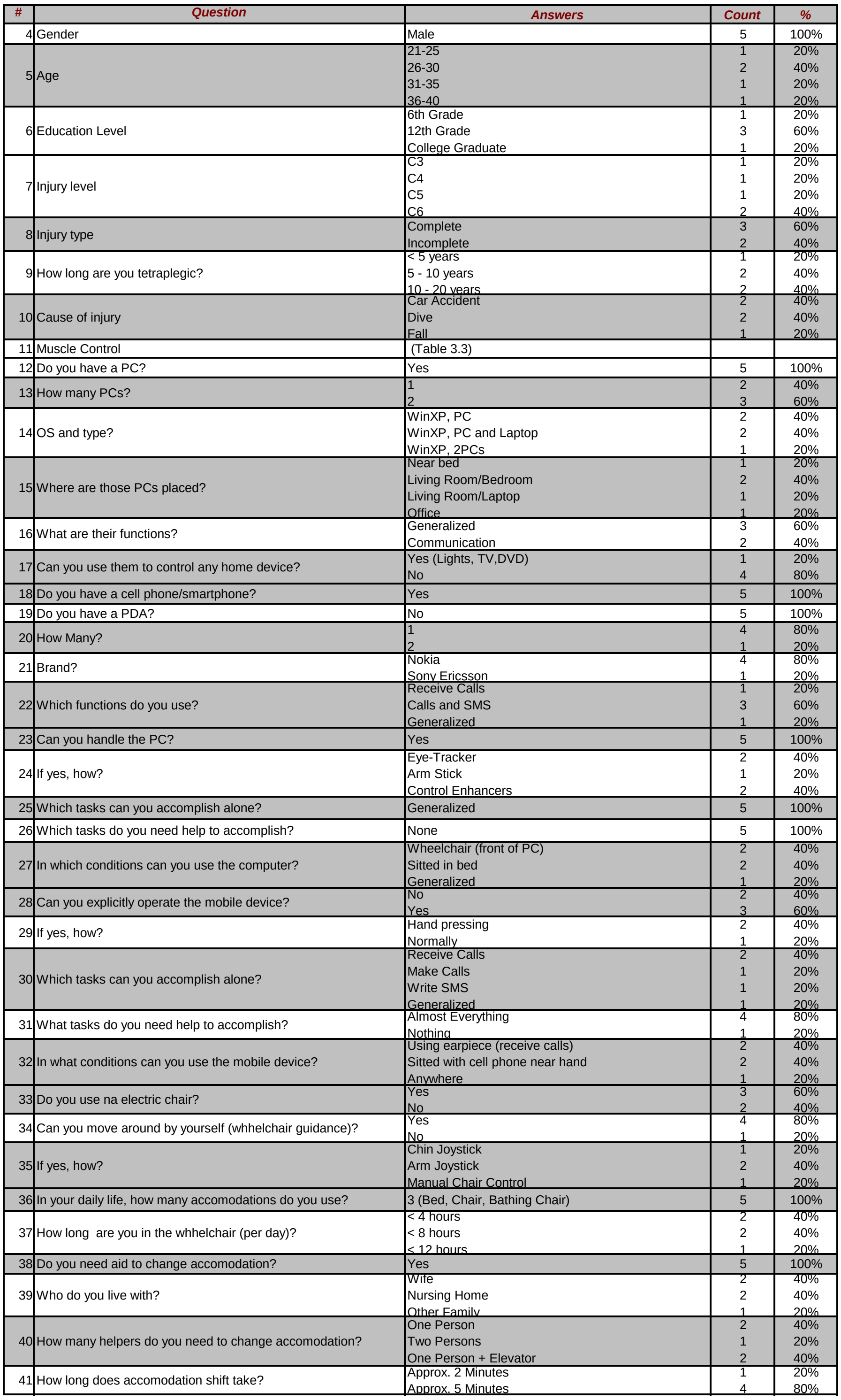
38) Who do you live with ? ____________________

39) Need caretakers aid for accommodation shifts? ____________________

40) How many persons and equipment are required? ____________________

41) How much time for the shift? ____________________

A1.2. User Analysis Results



#	Question	Answers	Count	%
4	Gender	Male	5	100%
5	Age	21-25	1	20%
		26-30	2	40%
		31-35	1	20%
		36-40	1	20%
6	Education Level	6th Grade	1	20%
		12th Grade	3	60%
		College Graduate	1	20%
7	Injury level	C3	1	20%
		C4	1	20%
		C5	1	20%
		C6	2	40%
8	Injury type	Complete	3	60%
		Incomplete	2	40%
9	How long are you tetraplegic?	< 5 years	1	20%
		5 - 10 years	2	40%
		10 - 20 years	2	40%
10	Cause of injury	Car Accident	2	40%
		Dive	2	40%
		Fall	1	20%
11	Muscle Control	(Table 3.3)		
12	Do you have a PC?	Yes	5	100%
13	How many PCs?	1	2	40%
		2	3	60%
14	OS and type?	WinXP, PC	2	40%
		WinXP, PC and Laptop	2	40%
		WinXP, 2PCs	1	20%
15	Where are those PCs placed?	Near bed	1	20%
		Living Room/Bedroom	2	40%
		Living Room/Laptop	1	20%
		Office	1	20%
16	What are their functions?	Generalized	3	60%
		Communication	2	40%
17	Can you use them to control any home device?	Yes (Lights, TV,DVD)	1	20%
		No	4	80%
18	Do you have a cell phone/smartphone?	Yes	5	100%
19	Do you have a PDA?	No	5	100%
20	How Many?	1	4	80%
		2	1	20%
21	Brand?	Nokia	4	80%
		Sony Ericsson	1	20%
22	Which functions do you use?	Receive Calls	1	20%
		Calls and SMS	3	60%
		Generalized	1	20%
23	Can you handle the PC?	Yes	5	100%
24	If yes, how?	Eye-Tracker	2	40%
		Arm Stick	1	20%
		Control Enhancers	2	40%
25	Which tasks can you accomplish alone?	Generalized	5	100%
26	Which tasks do you need help to accomplish?	None	5	100%
27	In which conditions can you use the computer?	Wheelchair (front of PC)	2	40%
		Sitted in bed	2	40%
		Generalized	1	20%
28	Can you explicitly operate the mobile device?	No	2	40%
		Yes	3	60%
29	If yes, how?	Hand pressing	2	40%
		Normally	1	20%
30	Which tasks can you accomplish alone?	Receive Calls	2	40%
		Make Calls	1	20%
		Write SMS	1	20%
		Generalized	1	20%
31	What tasks do you need help to accomplish?	Almost Everything	4	80%
		Nothing	1	20%
32	In what conditions can you use the mobile device?	Using earpiece (receive calls)	2	40%
		Sitted with cell phone near hand	2	40%
		Anywhere	1	20%
33	Do you use na electric chair?	Yes	3	60%
		No	2	40%
34	Can you move around by yourself (whhelchair guidance)?	Yes	4	80%
		No	1	20%
35	If yes, how?	Chin Joystick	1	20%
		Arm Joystick	2	40%
		Manual Chair Control	1	20%
36	In your daily life, how many accomodations do you use?	3 (Bed, Chair, Bathing Chair)	5	100%
37	How long are you in the whhelchair (per day)?	< 4 hours	2	40%
		< 8 hours	2	40%
		< 12 hours	1	20%
38	Do you need aid to change accomodation?	Yes	5	100%
39	Who do you live with?	Wife	2	40%
		Nursing Home	2	40%
		Other Family	1	20%
40	How many helpers do you need to change accomodation?	One Person	2	40%
		Two Persons	1	20%
		One Person + Elevator	2	40%
41	How long does accomodation shift take?	Approx. 2 Minutes	1	20%
		Approx. 5 Minutes	4	80%

Table A1.1: User and Task Analysis Questionnaire Raw Data

A2

Interaction Preliminary Evaluation

A2.1. Preliminary Evaluation Consent Form

Thank you for participating in our research studies. We will conduct studies on the control of a mobile device through muscle contractions. You will be asked to fulfill predetermined tasks commonly performed with a mobile device. We will log the interactions performed with the system as well as their timings. In addition, we will be videotaping your session to allow further analysis. All the results collected from the evaluation will be anonymized. Please read the statements below and sign where indicated. Each statement is separated so you are able to disagree with any independent one. Thank you.

1. I agree to perform the evaluation session described and that the results are logged in text files.

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

2. I agree that the session is videotaped to further analysis by the researchers.

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

3. I agree that the multimedia (photos and video) captured during the evaluation are used by the researchers in dissemination events and publications (thesis, articles, press).

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

A2.2. Preliminary Evaluation Background Questionnaire and Results

#	Question	User #1	User #2	User #3	User #4
2	**Age**	27	21	31	28
3	**Gender**	Female	Male	Male	Female
4	**Education Level**	Graduation	Graduation	12th Grade	Graduation
5	**Have any neuro-muscular disease/injury?**	No	No	Yes	Yes
6	**What disease/injury?**	---	---	Tetraplegia	Tetraplegia
7	**Injury Level or Affected Areas**	---	---	C5/C6 I	C5/C6 C
8	**Has a mobile device?**	Yes	Yes	Yes	Yes
9	**Mobile device Brand**	Nokia	Sony Ericsson	Nokia	Nokia
10	**With touch screen?**	No	No	No	No
11	**Uses voice recognition?**	No	No	No	No
12	**Tasks performed?**	Communication Agenda, Alarms	Communication Media	Communication	Communicarion
13	**Usage Frequency?**	Several/day	Several/day	Daily	Daily
14	**Where do you keep the device while on the move?**	Bag	Pocket	Wheelchair	Wheelchair
16	**And in bed?**	Near bed	Near bed	Bed	Near bed
17	**Turn off the mobile device when you go to sleep?**	No	No	No	Yes

Table A2.1: Background Questionnaire Raw Data

A2.3. Preliminary Evaluation Plan

This annex presents the test plan for the preliminary user tests.

A2.3.1. Introduction

This document describes the test plan for the preliminary tests to the mobile interaction prototype. It features the motivation of the evaluation, its methodology, research questions to be answered as well as other environment, users and equipment related sections.

A2.3.2. Motivation

This preliminary evaluation is focused on interaction profiles and interfacing schemes. Despite of the input method, we aim to validate the dialogues between the mobile device and the user and information presentation. Therefore, we want to validate the output information offered by the mobile device (whether visual or auditory) and its suitability to several scenarios and accommodations but also to compare the performance and qualitative evaluation (through user's comments and subjective answers) between several interaction profiles. To guarantee the validity of our conclusions we will perform a Wizard-of Oz evaluation where the Wizard replaces the bridge between the user and the mobile device (the user performs a movement/gesture/contraction and the Wizard understands that action and changes the state of the system accordingly). At this point no physiological data is measured to exclude recognition or input-related errors.The obtained results will serve as a baseline to future usability tests.

This evaluation is composed by the mobile device main tasks (Making and Receiving Calls, Sending and Receiving Messages, Menu Navigation) performed with different parameters (Scanning type, Number of Input Commands, Feedback type). We will measure the time to complete the tasks, performance, identify errors, difficulties and preferences.

A2.3.3. Research Questions

This evaluation tries to answer the following research questions:

1. Are the users able to associate "body gestures" with a given action?

2. Are the users able to operate the device within different accommodations?

3. Does performance reflect accommodation and feedback type?
4. Do users require help during interaction?
5. Are there any main/universal collection point candidates?
6. How does the number of input commands influence performance?
7. How does the number of input commands influence confusion?
8. Are the users comfortable with the interaction profiles?
9. How do the users react to interfacing schemes shift?
10. Does the interaction time cause frustration or errors?

A2.3.4. User Profile

A total of four (4) participants will be tested, at their own homes. One or two participants will be tested per day. The only requirements to perform the evaluation is to know how to write, have time and space (as the evaluation is performed in the users' room) availability, and mobile device acquaintance. The evaluation features two groups of users divided accordingly to their physical capabilities:

- The first group is composed by two (2) full-capable individuals. Although this group does not present any physical impairment, the users will be asked to select input commands from their chest up. During the evaluation they will not be restricted. This group will serve as a baseline comparison to the second group (the real target users). This control group will give us the opportunity to identify possible differences between full-capable and impaired individuals and take those differences into account when designing the final version of the prototype.
- The second group is composed by two (2) tetraplegic participants. They are the main stakeholders and should be interested and motivated in the solution. The majority of the data will be collected from this group. We should be able to evaluate the system within several accommodations (wheelchair, lay down and to the side in bed).

A2.3.5. Evaluation Methodology

This evaluation consists in a Wizard-of-Oz simulation(Dix et al., 2004) to collect data and opinions from the user on several aspects on the human-device interaction dialogues and schemes. The evaluation session features six different sections:

Experiment Preparation The first step of the test plan is performed before the visit to the user's home. Indeed, there are several aspects that need to be prepared so the evaluation is performed with no interruptions. Also, there are several precautions that must be taken to ensure the recording of the interactions and the correct data extraction. Considering the experiment, the monitor must ensure that the mobile device is fully charged and the application is deployed and ready to be executed. Also, the scripts and configuration files must be prepared to allow quick parameterization. Also, considering data extraction, the questionnaires, instructions and consent forms should be printed and ready to use. Task descriptions should also be available. The recording equipment (camera and audio) must be checked for battery and ensure recording memory.

Participant Introduction, Consenting and Background Questionnaire In the first contact with each participant, the monitor should give a brief introduction and make the participant comfortable and relaxed. Also, the monitor must stress that the user is not being evaluated (the system is) and make the user understand that he is cooperating and that we are thankful for that.

After the first contact, the user will be told to fill the background questionnaire and to sign a consent form. This form asks for consent to record image and audio of the evaluation session for analysis and for publication (scientific articles, reports and thesis). The user can agree/disagree with any of the items in the form.

Experiment Equipment Setup As the evaluation is performed in the users' home, all the equipment is mounted after the introduction. The camera and audio recorder should be ready to start recording and the mobile device must be paired with the laptop (where the Wizard inputs commands). To avoid distractions during the evaluation session, the recording will not stop between tasks (even when the camera changes position) and will start at this point, before the orientation and ambientation phase.

Orientation Participants will receive a verbal introduction to the test. In this phase, we will explain the purpose of the test and offer an overview of the evaluation. Once again, it is important to stress that we are evaluating the system and not the user. Also, it is important that the user is comfortable and clearly states that he is ready to start the evaluation.

Test Execution The execution of the evaluation starts with the delivery of the written instructions and an overview of the system and tasks to be fulfilled. For each of the tasks, the procedure starts with the user reading the Task Description and clarifying any possible doubts. The monitor holds the Task Description maintaining the paper in the user's line of sight during task execution. During the test, the monitor will not interact with the participant unless a severe error occurs. However, the participants will be encouraged to verbalize their concerns or opinions during task execution. The monitor will note down errors, elapsed time, opinions and particular behaviors. Between tasks, the monitor changes parameterization but no intermediate feedback is collected.

Participant Debriefing As all the tasks are finished, the participant will be debriefed. An interview will take place to gather the user's opinions. This interviews include a set of base questions but every interview is likely to follow a different path to collect the user's comments, possible improvements and opinions regarding specific behaviors. At the end of this phase, the users will be thanked for their participation. The recording will be stopped.

Session Analysis To complement and assert the information gathered in the session, the monitor will review the recorded information.

A2.3.6. Task List

The evaluation features the following tasks:

- Menu navigation
  - In bed
  - In the wheelchair
- Message Reading
  - In bed
  - In the wheelchair
- Accepting/Rejecting Call
  - In bed
  - In the wheelchair
- Writing Message
  - In bed
  - In the wheelchair
- Making a Call
  - In bed
  - In the wheelchair

A2.3.7. Evaluation Environment

The evaluation will take place in the user's home. The tasks will be carried in the bed and in the wheelchair. The mobile device used will be the HTC S310 with Windows Mobile 5.0, paired with a laptop with Windows XP (for the Wizard). The bluetooth connection must working properly. The entire session will be recorded with a video camera.

A2.3.8. Evaluation Monitor/Wizard Roles

The monitor is responsible to ensure the evaluation session. It is also responsible to prepare the equipment and instruct the participant. The monitor also has to collect the evaluation data and the user's opinions. The test monitor is expected not to help the participants unless a severe error occurs.

The wizard is responsible for the interpretation and response to the user's input commands. He is expected not to intervene in any other task nor speak with the participant during the tasks to be fulfilled.

A2.3.9. Evaluation Data

We will collect the following measurements:

- Time users take to complete the task
- Number of errors
- Number of commands to complete the task
- Task success rate
- Time spent recovering from errors
- Error classification
- Subjective Evaluation

A2.3.10. Evaluation Report

The evaluation session report will include the procedure, goals, results and discussion. It will include the raw data.

A2.4. Preliminary Evaluation Scenarios

In this annex we present the task descriptions given to participants during the interaction preliminary evaluation. Also, this document features the system introduction and overall remarks.

A2.4.1. Introductory Remarks

We are developing a system to enable a tetraplegic user to effectively operate a mobile device. We aim to achieve this goal by using the individual residual capacities as input commands. The notion of capacity depends on the user's impairment but also on the situation. We will therefore evaluate the system through several tasks but also considering several impairments levels and location and accommodation restrictions.

We are in a preliminary stage and at this time want to address the effectiveness of the dialogues the device maintains with the user. It is important to notice that we are evaluating the system and not the user himself. Therefore, we would like to thank for your help and make you feel free to speak out your opinions, concerns and difficulties.

A2.4.2. Task Scenarios

This evaluation session features some of the main tasks performed with a mobile device. We focus on navigation and communication. For each of the goals, the user is asked to perform the evaluation in two different accommodations, which are supposedly the bed and the wheelchair, but can be any two accommodations that feature visual feedback and another with only auditory feedback (lay down). Also, within this tasks and accommodations, we will vary the number of input commands (simulating different capacities and testing different interaction profiles). To ensure the validity of the results, we not only randomly select the order of the tasks but also, the order of the number of input commands (Table A2.2). The accommodation is dependent on the user's availability.

	Visual Feedback	Auditory Feedback
Automatic Scanning	One	One
Directed Scanning	Three	Three

Table A2.2: Within-Task Variations and Number of Input Commands

The tasks to be fulfilled (with different restrictions are):

Menu Navigation and Message Reading You are going to a dinner today but you don't remember the place's name. You do remember that George sent you a SMS with that information. Navigate to your inbox and read the message you have received from George. You are at the main menu.

Accepting and Rejecting a Call Before going to the dinner everyone is calling but you are not in the mood and want to have a little rest. Alexander calls you and as you know it is just to chat you cancel the incoming call. One minute later, you receive a call from the dinner organizer and you want to take it.

Writing a Message You regret to have canceled Alexander's call and you want to send him a message. You are at the start of the message (Write Message Screen). Input the text "call later".

Making a Call You still don't know the place so you just decide to call George. His number is the 93 369 23 91 [randomly selected]. You start the task in the "Making Call" screen.

A2.5. Preliminary Evaluation Monitor Checklists

In this section we present the checklists used during the interaction preliminary evaluation sessions.

A2.5.1. Checklist 0 - The day Before the Evaluation

- Print the questionnaire, interview guidelines and consent form
- Print the Introduction and Overview
- Print the Task Descriptions
- Print the evaluation sheets and checklists
- Install and configure on the laptop the software to capture the image from the video camera
- Test the video camera and ensure that the disk space is enough for the real time capture
- Prepare configuration files to allow a faster shift between tasks
- Fully charge the camera, mobile device and laptop
- Review the scenarios with the wizard
- Perform one test

A2.5.2. Checklist 1 - The day of the Evaluation

Introducing the Session

- Greet the participant
- Give an overview of the system and the evaluation session
- Explain the goal of the evaluation (to test the system)
- Have the participant to fill the background questionnaire
- Explain the data logging and have the participant to fill the consent form

Before the Evaluation

- Create the recording setup
- Turn on the laptop and mobile device
- Pair the devices (bluetooth)
- Start the Wizard Application (laptop)
- Start the Mobile device Application
- Introduce the system and an overall view of the tasks to be fulfilled
- Ask the participants to feel free to talk and share their opinions while performing the tasks
- Be sure that there are no distractions
- Start video and audio recording

Before each Task

- Capture the task description with the camera
- Put the task description in the user's line of sight
- Ask the user to read the task
- Make sure the user has no doubts

During the Task

- Start the timer when the user begins performing the task
- Annotate errors, time, questions, opinions
- When a task is finished reset the timer
- Try to keep the user relaxed

After the evaluation

- Stop the recording
- Interview the participant

- Debrief the participant
- Thank the participant for his availability, opinions and help
- Clean up and pack the camera, mobile device and laptop

A2.5.3. Checklist 2 - The day after the Evaluation

- Review the evaluation logs and recordings
- Insert the gathered data in raw tables

A2.5.4. Checklist 3 - After all evaluation sessions

- Contact the participants and thank them again for their help
- Share with the participants the main conclusions retrieved from the evaluation and discuss them
- Write the report

A2.6. Preliminary Evaluation Interview Guidelines

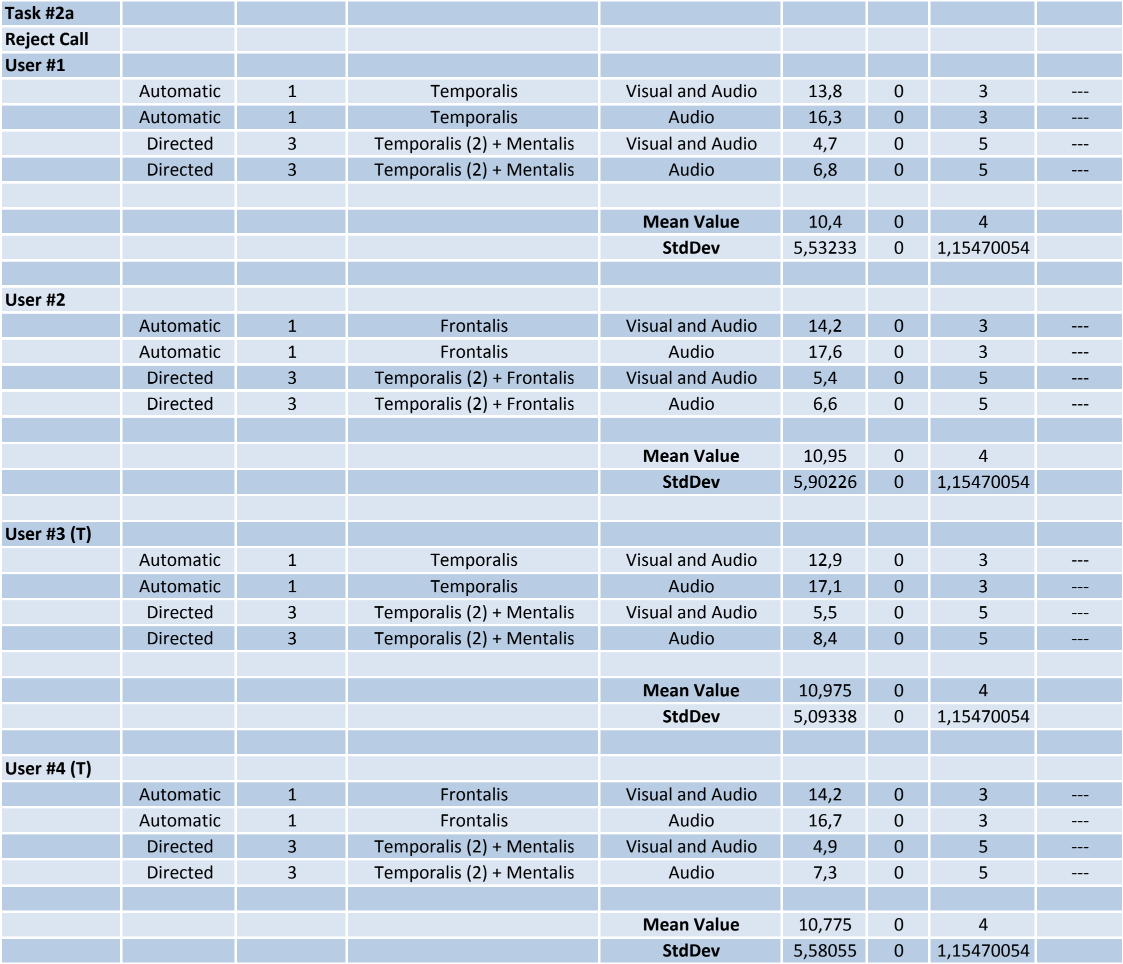
In this annex we present the set of base questions prepared for the interviews. While the interviews could follow different directions (and the users were encouraged to expand their thoughts), this set of questions helped us guarantee that the main focus points were stressed. These base questions served as a starting point to a line of conversation in a certain topic:

- Will it be interesting to control the mobile device with configured movements / gestures / contractions?
- In which situations you would use it?
- For each situation, what locations could be monitored?
- For any task or particular ones?
- Do you think it is awkward to perform those body gestures in public?

A2.7. Preliminary Evaluation Results

Task #1								
Menu Nav.	**Scheme**	**# Input Commands**	**Sites**	**Feedback**	**Time(s)**	**# Errors**	**# Commands**	**Recover Time**
User #1								
	Automatic	1	Temporalis	Visual and Audio	44,2	0	11	---
	Automatic	1	Temporalis	Audio	64	1	12	9
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	24,3	0	17	---
	Directed	3	Temporalis (2) + Mentalis	Audio	35,2	0	17	---
				Mean Value	41,925	0,25	14,25	9
				StdDev	16,8161	0,5	3,20156212	
User #2								
	Automatic	1	Frontalis	Visual and Audio	45,3	0	11	---
	Automatic	1	Frontalis	Audio	55	0	11	---
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	33,6	1	18	8,5
	Directed	3	Temporalis (2) + Frontalis	Audio	39,3	0	17	---
				Mean Value	43,3	0,25	14,25	8,5
				StdDev	9,14658	0,5	3,77491722	
User #3 (T)								
	Automatic	1	Temporalis	Visual and Audio	42,4	0	11	---
	Automatic	1	Temporalis	Audio	79,1	2	13	11,3
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	27,1	0	17	---
	Directed	3	Temporalis (2) + Mentalis	Audio	37,9	0	17	---
				Mean Value	46,625	0,5	14,5	11,3
				StdDev	22,5819	1	3	
User #4 (T)								
	Automatic	1	Frontalis	Visual and Audio	46	0	11	---
	Automatic	1	Frontalis	Audio	62,4	1	12	8,4
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	23,6	0	17	---
	Directed	3	Temporalis (2) + Mentalis	Audio	36,8	0	17	---
				Mean Value	42,2	0,25	14,25	8,4
				StdDev	16,3054	0,5	3,20156212	

Table A2.3: Preliminary Evaluation Results (Menu Navigation)



Task #2a								
Reject Call								
User #1								
	Automatic	1	Temporalis	Visual and Audio	13,8	0	3	---
	Automatic	1	Temporalis	Audio	16,3	0	3	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	4,7	0	5	---
	Directed	3	Temporalis (2) + Mentalis	Audio	6,8	0	5	---
				Mean Value	10,4	0	4	
				StdDev	5,53233	0	1,15470054	
User #2								
	Automatic	1	Frontalis	Visual and Audio	14,2	0	3	---
	Automatic	1	Frontalis	Audio	17,6	0	3	---
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	5,4	0	5	---
	Directed	3	Temporalis (2) + Frontalis	Audio	6,6	0	5	---
				Mean Value	10,95	0	4	
				StdDev	5,90226	0	1,15470054	
User #3 (T)								
	Automatic	1	Temporalis	Visual and Audio	12,9	0	3	---
	Automatic	1	Temporalis	Audio	17,1	0	3	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	5,5	0	5	---
	Directed	3	Temporalis (2) + Mentalis	Audio	8,4	0	5	---
				Mean Value	10,975	0	4	
				StdDev	5,09338	0	1,15470054	
User #4 (T)								
	Automatic	1	Frontalis	Visual and Audio	14,2	0	3	---
	Automatic	1	Frontalis	Audio	16,7	0	3	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	4,9	0	5	---
	Directed	3	Temporalis (2) + Mentalis	Audio	7,3	0	5	---
				Mean Value	10,775	0	4	
				StdDev	5,58055	0	1,15470054	

Table A2.4: Preliminary Evaluation Results (Rejecting a Call)

Task #2b								
Accept Call								
User #1								
	Automatic	1	Temporalis	Visual and Audio	8,2	0	3	---
	Automatic	1	Temporalis	Audio	11,4	0	3	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	2,8	0	4	---
	Directed	3	Temporalis (2) + Mentalis	Audio	3,6	0	4	---
				Mean Value	6,5	0	3,5	
				StdDev	4,04145	0	0,57735027	
User #2								
	Automatic	1	Frontalis	Visual and Audio	10,3	0	3	---
	Automatic	1	Frontalis	Audio	12,9	0	3	---
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	2,5	0	4	---
	Directed	3	Temporalis (2) + Frontalis	Audio	3,3	0	4	---
				Mean Value	7,25	0	3,5	
				StdDev	5,14425	0	0,57735027	
User #3 (T)								
	Automatic	1	Temporalis	Visual and Audio	7,8	0	3	---
	Automatic	1	Temporalis	Audio	12,8	0	3	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	4,1	0	4	---
	Directed	3	Temporalis (2) + Mentalis	Audio	5,6	0	4	---
				Mean Value	7,575	0	3,5	
				StdDev	3,80033	0	0,57735027	
User #4 (T)								
	Automatic	1	Frontalis	Visual and Audio	9,2	0	3	---
	Automatic	1	Frontalis	Audio	13,1	0	3	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	3,2	0	4	---
	Directed	3	Temporalis (2) + Mentalis	Audio	4,8	0	4	---
				Mean Value	7,575	0	3,5	
				StdDev	4,47242	0	0,57735027	

Table A2.5: Preliminary Evaluation Results (Accepting a Call)

Task #3								
Write Msg								
User #1								
	Automatic	1	Temporalis	Visual and Audio	153,2	0	33	---
	Automatic	1	Temporalis	Audio	159,8	0	33	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	33	0	77	---
	Directed	3	Temporalis (2) + Mentalis	Audio	42,3	0	77	---
				Mean Value	97,075	0	55	
				StdDev	68,7758	0	25,4034118	
User #2								
	Automatic	1	Frontalis	Visual and Audio	162,2	0	33	---
	Automatic	1	Frontalis	Audio	168,4	0	33	---
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	36,7	0	77	---
	Directed	3	Temporalis (2) + Frontalis	Audio	43,1	0	77	---
				Mean Value	102,6	0	55	
				StdDev	72,4911	0	25,4034118	
User #3 (T)								
	Automatic	1	Temporalis	Visual and Audio	158,6	0	33	---
	Automatic	1	Temporalis	Audio	167,8	0	33	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	34,2	0	77	---
	Directed	3	Temporalis (2) + Mentalis	Audio	52,3	0	79	---
				Mean Value	103,225	0	55,5	
				StdDev	69,7475	0	25,993589	
User #4 (T)								
	Automatic	1	Frontalis	Visual and Audio	154	0	33	---
	Automatic	1	Frontalis	Audio	159,2	0	33	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	36,3	0	77	---
	Directed	3	Temporalis (2) + Mentalis	Audio	46,8	0	79	---
				Mean Value	99,075	0	55,5	
				StdDev	66,5962	0	25,993589	

Table A2.6: Preliminary Evaluation Results (Writing a Message)

Task #4								
Make Call								
User #1								
	Automatic	1	Temporalis	Visual and Audio	91,1	0	40	---
	Automatic	1	Temporalis	Audio	95,4	0	40	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	25,2	0	65	---
	Directed	3	Temporalis (2) + Mentalis	Audio	27,9	0	65	---
				Mean Value	59,9	0	52,5	
				StdDev	38,565	0	14,4337567	
User #2								
	Automatic	1	Frontalis	Visual and Audio	93,2	0	40	---
	Automatic	1	Frontalis	Audio	97,4	0	40	---
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	26,6	0	65	---
	Directed	3	Temporalis (2) + Frontalis	Audio	33,5	0	67	---
				Mean Value	62,675	0	53	
				StdDev	37,8162	0	15,0332964	
User #3 (T)								
	Automatic	1	Temporalis	Visual and Audio	90,9	0	40	---
	Automatic	1	Temporalis	Audio	93,7	0	40	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	26,3	0	65	---
	Directed	3	Temporalis (2) + Mentalis	Audio	29,3	0	65	---
				Mean Value	60,05	0	52,5	
				StdDev	37,2768	0	14,4337567	
User #4 (T)								
	Automatic	1	Frontalis	Visual and Audio	94,2	0	40	---
	Automatic	1	Frontalis	Audio	96,5	0	40	---
	Directed	3	Temporalis (2) + Mentalis	Visual and Audio	26,1	0	65	---
	Directed	3	Temporalis (2) + Mentalis	Audio	28,7	0	65	---
				Mean Value	61,375	0	52,5	
				StdDev	39,2565	0	14,4337567	

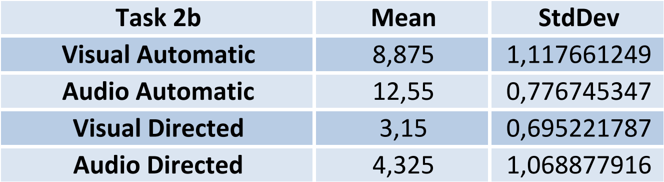
Table A2.7: Preliminary Evaluation Results (Making a Call)

Task 1	**Mean**	**StdDev**
Visual Automatic	44,475	1,569235483
Audio Automatic	65,125	10,10787647
Visual Directed	27,15	4,558142897
Audio Directed	37,3	1,73397424

Table A2.8: Preliminary Evaluation Resumed Results (Menu Navigation)

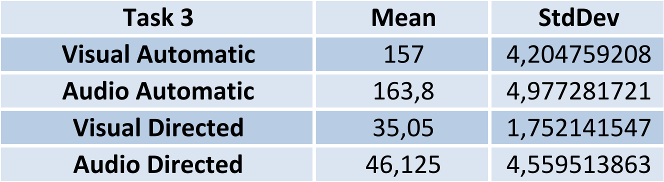
Task 2a	**Mean**	**StdDev**
Visual Automatic	13,775	0,613052472
Audio Automatic	16,925	0,556027577
Visual Directed	5,125	0,386221008
Audio Directed	7,275	0,805708798

Table A2.9: Preliminary Evaluation Resumed Results (Reject Call)



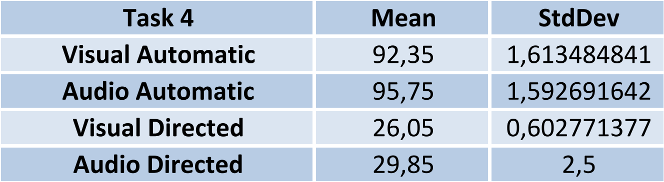
Task 2b	Mean	StdDev
Visual Automatic	8,875	1,117661249
Audio Automatic	12,55	0,776745347
Visual Directed	3,15	0,695221787
Audio Directed	4,325	1,068877916

Table A2.10: Preliminary Evaluation Resumed Results (Accept Call)



Task 3	Mean	StdDev
Visual Automatic	157	4,204759208
Audio Automatic	163,8	4,977281721
Visual Directed	35,05	1,752141547
Audio Directed	46,125	4,559513863

Table A2.11: Preliminary Evaluation Resumed Results (Write Message)



Task 4	Mean	StdDev
Visual Automatic	92,35	1,613484841
Audio Automatic	95,75	1,592691642
Visual Directed	26,05	0,602771377
Audio Directed	29,85	2,5

Table A2.12: Preliminary Evaluation Resumed Results (Make Call)

A3

System Recognition Evaluation

A3.1. System Evaluation Consent Form

Thank you for participating in our research studies. We will conduct studies on the recognition of muscle contractions using electromyography. During these studies, we will attach surface electrodes to your body (face and neck) and ask you to randomly recall a certain contraction. The system will collect the raw EMG signal from all the collected sites. In addition, we will be videotaping your session to allow further analysis. All the results collected from the evaluation will be anonymized. Please read the statements below and sign where indicated. Each statement is separated so you are able to disagree with any independent one. Thank you.

1. I agree to perform the evaluation session described and that the results are logged in text files.

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

2. I agree that the session is videotaped to further analysis by the researchers.

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

3. I agree that the multimedia (photos and video) captured during the evaluation are used by the researchers in dissemination events and publications (thesis, articles, press).

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

A3.2. System Evaluation Background Questionnaire and Results

#	Question	User #1	User #2	User #3	User #4	User #5	User #6	User #7	User #8
2	**Age**	27	28	26	32	53	21	26	31
3	**Gender**	Male	Female	Male	Female	Male	Male	Male	Male
4	**Education Level**	MsC	Graduation	Graduation	Graduation	Graduation	Graduation	MsC	12th Grade
5	**Have any neuro-muscular disease/injury?**	No	Yes	No	No	No	No	No	Yes
6	**What disease/injury?**	--	Tetraplegia	--	--	--	--	--	Tetraplegia
7	**Injury Level or Affected Areas**	--	C5/C6 C	--	--	--	--	--	C5/C6 I
8	**Uses eye-glasses?**	No	Yes	No	No	No	No	Yes	No
9	**Has a beard?**	Small	No	No	No	No	Small	Small	No
10	**Has a moustache?**	Small	No	No	No	Yes	No	No	No
11	**Is able to blink both eyes independently?**	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
12	**Is able to blink clench teeth independently?**	Yes	Maybe	Yes	Yes	Yes	Yes	Yes	Yes

Table A3.1: Background Questionnaire Raw Data

A3.3. System Evaluation Methodology

This annex presents the test plan for the system evaluation.

A3.3.1. Introduction

This document describes the test plan for the system evaluation. It features the motivation of the evaluation, its methodology, research questions to be answered as well as other environment, users and equipment related sections.

A3.3.2. Motivation

The system evaluation is focused on the technical details of the solution. It is focused on the input method, electromyography, and tries to evaluate task independent measures.

This evaluation is based on the recall of muscle contractions/movements with different setup apparatus. The users will test several positions and setup sets. We will measure the recognition accuracy, errors and signal-related measures.

A3.3.3. Research Questions

This evaluation tries to answer the following research questions:

1. Can we accurately identify a ”body gesture”?
2. Is the system able to cope with multi-electrodes setup?
3. Which are the most probable collisions?
4. Which are the best placement positions?
5. Which are the candidate locations for each impairment?
6. In similar mountings, is there a difference between impaired and non-impaired users?

A3.3.4. User Profile

A total of eight (8) participants will be tested. Two to four participants will be tested per day. The evaluation features two groups of users divided accordingly to their physical capabilities:

- The first group is composed by six (6) full-capable individuals. Although this group does not present any physical impairment, the users will be asked to perform contractions from their chest up. During the evaluation they will not be restricted. This group will serve as a baseline comparison to the second group (the real target users). This control group will give us the opportunity to identify possible differences between full-capable and impaired individuals and take those differences into account when designing the final version of the prototype.
- The second group is composed by two (2) tetraplegic participants. They are the main stakeholders and should be interested and motivated in the solution. The majority of the data will be collected from this group.

A3.3.5. Evaluation Methodology

This evaluation consists in varying the number of electrodes and placement positions and ask the users to ″activate″ the monitored zones sequentially. The evaluation session features six different sections:

Experiment Preparation The first step of the test plan is performed before the user is involved. Indeed, there are several aspects that need to be prepared so the evaluation is performed with no interruptions. Also, there are several precautions that must be taken to ensure the recording of the interactions and the correct data extraction. Considering the experiment, the monitor must ensure that the application is deployed and ready to be executed. Also, considering data extraction, the questionnaires, instructions and consent forms should be printed and ready to use. The recording equipment (camera and audio) must be checked for battery and ensure recording memory. The camera and audio recorder should be ready to start recording and the laptop must be paired with the EMG device. To avoid distractions during the evaluation session, the recording will not stop between tasks (even when the camera changes position) and will start at this point, before the orientation and ambientation phase.

Participant Introduction, Consenting and Pre-Questionnaire In the first contact with each participant, the monitor should give a brief introduction and make the participant comfortable and relaxed. Also, the monitor must stress that the user is not being evaluated (the system is) and make the user understand that he is cooperating and that we are thankful for that.

After the first contact, the user will be told to fill the background questionnaire and to sign a consent form. This form asks for consent to record image and audio of the evaluation session for analysis and for publication (scientific articles, reports and thesis). The user can agree/disagree with any of the items in the form. If the user is not able to sign, the consent is video captured.

Orientation Participants will receive a verbal introduction to the test. In this phase, we will explain the purpose of the test and offer an overview of the evaluation. Once again, it is important to stress that we are evaluating the system and not the user. Also, it is important that the user is comfortable and clearly states that he is ready to start the evaluation.

Test Execution The execution of the evaluation starts with an overview of the system and the mounting for the first task. The user is asked to perform a gesture to verify that the system is working properly and the user understands the concept. For each of the setups, the monitor will sequentially ask the user to perform a certain gesture. No feedback is offered. An interval of 5 seconds between gestures should be maintained. All the electromyographic data is logged. The monitor does not need to take notes. Between tasks, the monitor changes parameterization and electrodes location but no intermediate feedback is collected.

Participant Debriefing As all the tasks are finished, the participant will be debriefed. The users will be thanked for their participation. The recording will be stopped.

Session Analysis To complement and assert the information gathered in the session, the monitor will review the recorded information.

A3.3.6. Evaluation Environment

The evaluation will take place in the user's home or at IST-Tagus Park. The electromyographic system will be a BioPlux4 electromyographic device with Ag/Acl surface electrodes. The bluetooth connection must be working properly. The entire session will be recorded with a video camera.

A3.3.7. Evaluation Monitor Roles

The monitor is responsible to ensure the evaluation session. It is also responsible to prepare the equipment and instruct the participant. The monitor also has to collect the evaluation data.

A3.3.8. Evaluation Data

We will collect the following measurements and data:

- Number of errors
- Number of hits
- Type of error
- Raw EMG Signal and from it other features (MVC, Standard Deviation, Mean, Energy)

A3.3.9. Evaluation Report

The evaluation session report will include the procedure, goals, results and discussion. It will include the raw data (except the complete EMG signal).

A3.4. System Evaluation Monitor Checklists

In this section we present the checklists used during the system evaluation sessions.

A3.4.1. Checklist 0 – The day Before the Evaluation

- Print the questionnaires (pre-questionnaire) and consent form
- Print the evaluation sheets and checklists
- Install and configure on the laptop the software to capture the image from the video camera
- Test the video camera and ensure that the disk space is enough for the real time capture
- Prepare configuration files to allow a faster shift between tasks
- Fully charge the camera, mobile device and electromyographic device
- Perform one test

A3.4.2. Checklist 1 – The day of the Evaluation

Introducing the Session

- Greet the participant
- Give an overview of the evaluation session
- Explain the goal of the evaluation (to test the system)
- Have the participant to fill the background questionnaire
- Explain the data logging and have the participant to fill the consent form

Before the Evaluation

- Create the recording setup
- Turn on the electromyographic (EMG) and mobile device
- Pair the devices (bluetooth)

- Start the laptop Application
- Be sure that there are no distractions
- Start video and audio recording

Before each Task

- Place the electrodes
- Ask the user if he is comfortable
- Explain the task and ask the user to perform the required actions

During the Task

- Annotate time, errors, questions, opinions
- Try to keep the user relaxed

After the evaluation

- Stop the recording
- Debrief the participant
- Thank the participant for his availability, opinions and help
- Clean up and pack the camera, mobile device and EMG device

A3.4.3. Checklist 2 - The day after the Evaluation

- Review the evaluation logs and recordings
- Insert the gathered data in raw tables

A3.4.4. Checklist 3 - After all evaluation sessions

- Contact the participants and thank them again for their help
- Write the report

A3.5. System Evaluation Results

		Recalled			
	User #1	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	4	0	0	0
	Temporalis Left	0	4	0	0
	Frontalis	0	0	4	0
	None	1	1	1	

		Recalled			
	User #2	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	5	0	0	0
	Temporalis Left	0	5	0	0
	Frontalis	0	3	5	0
	None	0	0	0	

		Recalled			
	User #3	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	5	0	0	0
	Temporalis Left	0	5	0	0
	Frontalis	1	0	3	0
	None	0	0	2	

		Recalled			
	User #4	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	5	0	0	0
	Temporalis Left	0	0	0	0
	Frontalis	1	5	5	0
	None	0	0	0	

		Recalled			
	User #5	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	5	0	0	0
	Temporalis Left	0	5	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

		Recalled			
	User #6	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	5	0	0	0
	Temporalis Left	0	5	1	0
	Frontalis	4	2	5	0
	None	0	0	0	

		Recalled			
	User #7	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	5	0	0	0
	Temporalis Left	0	5	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

		Recalled			
	User #8	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	5	0	0	0
	Temporalis Left	0	5	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

Table A3.2: Confusion Matrix Absolute Values - Recognition Evaluation (Temporalis and Frontalis)

		Recalled			
	User #1	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	80,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	80,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	80,00%	0,00%
	None	20,00%	20,00%	20,00%	

		Recalled			
	User #2	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	60,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #3	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	100,00%	0,00%	0,00%
	Frontalis	20,00%	0,00%	60,00%	0,00%
	None	0,00%	0,00%	40,00%	

		Recalled			
	User #4	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	0,00%	0,00%	0,00%
	Frontalis	20,00%	100,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

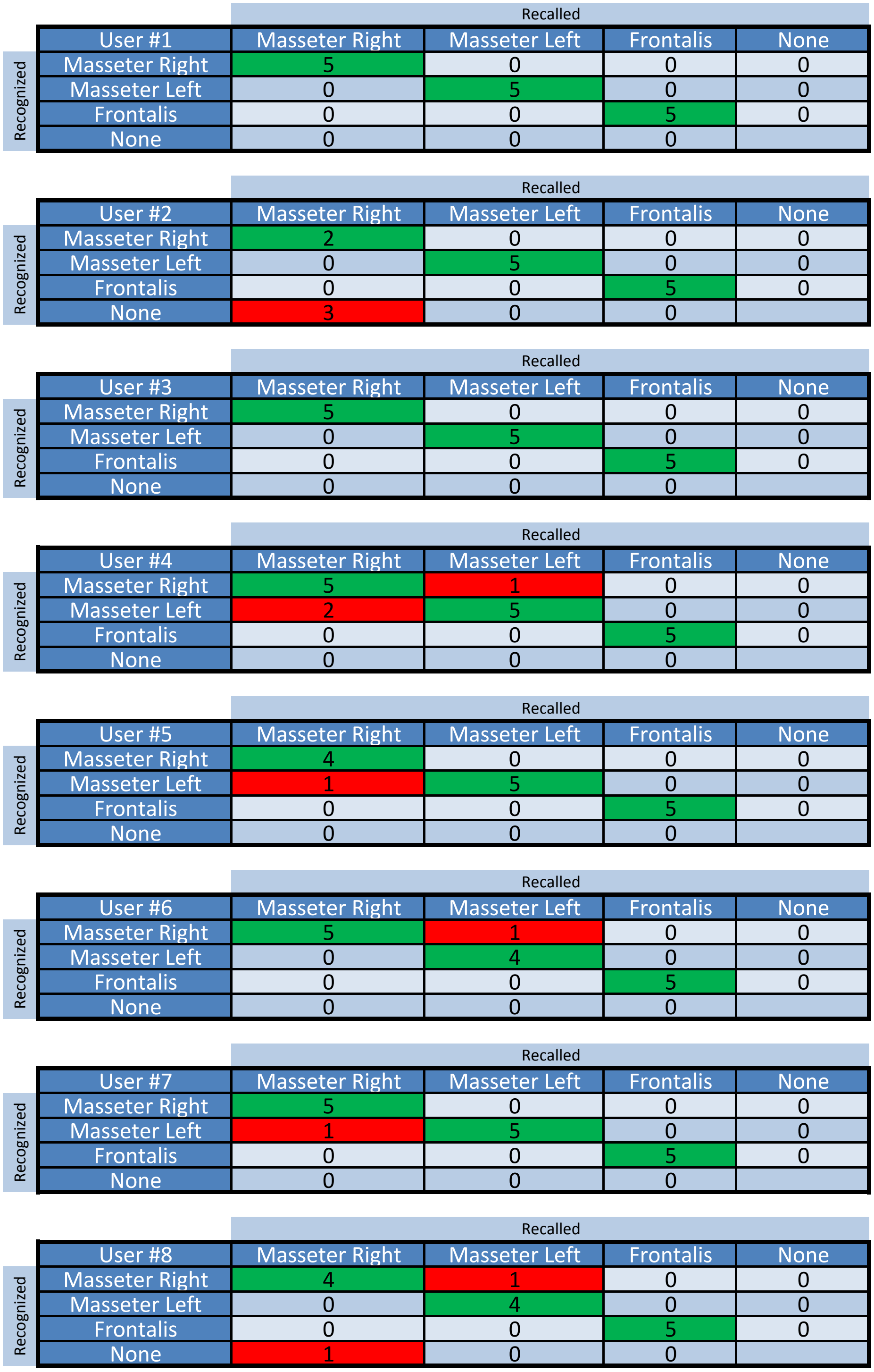
		Recalled			
	User #5	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #6	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	100,00%	20,00%	0,00%
	Frontalis	80,00%	40,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #7	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #8	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

Table A3.3: Confusion Matrix Relative Values - Recognition Evaluation (Temporalis and Frontalis)



		Recalled			
	User #1	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	5	0	0	0
	Masseter Left	0	5	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

		Recalled			
	User #2	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	2	0	0	0
	Masseter Left	0	5	0	0
	Frontalis	0	0	5	0
	None	3	0	0	

		Recalled			
	User #3	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	5	0	0	0
	Masseter Left	0	5	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

		Recalled			
	User #4	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	5	1	0	0
	Masseter Left	2	5	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

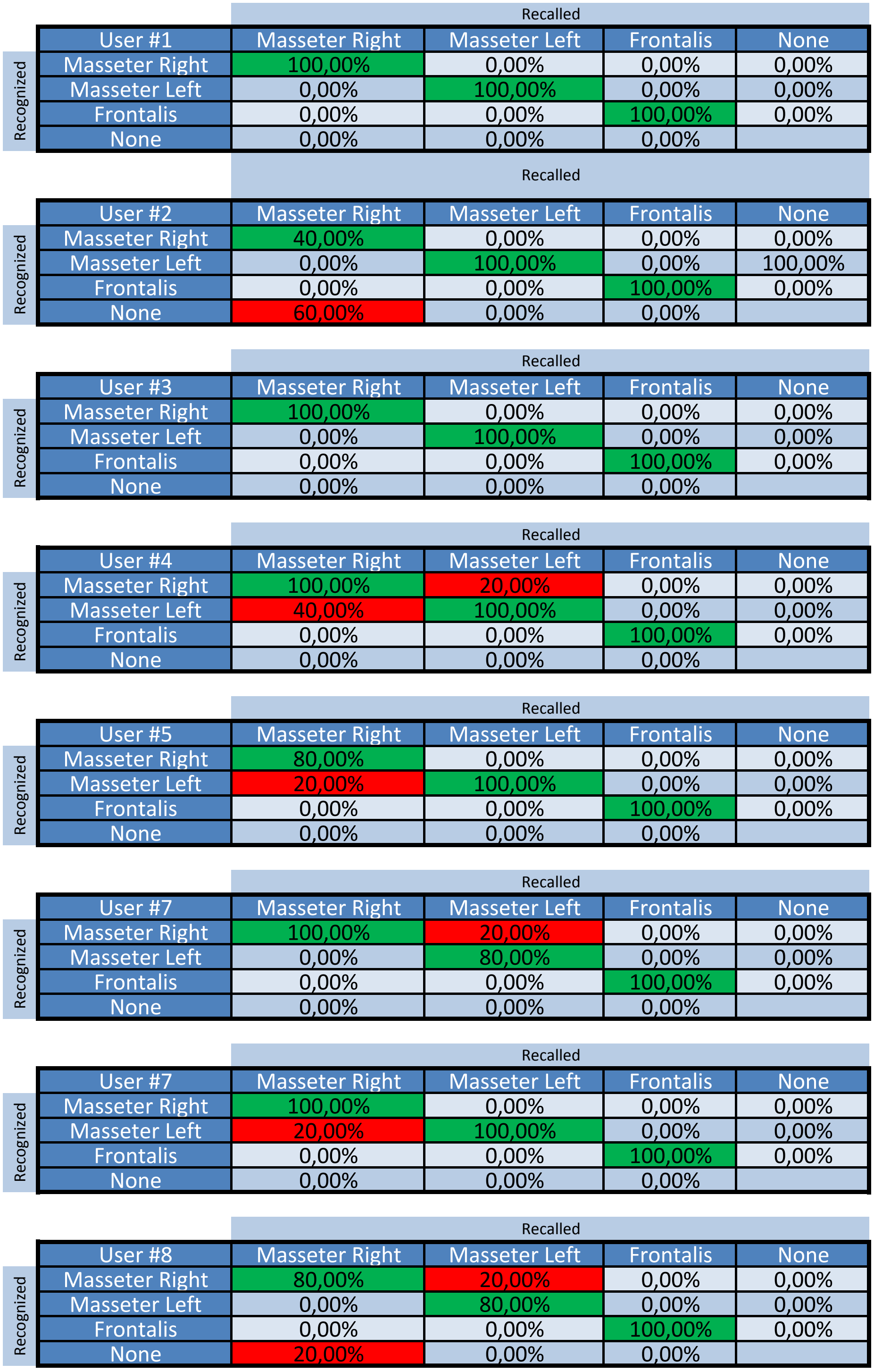
		Recalled			
	User #5	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	4	0	0	0
	Masseter Left	1	5	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

		Recalled			
	User #6	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	5	1	0	0
	Masseter Left	0	4	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

		Recalled			
	User #7	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	5	0	0	0
	Masseter Left	1	5	0	0
	Frontalis	0	0	5	0
	None	0	0	0	

		Recalled			
	User #8	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	4	1	0	0
	Masseter Left	0	4	0	0
	Frontalis	0	0	5	0
	None	1	0	0	

Table A3.4: Confusion Matrix Absolute Values - Recognition Evaluation (Masseter and Frontalis)



		Recalled			
	User #1	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	100,00%	0,00%	0,00%	0,00%
	Masseter Left	0,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #2	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	40,00%	0,00%	0,00%	0,00%
	Masseter Left	0,00%	100,00%	0,00%	100,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	60,00%	0,00%	0,00%	

		Recalled			
	User #3	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	100,00%	0,00%	0,00%	0,00%
	Masseter Left	0,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #4	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	100,00%	20,00%	0,00%	0,00%
	Masseter Left	40,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #5	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	80,00%	0,00%	0,00%	0,00%
	Masseter Left	20,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #7	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	100,00%	20,00%	0,00%	0,00%
	Masseter Left	0,00%	80,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #7	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	100,00%	0,00%	0,00%	0,00%
	Masseter Left	20,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #8	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	80,00%	20,00%	0,00%	0,00%
	Masseter Left	0,00%	80,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	20,00%	0,00%	0,00%	

Table A3.5: Confusion Matrix Relative Values - Recognition Evaluation (Masseter and Frontalis)

		Recalled		
	User #1	Frontalis	Mentalis	None
Recognize	Frontalis	5	0	0
	Mentalis	0	5	0
	None	0	0	

		Recalled		
	User #2	Frontalis	Mentalis	None
Recognize	Frontalis	5	0	0
	Mentalis	0	5	0
	None	0	0	

		Recalled		
	User #3	Frontalis	Mentalis	None
Recognize	Frontalis	5	0	0
	Mentalis	0	5	0
	None	0	0	

		Recalled		
	User #4	Frontalis	Mentalis	None
Recognize	Frontalis	5	0	0
	Mentalis	0	5	0
	None	0	0	

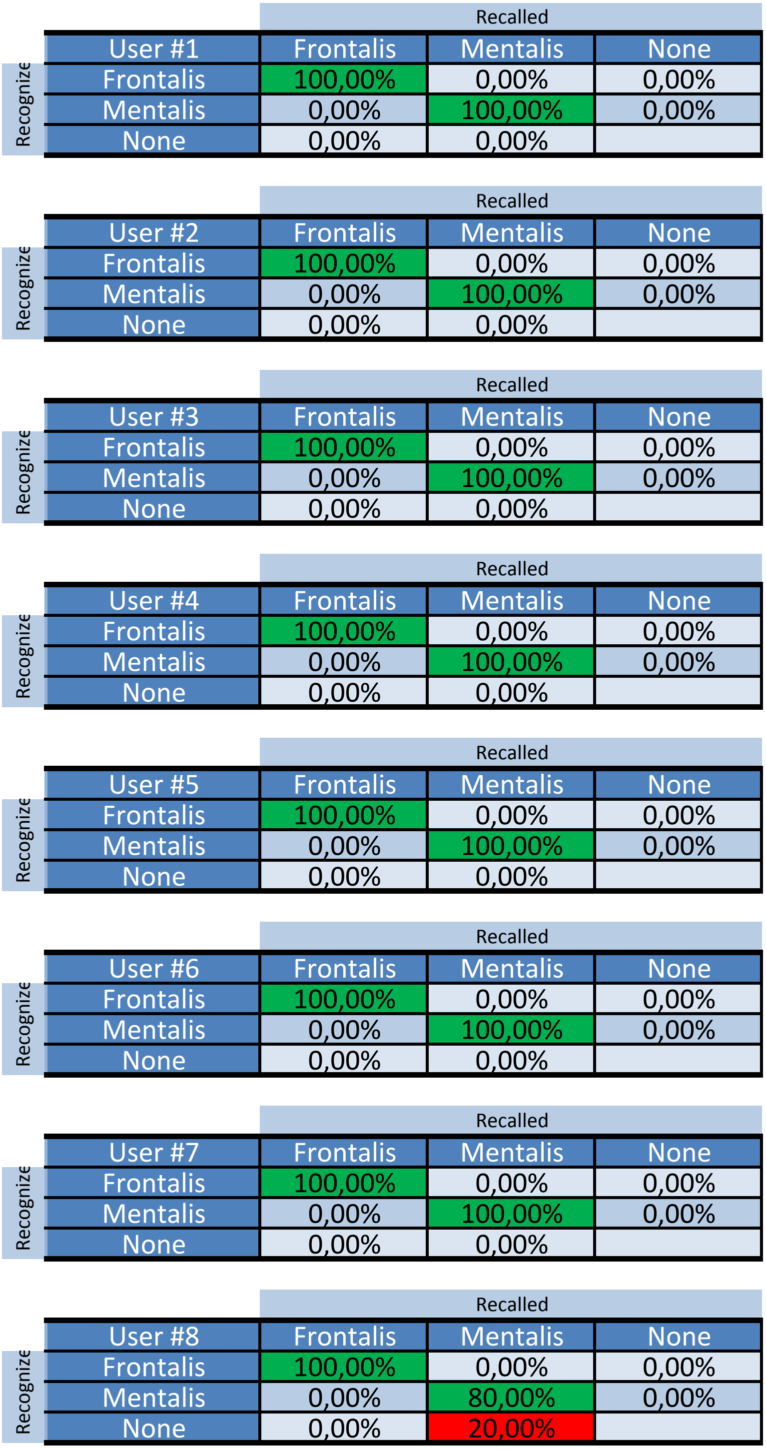
		Recalled		
	User #5	Frontalis	Mentalis	None
Recognize	Frontalis	5	0	0
	Mentalis	0	5	0
	None	0	0	

		Recalled		
	User #6	Frontalis	Mentalis	None
Recognize	Frontalis	5	0	0
	Mentalis	0	5	0
	None	0	0	

		Recalled		
	User #7	Frontalis	Mentalis	None
Recognize	Frontalis	5	0	0
	Mentalis	0	5	0
	None	0	0	

		Recalled		
	User #8	Frontalis	Mentalis	None
Recognize	Frontalis	5	0	0
	Mentalis	0	4	0
	None	0	1	

Table A3.6: Confusion Matrix Absolute Values - Recognition Evaluation (Frontalis and Mentalis)



		Recalled		
	User #1	Frontalis	Mentalis	None
Recognize	Frontalis	100,00% 🟩	0,00%	0,00%
	Mentalis	0,00%	100,00% 🟩	0,00%
	None	0,00%	0,00%	

		Recalled		
	User #2	Frontalis	Mentalis	None
Recognize	Frontalis	100,00% 🟩	0,00%	0,00%
	Mentalis	0,00%	100,00% 🟩	0,00%
	None	0,00%	0,00%	

		Recalled		
	User #3	Frontalis	Mentalis	None
Recognize	Frontalis	100,00% 🟩	0,00%	0,00%
	Mentalis	0,00%	100,00% 🟩	0,00%
	None	0,00%	0,00%	

		Recalled		
	User #4	Frontalis	Mentalis	None
Recognize	Frontalis	100,00% 🟩	0,00%	0,00%
	Mentalis	0,00%	100,00% 🟩	0,00%
	None	0,00%	0,00%	

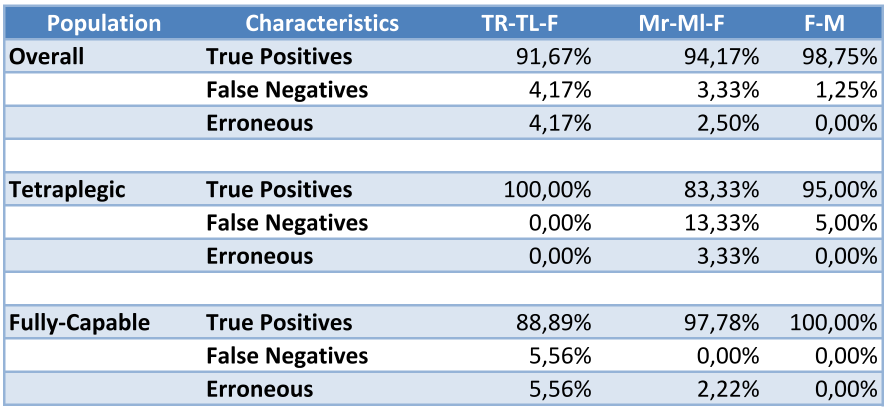
		Recalled		
	User #5	Frontalis	Mentalis	None
Recognize	Frontalis	100,00% 🟩	0,00%	0,00%
	Mentalis	0,00%	100,00% 🟩	0,00%
	None	0,00%	0,00%	

		Recalled		
	User #6	Frontalis	Mentalis	None
Recognize	Frontalis	100,00% 🟩	0,00%	0,00%
	Mentalis	0,00%	100,00% 🟩	0,00%
	None	0,00%	0,00%	

		Recalled		
	User #7	Frontalis	Mentalis	None
Recognize	Frontalis	100,00% 🟩	0,00%	0,00%
	Mentalis	0,00%	100,00% 🟩	0,00%
	None	0,00%	0,00%	

		Recalled		
	User #8	Frontalis	Mentalis	None
Recognize	Frontalis	100,00% 🟩	0,00%	0,00%
	Mentalis	0,00%	80,00% 🟩	0,00%
	None	0,00%	20,00% 🟥	

Table A3.7: Confusion Matrix Relative Values - Recognition Evaluation (Frontalis and Mentalis)



Population	Characteristics	TR-TL-F	Mr-Ml-F	F-M
Overall	**True Positives**	91,67%	94,17%	98,75%
	False Negatives	4,17%	3,33%	1,25%
	Erroneous	4,17%	2,50%	0,00%
Tetraplegic	**True Positives**	100,00%	83,33%	95,00%
	False Negatives	0,00%	13,33%	5,00%
	Erroneous	0,00%	3,33%	0,00%
Fully-Capable	**True Positives**	88,89%	97,78%	100,00%
	False Negatives	5,56%	0,00%	0,00%
	Erroneous	5,56%	2,22%	0,00%

Table A3.8: System Recognition Resumed Results

A4

Usability Evaluation

A4.1. Usability Evaluation Background Questionnaire and Results

#	Question	User #1	User #2
2	Age	28	31
3	Gender	Female	Male
4	Education Level	Graduation	12th Grade
5	Have any neuro-muscular disease/injury?	Yes	Yes
6	What disease/injury?	Tetraplegia	Tetraplegia
7	Injury Level or Affected Areas	C5/C6 C	C5/C6 I
8	Has a mobile device?	Yes	Yes
9	Mobile device Model?	Nokia	Nokia
10	With touch screen?	No	No
11	Uses voice recognition?	No	No
12	Tasks performed?	Receives Calls	Makes/Receives Calls
13	Usage Frequency?	Daily	Daily
14	Where do you keep the mobile device while on the move?	Wheelchair plate	Wheelchair plate
15	And in the car?	Wheelchair plate	Wheelchair plate
16	And in bed?	Near bed	Bed
17	Do you turn the mobile device when you go to sleep?	No	No
18	Which is the most frequent task you perform with the mobile device?	Receive Calls	Receive calls
19	How many persons do you contact (or get contacted) through the mobile device in a daily basis?	1	2
20	Do you use mobile device shortcuts?	No	No

Table A4.1: Background Questionnaire and Results

A4.2. Usability Evaluation Consent Form

Thank you for participating in our research studies. We will conduct studies on the usability of a muscle-controlled mobile device interface. During these studies, we will attach surface electrodes to your body (face and neck) and ask you to perform predetermined tasks by issuing commands through your muscles. The system will collect the raw EMG signal from all the collected sites as well as the timings and number of errors. In addition, we will be videotaping your session to allow further analysis. All the results collected from the evaluation will be anonymized. Please read the statements below and sign where indicated. Each statement is separated so you are able to disagree with any independent one. Thank you.

1. I agree to perform the evaluation session described and that the results are logged in text files.

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

2. I agree that the session is videotaped to further analysis by the researchers.

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

3. I agree that the multimedia (photos and video) captured during the evaluation are used by the researchers in dissemination events and publications (thesis, articles, press).

Print Name: ______________________________

Signature: ______________________________

Date: ______________________________

A4.3. Usability Evaluation Methodology

This annex presents the test plan for the final usability tests.

A4.3.1. Introduction

This document describes the test plan for the final usability tests to the electromyographic mobile interaction prototype. It features the motivation of the evaluation, its methodology, research questions to be answered as well as other environment, users and equipment related sections.

A4.3.2. Motivation

These usability tests try to validate the developed solution with the target population. This phase is composed by a set of tasks commonly executed in a mobile interaction scenario. The evaluation tries to validate the product comparing the results with pre-established benchmarks but also to identify possible usability problems.

In the final usability evaluation, we will focus our attention on the execution of mobile device main tasks (Making and Receiving Calls, Sending and Receiving Messages, Menu Navigation) performed with the user's preferred parameterizations but also to assess the system's accuracy, speed and daily wearability. We will measure the time to complete the tasks, performance, identify errors, difficulties and preferences.

A4.3.3. Research Questions

This evaluation tries to answer the following research questions:

1. Is the system wearable? Can it be used daily?
2. Can the users control the device and execute the tasks without help?
3. Is the system response fast and accurate?
4. Are the user's able to maintain a correct mapping between body movements and actions?
5. Does the system deal with different accommodations?
6. Is EMG adequate as an input method for mobile interaction?

7. Is the system easy to use?
8. Is the system easy to learn?
9. Is the system effective?
10. Do the users like the system and are interested in using it?

A4.3.4. User Profile

A total of two (2) participants will be tested, at their own homes. One participant will be tested per day. The only requirements to perform the evaluation is to know how to write, have time and space (as the evaluation is performed in the users' room) availability, and mobile device acquaintance. The sample group is composed by two (2) tetraplegic participants. They are the main stakeholders and should be interested and motivated in the solution. We should be able to evaluate the system within several accommodations (wheelchair, lay down and to the side in bed).

A4.3.5. Evaluation Methodology

The evaluation session features six different sections:

Experiment Preparation The first step of the test plan is performed before the visit to the user's home. Indeed, there are several aspects that need to be prepared so the evaluation is performed with no interruptions. Also, there are several precautions that must be taken to ensure the recording of the interactions and the correct data extraction. Considering the experiment, the monitor must ensure that the mobile device is fully charged and the application is deployed and ready to be executed. Also, the scripts and configuration files must be prepared to allow quick parameterization. Also, considering data extraction, the questionnaires, instructions and consent forms should be printed and ready to use. Task descriptions should also be available. The recording equipment (camera and audio) must be checked for battery and ensure recording memory.

Participant Introduction, Consenting and Background Questionnaire In the first contact with each participant, the monitor should give a brief introduction and make the participant comfortable and relaxed. Also, the monitor must stress that the user is not being evaluated (the system is) and make the user understand that he is cooperating and that we are thankful for that.

After the first contact, the user will be told to fill the background questionnaire and to sign a consent form. This form asks for consent to record image and audio of the evaluation session for analysis and for publication (scientific articles, reports and thesis). The user can agree/disagree with any of the items in the form.

Experiment Equipment Setup As the evaluation is performed in the users' home, all the equipment is mounted after the introduction. The camera and audio recorder should be ready to start recording and the mobile device/laptop must be paired with the EMG device. To avoid distractions during the evaluation session, the recording will not stop between tasks (even when the camera changes position) and will start at this point, before the orientation and ambientation phase. The user selects the monitored locations and the monitor performs the mounting.

Orientation Participants will receive a verbal introduction to the test. In this phase, we will explain the purpose of the test and offer an overview of the evaluation. Once again, it is important to stress that we are evaluating the system and not the user. Also, it is important that the user is comfortable and clearly states that he is ready to start the evaluation.

Test Execution The execution of the evaluation starts with the delivery of the written instructions and an overview of the system and tasks to be fulfilled. For each of the tasks, the procedure starts with the user reading the Task Description and clarifying any possible doubts. The monitor holds the Task Description maintaining the paper in the user's line of sight during task execution. During the test, the monitor will not interact with the participant unless a severe error occurs. However, the participants will be encouraged to verbalize their concerns or opinions during task execution. The monitor will note down errors, elapsed time, opinions and particular behaviors. Between tasks, the monitor changes parameterization but no intermediate feedback is collected. When there is an accommodation shift, the user may select a new electrodes setup.

Participant Debriefing As all the tasks are finished, the participant will be debriefed. An interview will take place to gather the user's opinions. This interviews include a set of base questions but every interview is likely to follow a different path to collect the user's comments, possible improvements and opinions regarding specific behaviors. At the end of this phase, the users will be thanked for their participation. The recording will be stopped.

Session Analysis To complement and assert the information gathered in the session, the monitor will review the recorded information.

A4.3.6. Task List

Evaluating Usability features the following tasks:

- Menu navigation
  - In bed
  - In the wheelchair
- Message Reading
  - In bed
  - In the wheelchair
- Accepting/Rejecting Call
  - In bed
  - In the wheelchair
- Writing Message
  - In bed
  - In the wheelchair
- Making a Call
  - In bed
  - In the wheelchair

A4.3.7. Evaluation Environment

The evaluation will take place in the user's home. The tasks will be carried in the bed and in the wheelchair. The mobile device used will be the HTC S310 with Windows Mobile 5.0, and a laptop with Windows XP. The electromyographic device is a BioPlux4 with Ag/Acl surface electrodes. The bluetooth connection must be working properly. The entire session will be recorded with a video camera.

A4.3.8. Evaluation Monitor Roles

The monitor is responsible to ensure the evaluation session. It is also responsible to prepare the equipment and instruct the participant. The monitor also has to collect the evaluation data and the user's opinions. The test monitor is expected not to help the participants unless a severe error occurs.

A4.3.9. Evaluation Data

We will collect the following measurements:

- Time users take to complete the task
- Number of errors
- Number of commands to complete the task
- Task success rate
- Time spent recovering from errors
- Error classification
- Subjective Evaluation

A4.3.10. Evaluation Report

The evaluation session report will include the procedure, goals, results and discussion. It will include the raw data.

A4.4. Usability Evaluation Test Scenarios and Goals

In this annex we present the task descriptions given to participants during the final usability evaluation. Also, this document features the system introduction and overall remarks.

A4.4.1. Introductory Remarks

We are developing a system to enable a tetraplegic user to effectively operate a mobile device. We aim to achieve this goal by using the individual residual capacities as input commands. The notion of capacity depends on the user's impairment but also on the situation. We will therefore evaluate the system through several tasks but also considering several impairments levels and location and accommodation restrictions.

We are evaluating the performance of several tasks but also the system response and adaptability to real life scenarios. It is important to notice that we are evaluating the system and not the user himself. Therefore, we would like to thank for your help and make you feel free to speak out your opinions, concerns and difficulties.

A4.4.2. Task Scenarios

This evaluation session features some of the main tasks performed with a mobile device. We focus on navigation and communication. For each of the goals, the user is asked to perform the evaluation in two different accommodations, which are supposedly the bed and the wheelchair, but can be any two accommodations that feature visual feedback and another with only auditory feedback (lay down). This evaluation session also features a test of the system wearability and the system's accuracy (tested in a laptop instead of a mobile device).

Evaluating Accuracy and Speed:

Point and Click You will be asked sequentially to hit a start button that appears in the screen and navigate until the stop button. The buttons will change position and size.

Writing a Sentence (On-Screen Keyboard) Write the sentence "I will be home late" using the On-Screen Keyboard

Writing a Sentence (Dasher) Write the sentence ″I will be home late″ navigating within Dasher.

Evaluating Wearability:

Walk the room Walk the designed path and recall the body muscle you are asked.

Evaluating Usability:

Menu Navigation and Message Reading You are going to a dinner today but you don′t remember the place′s name. You do remember that George sent you a SMS with that information. Navigate to your inbox and read the message you have received from George. You are at the main menu.

Accepting and Rejecting a Call Before going to the dinner everyone is calling but you are not in the mood and want to have a little rest. Alexander calls you and as you know it is just to chat you cancel the incoming call. One minute later, you receive a call from the dinner organizer and you want to take it. The phone will ring. Just wait.

Writing a Message You regret to have canceled Alexander′s call and you want to send him a message. You are at the start of the message (Write Message Screen). Input the text ″call later″.

Making a Call You still don′t know the place so you just decide to call George. His number is the 93 369 23 91 [randomly selected]. You start the task in the ″Making Call″ screen.

A4.5. Usability Evaluation Monitor Checklists

In this section we present the checklists used during the final usability evaluation sessions.

A4.5.1. Checklist 0 – The day Before the Evaluation

- Print the questionnaires (pre and post questionnaire) and consent form
- Print the Introduction and Overview
- Print the Task Descriptions
- Print the evaluation sheets and checklists
- Install and configure on the laptop the software to capture the image from the video camera
- Test the video camera and ensure that the disk space is enough for the real time capture
- Prepare configuration files to allow a faster shift between tasks
- Fully charge the camera, mobile device and electromyographic (EMG) device
- Perform one test

A4.5.2. Checklist 1 – The day of the Evaluation

Introducing the Session

- Greet the participant
- Give an overview of the system and the evaluation session
- Explain the goal of the evaluation (to test the system)
- Have the participant to fill the background questionnaire
- Explain the data logging and have the participant to fill the consent form

Before the Evaluation

- Create the recording setup
- Turn on the EMG device and mobile device
- Pair the devices (bluetooth)
- Start the Mobile device Application
- Introduce the system and an overall view of the tasks to be fulfilled
- Ask the participants to feel free to talk and share their opinions while performing the tasks
- Be sure that there are no distractions
- Start video and audio recording

Before each Task

- Setup the user's preferences (electrodes position)
- Capture the task description with the camera
- Put the task description in the user's line of sight
- Ask the user to read the task
- Make sure the user has no doubts

During the Task

- Start the timer when the user begins performing the task
- Annotate errors, time, questions, opinions
- When a task is finished reset the timer
- Try to keep the user relaxed

After the evaluation

- Stop the recording
- Have the participant fill the post-questionnaire

- Debrief the participant
- Thank the participant for his availability, opinions and help
- Clean up and pack the camera, mobile device and EMG device

A4.5.3. Checklist 2 - The day after the Evaluation

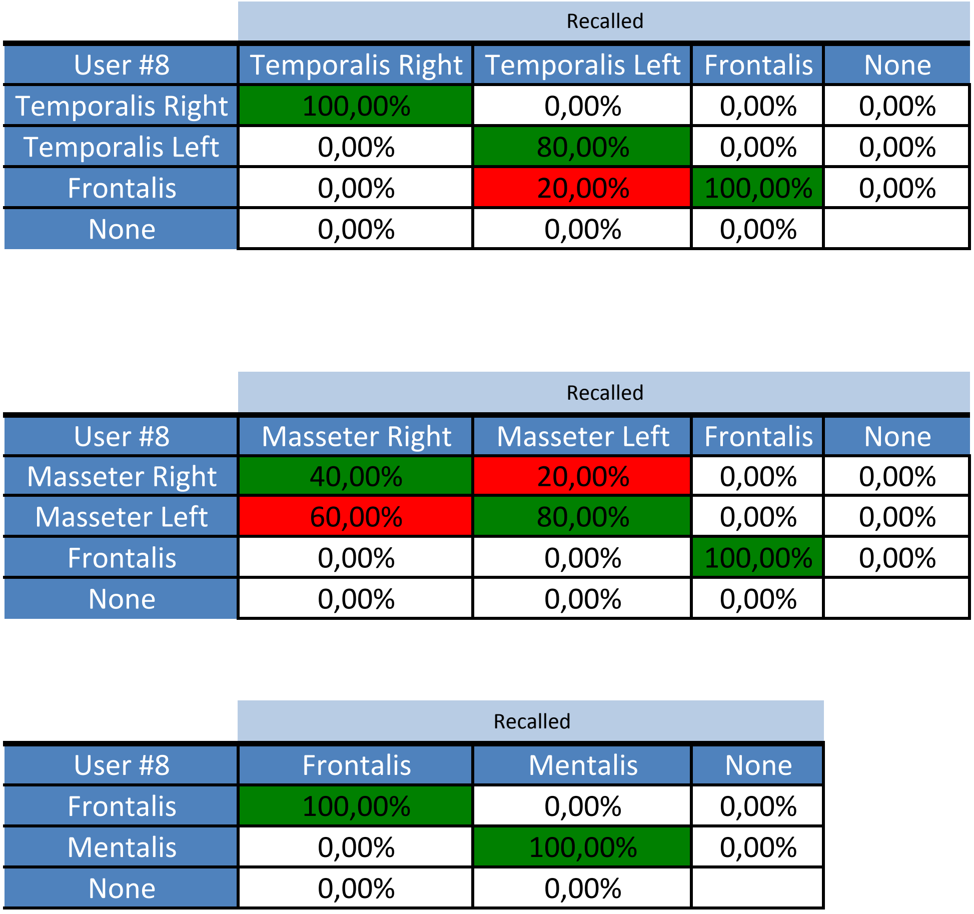
- Review the evaluation logs and recordings
- Insert the gathered data in raw tables

A4.5.4. Checklist 3 - After all evaluation sessions

- Contact the participants and thank them again for their help
- Share with the participants the main conclusions retrieved from the evaluation and discuss them
- Write the report

A4.6. Usability Evaluation Results

A4.6.1. Setup Usability and Repeatability Results

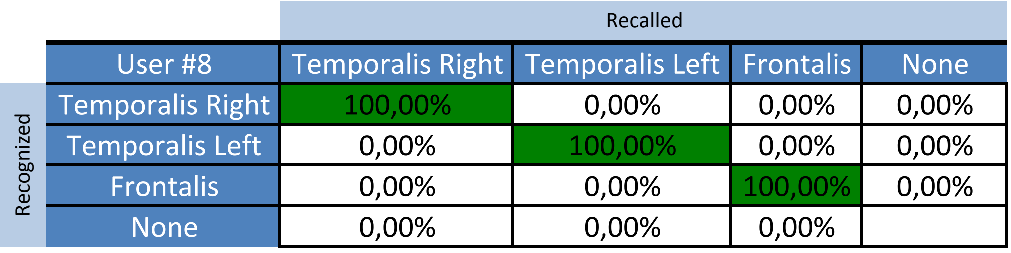


	Recalled			
User #8	Temporalis Right	Temporalis Left	Frontalis	None
Temporalis Right	100,00%	0,00%	0,00%	0,00%
Temporalis Left	0,00%	80,00%	0,00%	0,00%
Frontalis	0,00%	20,00%	100,00%	0,00%
None	0,00%	0,00%	0,00%	

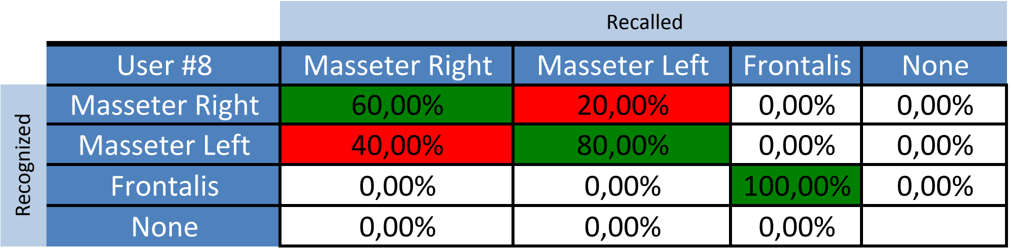
	Recalled			
User #8	Masseter Right	Masseter Left	Frontalis	None
Masseter Right	40,00%	20,00%	0,00%	0,00%
Masseter Left	60,00%	80,00%	0,00%	0,00%
Frontalis	0,00%	0,00%	100,00%	0,00%
None	0,00%	0,00%	0,00%	

	Recalled		
User #8	Frontalis	Mentalis	None
Frontalis	100,00%	0,00%	0,00%
Mentalis	0,00%	100,00%	0,00%
None	0,00%	0,00%	

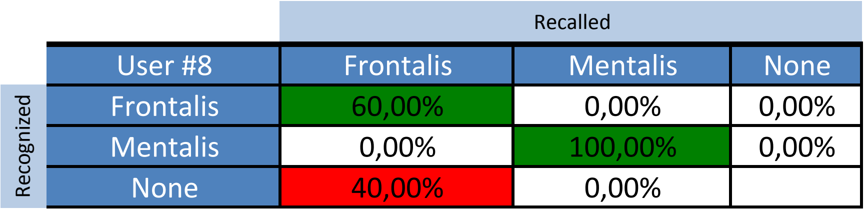
Table A4.2: Confusion Matrices Relative Values - Evaluation on Repeatability First Session



		Recalled			
	User #8	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	100,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	



		Recalled			
	User #8	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	60,00%	20,00%	0,00%	0,00%
	Masseter Left	40,00%	80,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	



		Recalled		
	User #8	Frontalis	Mentalis	None
Recognized	Frontalis	60,00%	0,00%	0,00%
	Mentalis	0,00%	100,00%	0,00%
	None	40,00%	0,00%	

Table A4.3: Confusion Matrices Relative Values - Evaluation on Repeatability Second Session

		Recalled			
	User #8	Temporalis Right	Temporalis Left	Frontalis	None
Recognized	Temporalis Right	100,00%	0,00%	0,00%	0,00%
	Temporalis Left	0,00%	80,00%	0,00%	0,00%
	Frontalis	0,00%	20,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled			
	User #8	Masseter Right	Masseter Left	Frontalis	None
Recognized	Masseter Right	80,00%	20,00%	0,00%	0,00%
	Masseter Left	20,00%	80,00%	0,00%	0,00%
	Frontalis	0,00%	0,00%	100,00%	0,00%
	None	0,00%	0,00%	0,00%	

		Recalled		
	User #8	Frontalis	Mentalis	None
Recognized	Frontalis	100,00%	0,00%	0,00%
	Mentalis	0,00%	100,00%	0,00%
	None	0,00%	0,00%	

Table A4.4: Confusion Matrices Relative Values - Evaluation on Repeatability Third Session

A4.6.2. Mobile Interaction Usability Results

Task #1								
Menu Nav.	**Selected Scheme**	**# Commands**	**Sites**	**Feedback**	**Time(s)**	**# Errors**	**# Steps**	**Recovering Time (mean)**
User #1 (T)								
	Directed	2	Frontalis + Mentalis	Visual + Audio	26,8	0	17	---
	Directed	2	Frontalis + Mentalis	Audio	38,7	0	17	---
User #2 (T)								
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	48,2	2	19	9,2
	Automatic	1	Temporalis Right	Audio	61,2	0	11	---
Task #2a								
Reject Call								
User #1 (T)								
	Directed	2	Frontalis + Mentalis	Visual + Audio	6,8	0	5	---
	Directed	2	Frontalis + Mentalis	Audio	7,4	0	5	---
User #2 (T)								
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	12,6	1	8	5,3
	Automatic	1	Temporalis Right	Audio	13,3	0	3	---
Task #2b								
Accept Call								
User #1 (T)								
	Directed	2	Frontalis + Mentalis	Visual + Audio	2,8	0	4	---
	Directed	2	Frontalis + Mentalis	Audio	3,6	0	4	---
User #2 (T)								
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	3,4	0	4	---
	Automatic	1	Temporalis Right	Audio	13,2	0	3	---
Task #3								
Write Msg								
User #1 (T)								
	Directed	**2**	Frontalis + Mentalis	Visual + Audio	38,2	1	83	3,2
	Directed	2	Frontalis + Mentalis	Audio	48,2	0	77	---
User #2 (T)								
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	36,2	0	77	---
	Automatic	1	Temporalis Right	Audio	171,3	1	33	9,5
Task #4								
Make Call								
User #1 (T)								
	Directed	**2**	Frontalis + Mentalis	Visual + Audio	28,4	0	65	---
	Directed	**2**	Frontalis + Mentalis	Audio	35,1	0	65	---
User #2 (T)								
	Directed	3	Temporalis (2) + Frontalis	Visual and Audio	29,2	0	65	---
	Automatic	1	Temporalis Right	Audio	96,2	0	40	---

Table A4.5: Usability Evaluation Results

A4.7. Usability Evaluation Post-Questionnaire and Results

#	Question	User #1	User #2
1	It is easy to issue commands with the muscles	5	5
2	It is easy to understand and perform the dialogues	5	5
3	I was able to control the mobile device	4	5
4	The system adapts to my accomodation and location	5	5
5	Comments and Suggestions		

Table A4.6: Post-Questionnaire Questions and Results

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