Multidisciplinary design of suitable assistive technologies for motor disabilities in Colombia

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Abstract—**Traumatic or pathological brain lesions often result in motor disabilities that have strong personal and social effects. Assistive technologies can support this population, potentially improving their autonomy and promoting their participation in society. However, most existing research does not explicitly consider socio-cultural aspects, which differ between developing and developed countries. In this paper, we describe a multidisciplinary research line on technology-based assistive solutions for motor disabilities involving institutions in Colombia and Switzerland. The key aspect of our approach is the involvement of engineers, therapists, designers and end-users from early stages of the design process. This allowed us to characterize the local population with motor disabilities, highlighting a large incidence of violence- related injuries, reduced accessibility to assistive technologies and a perception of social exclusion. In the quest for context- suited solutions, we have developed a mechanical wheelchair and a sensorized facility for motor rehabilitation. The prototypes of these devices will be tested in the upcoming months. Importantly, we established a training program that uniquely covers both clinical and technical aspects of motor rehabilitation; providing experts from different domains with a common knowledge that facilitates the multidisciplinary work, enabling us to initiate experiments on clinical research; thus strengthening the links between academic, clinical and rehabilitation institutions.**

Keywords– Motor rehabilitation, Assistive technologies, Multidisciplinary teams, Education, User-centered design, Body-sensor networks

I. Introduction

People with motor disabilities represent approximately 15% of the population in the world [1]. They often experience barriers to fully participate in society and therefore it is important to develop an adequate social and physical environment in order to promote their social inclusion. One way of doing it so is by means of technology-based assistive products that contribute to improving their quality of life. However, some proposed solutions to this problems are not suitable for people in emerging and developing countries since the socio-cultural aspects of the populations are not taken into account in the design process. Furthermore, often the design process of assistive solutions does not follow an interdisciplinary approach [2]. We describe in this paper the efforts we have undertaken on research and development of technology based assistive technologies for people with motor disabilities in Colombia. This works relies on an interdisciplinary approach and puts the user at the center of the design process. To this end we have worked along three main lines of action as follows. The first line of action is the *characterization of the problem and and socio-cultural aspects of the population*, taking into account the new concept of disability that goes beyond the health problem. This allow us to specific information that should be considered when designing solutions that are suitable for their intended users. Special attention is paid to the need for these solutions to contribute to facilitate the participation of their users in society.

The second line focused on state-of-the-art *research and development* of technology-based assistive solutions. Based on the characterization obtained in the previous activity we have have worked on solutions for mobility substitution and manipulation recovery. In both cases, a multidisciplinary team have applied formal techniques for product design to identify the problem, propose and evaluate alternative solutions and develop a prototype solutions. This process involved engineers, industrial designers, therapists, as well as potential end-users (i.e., people with disabilities). These solutions are now about to start the validation phase.

The third line of action, and an enabling factor to achieve the previous activities is devoted to *community building* through the involvement of different stake holders (i.e. end-users, relatives, therapists, clinicians, etc.). We consider the interdisciplinary approach a key factor for the development of successful solutions. However, currently there is little interaction among professionals of different disciplines or such interaction only takes place at later stages of development; e.g., clinical experts or physical therapists are involved to test engineering solutions. In order to promote further interaction between different disciplines we have organized several activities including workshops, public seminars directed to people with different formations and levels of expertise. This provides a common space for them to get acquainted with the challenges of the problem from different perspectives and allows them to work together in the conception of new possible solutions.

The paper is organized along these three lines of action. We first report the characterization we have made of the population with motor disabilities in Cali, Colombia. This work was made using two surveys with the collaboration of local rehabilitation centers. The first survey was conducted among people with motor disability in lower limbs caused by spinal cord injury (SCI). The second was conducted among people with upper limb motor disability caused by brain injury. In the second part of the paper we describe the interdisciplinary

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design process of technology-based assistive products. The third part presents the activities towards on disseminate our approach and establish an interdisciplinary community on this field through conferences, workshops, courses and papers. Importantly, these activities have gathered participants from different sectors including academic institutions (including engineering, design and medical schools), rehabilitation centers, and industry.

II. Characterization of needs and socioeconomical situation of population with motor disabilities

In the design process, knowing the user's necessities is a key factor for proposing new devices. On the other hand, identifying particular features of the social and physical context allows proposing new products with adequate acceptance by the users. Finally, an adequate revision of current technological products allows delivering products with innovative characteristics. Taking this into account, we conducted two studies about motor disability for the purpose of knowing the real situation of people with disability in Cali, Colombia. The first study was focused on people with motor disabilities in lower limbs caused by different reasons and the second was aimed at people with disability caused by pathological brain lesions [3]. Both studies were focused to aid people with motor disability in order to promote their social inclusion. However, the first study was aimed to optimize the current assistive products of mobility and the second one was aimed to help the rehabilitation process with emerging techniques with people with disabilities caused by cerebral-vascular origin.

A. First study: Lower limbs disabilities caused by SCI

This study was based in the International Classification of Functionality -ICF- of the World Health Organization -WHO and used the Standard ISO9999 [4] to enquire about the assistive products. The ICF considers aspects associated with health, limitations with the activity and the context barriers. The questions associated with the assistive products were addressed in order to know the usefulness, knowledge and acquisition capacity of these products.

The population with disability reported in Cali, Colombia in 2011 was of 4922 people [5]. Among the 45 people who take part in the survey, a majority has a daily income lower than 2 dollars (75%). Moreover, in contrast to other countries, violence was the main cause of disability (42%). They identify barriers to their mobility in public transport (62%), as well as the streets of the city (75%). Furthermore, people with motor disability reported that they require assistance of a caregiver (71%).

Wheelchairs were the assistive products of main preference for motor disability (100%). In a large proportion these products were acquired with their own resources (41%). The main limitations of the people with motor disabilities were: Use of public transportation (71%), moving inside house (82%), enjoying of the physical environment, information and communication (67%), having equality of opportunities (63%), participating in professional education (83%) and having a remunerated job (73%). The main physical barriers identified were public buildings (54%).

B. Second study: Upper limb disabilities caused by pathological brain lesions

We apply the *WHO Disability Assessment Schedule II* (WHODAS II) survey on 26 people with disability caused by pathological brain lesions in Cali, Colombia. This tool allows determining an objective profile of functionality in six areas of performance and also allows obtaining the subjective perception of the impact produced by their lesion in each one of them. The six activities are: activities associated with cognition, ability to move in the environment, personal care, ability of relating with others, activities of daily life and societal participation.

People have difficulty to obtain a job due to a disability situation (35%). The main difficulty in performing daily activities was the comprehension and communication (54%) followed by personal care (44%) and mobility around the surroundings (43%). We found a correlation between age and personal care and also between age and societal participation. This means there is a difficulty in people with disability to participate actively in societal activities as they get older. Finally, we found a correlation between work participation and both personal care and societal participation. This means there is a difficulty in obtaining a job when there are problems in personal care and societal participation.

III. Design of technology-based assistive solutions

Taking into account the information gathered in the previous studies we designed two assistive products for disability centered in the user with an interdisciplinary participation. For the formal analysis of the problem we can model the person as a Technical System with four main subsystems [6]: Motor, Transmission, Tool and Control. The motor subsystem is associated with the muscles, the transmission subsystem with the skeleton and neural system. The tool subsystem is associated with the part of the body that carries out a function, for example the hand when it catches an object, and the control subsystem is associated with the brain. This system requires energy for working and does a main function over an object according to the analysis of functionality. The user must be considered within a particular environment where the designed product must be used.

Then a systemic analysis of the problem is required. We used a systematic analysis using the Nine Windows technique from the Theory of Inventive Problem Solving, TRIZ [7]. The Nine Windows technique allows analyzing the products in two dimensions. The first is its evolution throughout time: past, present and future, and the second dimension is the systemic hierarchy of the product. This means that every product has an evolving behavior and also is part of a hierarchy corresponding to itself, called the system. Also every product has a context associated to it (i.e., the supersystem) and is composed of parts (i.e., the subsystem) that make it possible to carry out its main function. In this analysis the challenge consists in identifying the future scenario of the product with the purpose of designing a new product. The final part of the design process consists in the structuring of this process using a rational method based on Axiomatic Design [8].

The two solutions described below were developed by interdisciplinary teams. In this process, each discipline contributed to the problem analysis as well as to the alternative proposals. Engineers characterized the current and past technical system for mobility and described with precision the parts of the system. Industrial designers guaranteed the user interaction and provided ergonomic suggestions in the alternatives of design. The occupational therapist and psychologist were important for analyzing the problem of social inclusion of people with motor disability. Additionally, in case of the product for mobility support we also worked on developing business models for integrating people with motor disability in the process of production and sales of this type of products [9].

A. First product: An assistive mobility device

The objective of this design was to propose a new product for mobility to improve the social inclusion of people with motor disability. The interdisciplinary team for designing it was composed by engineers, an occupational therapist, industrial designers and a psychologist. The user of reference was the person with motor disability caused by spinal cord injury.

From the point of view of the technical system, we identified a problem with its transmission corresponding to the neural and muscle composition of the body. Particularly, this population has an SCI that interrupts the signal transmission to the lower limbs thus impeding the movement. We made a systematic analysis of the problem starting with a particular reference wheelchair [10]. The survey presented in Section II-A was used for a landscape analysis. We made a technical description of current wheelchairs with their components, and we analyzed the input from the potential users to describe the ideal characteristics of a new technical system. We obtained four main requirements for the assistive products: Moving the technical system, carrying the user, allowing bipedestation and folding the structure for its transportation.

The different proposals for a new assistive product were derived from new ideas that arose from another technique of TRIZ, called Contradiction Matrix, based on looking for solutions from conflicts identified in the problem analysis [11]. These proposals are formally evaluated according to the identified functional and non-functional proposals [12]. Based on this evaluation one alternative was selected. Figure 1 shows the conceptual design of the selected solution for mobility and bipedestation designed from a systemic analysis of the problem with interdisciplinary participation.

These are some technical characteristics of the chosen design product: mechanical advantage using levers diminishing efforts in joints, pneumatic system for bipedestation, ergonomic considerations for carrying, sitting and the gear system for aiding in sloped terrain among others.

B. Second product: A therapy station for rehabilitation processes after brain injury

The objective of this design was to propose a new station facility in order to support neurorehabilitation of people with disability caused by brain injury. In particular, using functional electrical neuro-stimulation (FES). The interdisciplinary team designing it was composed by engineers, an occupational therapist, industrial designers and a physiotherapist. The user of reference was a person with brain injury with hemiparesis who was receiving treatment in a rehabilitation center in Cali, Colombia.

From the point of view of the technical system, we identified a problem with the control of the technical system because one zone of the brain has been injured and this part affects the motor control of one side of the body. These people have a brain lesion and the therapy is aimed to promote neural plasticity to recover motor functionalities. We performed a systematic analysis on the current systems of rehabilitation processes using FES [13]–[18]. The survey (c.f., Section II-B) was a useful element for global analysis of the problem and served to identify the user necessities. The description of current facilities with their technical components was used for understanding the technical system. As before, the input from the end-users is of outmost importance. It is worth notice that in this case, the intended users are both the people with brain injury and the physiotherapists who provide the rehabilitation therapy. This process yielded a set of main requirements for the assistive facility including: Alignment of the body in decubitus position; alignment of the body in a sitting position; guarantee of space to move upper limbs in functional activities; localization of objects in different spatial positions; trajectory measurement of movement of an upper limb; recording of the time of movements during therapy; visual feedback of the activity; storage of personal and therapy information; handling of devices for FES therapy. Figure 2 shows the conceptual design of a new station facility for FES therapy based on the analysis of the contradiction matrix.

These are some technical characteristics of the design product: a set of ergonomic devices for improving the rehabilitation process, an information system to record the movement of patient in therapy and a historical behavior of therapy process. We proposed a system for tracking the physical movement of patient in the therapy using Kinect sensors and a software of feedback when doing exercises in the rehabilitation therapy.

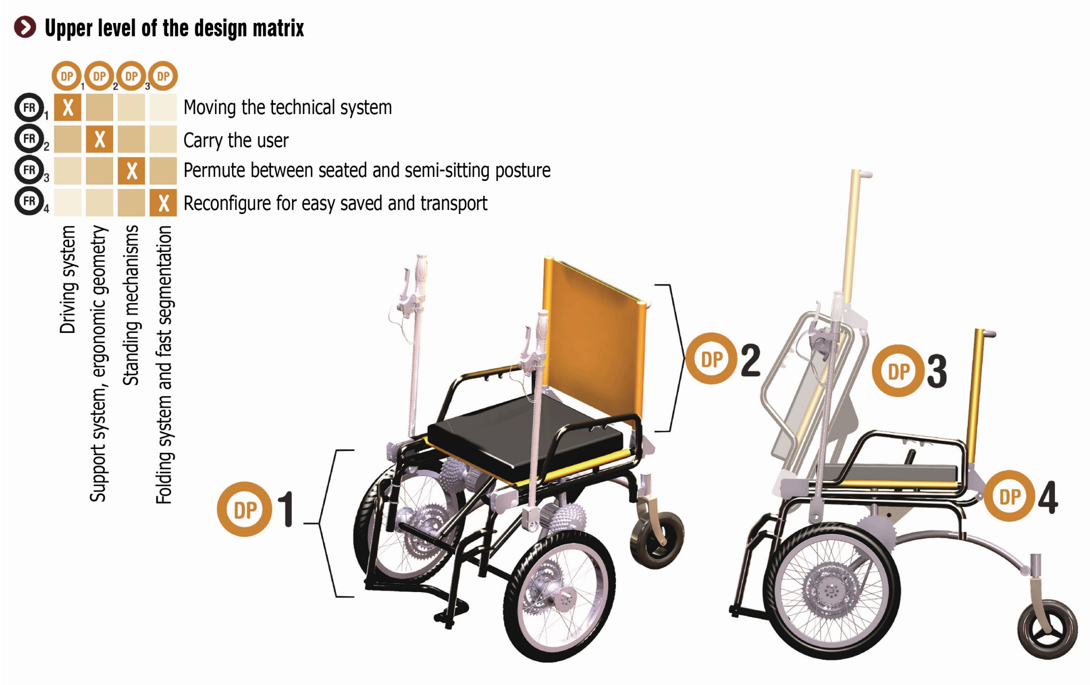

Fig. 1. Designed assistive product for people with motor disability. It consists of a wheelchair that is manually propelled by levers, allowing the user to keep active her/his upper limbs. The possibility of changing posture from sitting to standing position and gear systems for difficult terrains.

C. Ongoing research study on the effects of neuromuscular stimulation

In parallel to the development of the rehabilitation station, we are undergoing a research study on the effects of FES in the rehabilitation of upper limb motor capabilities after stroke. This is part of a collaboration with the center of neuroprosthetics at EPFL to evaluate novel approaches for motor rehabilitation in different centers across the world [19]. This study involves people with brain injury suffering hemiparesis and aims at comparing the effects of FES with respect to the traditional therapy. This study uses of a set of tools for evaluating functional conditions of patients before entering the study where we establish the baseline. Next, we used conventional therapy for six weeks, and we assessed the physical performance of the patient with same battery. Finally, we used FES for six additional weeks and we will evaluate the progress with the same battery. More than a dozen of subjects have been enrolled in the study that is planned to conclude in autumn 2014.

This work has required an interaction between engineers and physiotherapists because we used a technical system for stimulation with a technical parameter for operating and we also used software for feedback and stimulate the developing of therapy. We did training activities for this purpose as is illustrated in Figure 3a. FES requires active participation of the patients because the stimulation is intended to complement their movement capabilities. Physiotherapists are in charge of organizing the therapeutic process, locating the electrodes for functional movement and giving feedback to the patients when they do not use the software application.

This work of rehabilitation using FES and the survey with WHODAS has served to identify the power of the communication process for restoring physical and social dimensions in the patient who has had a brain injury. In this sense, this must be an element of consideration in the design of new assistive products for rehabilitation. These products must include verbal interaction with the patient for improving the therapy.

IV. Community building

As mentioned above our approach relies heavily on the interdisciplinary work. This requires efficient interaction of people with different expertise and background. To achieve this we have organized different activities in order to allow these people to interact and get a common methodology to propose new solutions.

A first set of activities is oriented to raise awareness on the need for suitable solutions for people with motor disabilities. To this end we have organized three public lectures since 2012 in Cali, Colombia. One of them showed the results of the initial project on the the design of the assistive product for mobility. The second focused on the emerging field of neuroprosthesis for motor restoration and substitution and the last one detailed the development of assistive products for neurorehabilitation of upper limb functionality.

In addition, the results of the first survey were officially presented to the governmental entity in charge of social service for people with disability. This conference was called Identification of Barriers of the Environment that affects Social Inclusion of People with Motor Disability. In this conference we stated the message about of violence as the main cause of disability in Cali, Colombia and we also said that the poverty and the lack of accessibility to the city are

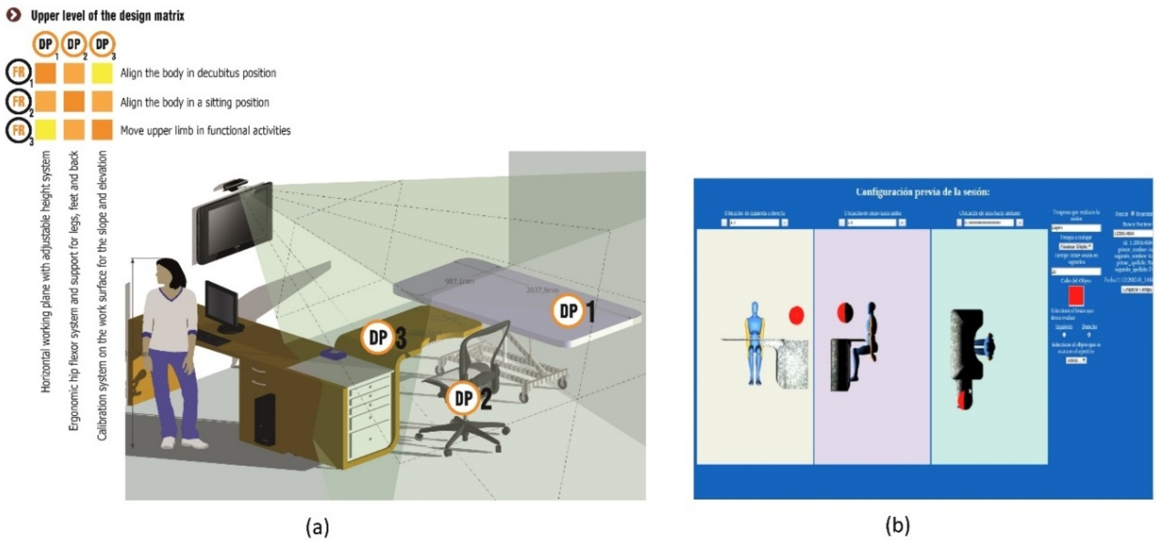

Fig. 2. Designed station facility for rehabilitation with FES (a) Physical system including the furniture allowing to position the patient in different ways according the intended therapy and the sensor platforms for monitoring her/his performance in a quantitative manner. (b) Software platform for rehabilitation. It gathers information from motion capture devices based on cameras and wearable sensors (e.g., accelerometers. It also provides feedback to the user and therapists and records patient information, and quantitative measures during the rehabilitation period.)

the main barriers of disability.

Furthermore, we have offered several workshops on the design of creative solutions using the TRIZ approach (c.f., Figure 3b). These workshops, of about 20 hrs, have been attended by people from different health, education, and service organizations. This work seeks to strengthen the interdisciplinary work in the organizations including activities for increasing team work, communication and leadership.

Last but not least, we designed a course on ”Interdisciplinary design of technological products for people with motor disability”. This 40 hrs course provides a comprehensive view of the problem including modules on the neural basis of human motor control, current rehabilitation approaches, processing of physiological signals, and neuroprostheses. Each of these modules is taught by an expert on the particular field including the engineering and medical school of the Pontificia Universidad Javeriana Cali (Colombia), an occupational therapists from Universidad del Valle (Cali, Colombia), an expert on rehabilitation from Surgir rehabilitation center (Cali, Colombia) and a senior researcher from EPFL (Lausanne, Switzerland).

This course was first offered in december 2013 and was attended by 21 persons from diverse disciplines such as: mechanical engineering, industrial design, electronic engineering, industrial engineering, mechatronic engineering, health and occupational therapy. It will be offered in a yearly basis and is now integrated as an elective undergraduate course in both the engineering and medical school of the Pontificia Universidad Javeriana Cali.

Moreover, our efforts have also been disseminated to the scientific community at a local and international level in different areas of knowledge like engineering [9], [8], [20], health [3] and design [8], [10], [12], [21].

V. Conclusion

The problems of people with disability are complex and require an interdisciplinary approach to solve them adequately. The context gives special constraints for the design of technological devices because a product in a developed country could be inadequate in another context because the environmental conditions are different.

The partnership between engineers and industrial designers seeks to improve the design of assistive products because it allows a more comprehensive approach to the design. In this collaboration the health professional together with patients have a main role in the design process because they are the users of this type of products. The interaction process is not easy because the classical education in the university is disciplinary and there are few scenarios for interacting like this project.

Collaboration among universities, industry and clinics is an adequate strategy to face problems that go beyond the health issue like social inclusion. This collaboration gives best results for employment, for governmental politics and for the participation of this population in society.

The relationship between different centers working in complementary ways around the disability allows increasing the capacity of each one of them and producing new products.

In the stages of the design process: Analysis, Synthesis and Evaluation, we have worked in the first two. Now, we are manufacturing our products for the next stage associated with

(a) (b)

Fig. 3. (a) Training process using FES. Therapists place electrodes on the paretic arm that deliver electrical stimulation that generate muscular contraction and thus, arm movements. The subjects wears an EEG cap that allows to simultaneously register her brain activity. (b) Participants in one of the workshops on design of creative solutions.

usability with the user. Also, we will continue evaluating the FES with new population with other clinical centers.

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