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Non-Invasive Brain-Computer Interface System to Operate Assistive Devices

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Abstract— **In this pilot study, a system that allows disabled persons to improve or recover their mobility and communication within the surrounding environment was implemented and validated. The system is based on a software controller that offers to the user a communication interface that is matched with the individual's residual motor abilities. Fourteen patients with severe motor disabilities due to progressive neurodegenerative disorders were trained to use the system prototype under a rehabilitation program. All users utilized regular assistive control options (e.g., microswitches or head trackers) while four patients learned to operate the system by means of a non-invasive EEG-based Brain-Computer Interface, based on the subjects' voluntary modulations of EEG sensorimotor rhythms recorded on the scalp.**

I. INTRODUCTION

THE DEVELOPMENT of electronic devices that are capable of assisting in communication and control needs (such as environmental control or Assistive Technology) has opened new avenues for patients affected by severe movement disorders. In the case of robotic assistive devices for severe motor impairments, they still suffer from limitations due to the necessity of residual motor ability (for instance, limb, head and/or eye movements, speech and/or vocalization). Patients in extreme pathological conditions (i.e., those that do not have any or only unreliable remaining muscle control) may in fact be prevented from use of such systems. Brain Computer Interface (BCI) technology "gives their users communication and control channels that do not depend on the brain's normal output channels of peripheral nerves and muscles." [1], and can allow completely paralyzed individuals to communicate with the surrounding environment [2][3]. Some BCI systems depend on brain activity recorded non-invasively from the surface of the scalp using electroencephalography (EEG). EEG-based BCIs can be operated by modulations of EEG rhythmic activity located over scalp sensorimotor areas that are induced by motor imagery tasks [4]; these modulations can be used to control a cursor on a computer screen [5] or a prosthetic device for limited hand movements [6][7]. A pioneering application of BCI consisted of controlling a small mobile robot through the rooms of a model house [8]. The recognition of mental activity could be put forward to guide devices (mobile robots) or to interact naturally with common devices within the external world (telephone, switch; etc). This possible application of BCI technology has not been studied yet.

These considerations prompted us to undertake a study with the aim of integrating different technologies (including a BCI and a robotic platform) into a prototype assistive communication platform. The goal of this effort was to demonstrate that application of BCI technology in people's daily life is possible, including for people who suffer from diseases that affect their mobility. The current study, which is part of a project named ASPICE [9], addressed the implementation and validation of a technological aid that allows people with motor disabilities to improve or recover their mobility and communicate within the surrounding environment. The key elements of the system are:

1) Interfaces for easy access to a computer: mouse, joystick, eye tracker, voice recognition, and utilization of signals collected directly but non-invasively from the brain using an EEG-based BCI system.

2) Controllers for intelligent motion devices that can follow complex paths based on a small set of commands;

3) Information transmission and domotics that establish the information flow between subjects and the appliances they are controlling.

II. METHODS

A. *Subjects and clinical experimental procedures*

In this study, 14 able-bodied subjects and 14 subjects suffering from Spinal Muscular Atrophy type II (SMA II) or

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Duchenne Muscular Dystrophy (DMD) underwent system training. These neuromuscular diseases cause a progressive and severe global motor impairment that substantially reduces the subject's autonomy. The study was approved by the local ethics committee and all subjects (and their relatives when required) gave written informed consent. All patients relied on an electrically powered wheelchair. They all had poor residual muscular strength either of proximal or distal arm muscles. Also, all patients required a mechanical support to maintain neck posture. Finally, all patients retained effective eye movement control. The clinical experimentation took place at the Santa Lucia Foundation and Hospital where the system prototype was installed in a three-room space that was furnished like a common house and devoted to Occupational Therapy. An initial interview determined several variables of interest as follows: the degree of motor impairment and reliance on the caregivers for everyday activities, as assessed by current standardized scale (Barthel Index -BI- for ability to perform daily activities [10]); the familiarity with transducers and aids; the level of informatics alphabetization measured by the number of hours/week spent in front of a computer. Corresponding questions were structured in a questionnaire that was administered to the patients at the beginning and end of the training. A level of system acceptance by the users was schematized by asking the users to indicate with a number ranging from 0 (not satisfied) to 5 (very satisfied) their degree of acceptance relative to each of the output devices controlled by the most individual adequate access. The training consisted of weekly sessions; for a period of time ranging from 3 to 4 weeks (except in the case of BCI training, see below), the patient and (when required) her/his caregivers were practicing with the system.

B. *System prototype input and output devices*

The system architecture, with its input and output devices, is outlined in Figure 1.

The core program was interfaced with several input devices that supported a wide range of motor capacities for a wide variety of users. For instance, keyboard, mouse, joystick, trackball, touchpad, and buttons allowed access to the system through upper limb residual motor abilities. Otherwise, microphone and head tracker could be used when motor disability was extremely impairing for the limbs but the neck muscles or comprehensible speech were preserved. When the user was not able to master any of the above mentioned devices, or when the nature of a degenerative disease suggested that the patient may not be able to use any of the devices in the future, the support team proposed to the patient to start training on the use of a BCI.

As for the system output devices, we considered (also based upon a patient's needs/wishes), a basic group of domotics appliances such as neon lights and bulbs, TV and stereo sets, motorized bed, acoustic alarm, front door opener, telephone and wireless cameras (to monitor the different rooms of the house). The system also included a robotic platform (a Sony AIBO) to act as an extension of the ability of the patient to move around the house ("virtual" mobility). The AIBO was meant to be controlled from the system control unit in order to accomplish few simple tasks with a small set of commands. The detailed description of both the implementation of the robotic platform (AIBO) and its control strategy are available at [9] and [11].

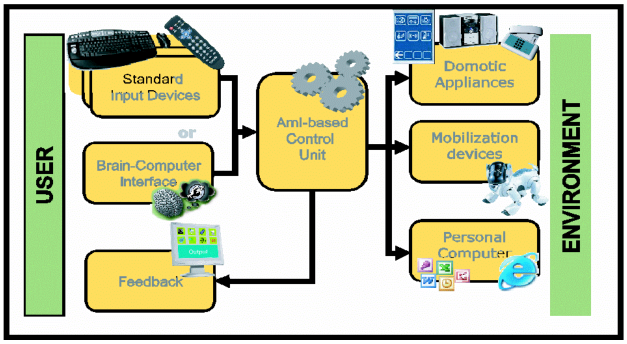

Fig. 1 Outline of the architecture of the ASPICE project. The figure shows that the system interfaces the user to the surrounding environment. The modularity is assured by the use of a core unit that takes inputs by one of the possible input devices and sends commands to one or more of the possible actuators. Feedback is provided to keep the user informed about the status of the system.

C. *Brain Computer Interface (BCI) framework and subject training*

The system contained a BCI module meant to translate commands from users that cannot use any of the conventional aids. This BCI system was based on detection of simple motor imagery (mediated by modulation of sensorimotor EEG rhythms) and was realized using the BCI2000 software system [12]. Detailed description of the BCI framework and training strategy have been reported elsewhere [9][12]. In brief, users were trained to modulate rhythms recorded over sensorimotor cortex. This training was performed using a binary selection task (i.e., 50% accuracy due to chance alone). Over the course of this training, they typically improved from an initial performance of 50-70% to 80-100% [13]. An initial screening session suggested, for each subject, the signal features (i.e., amplitudes at particular brain locations and frequencies) that could best discriminate between imagery and rest. During the following training sessions, the subjects were provided feedback of these features via a computer cursor whose position was controlled in real time by the amplitude or the subject's sensorimotor rhythms. The BCI system was then configured to use these brain signal feature, and to thus translate the user's brain signals into output control signals that were communicated to the system central unit. During sessions, scalp activity was collected with a 96 channel EEG system (BrainAmp, BrainProducts, GmbH, Germany; EEG data sampling frequency was 200 Hz and bandpass-filters were between 0.1 and 50 Hz). At the end of this process, we calculated the coefficient of determination (i.e., values of r^2) and showed them in a channel-frequency matrix and head topography (examples are shown in Figures 3). Using these analyses, we identified the set of candidate features to be enhanced with training. Each session lasted about 40 minutes and consists of eight 3-minutes runs of 30 trials each. We collected a total of 5-12 training sessions for each patient; training ended when performance was stabilized. Each subject's performance was assessed using accuracy (i.e., the percentage of trials in which the target was hit) and using r^2 value [13]. Upon successful training, the BCI was connected to the prototype system (via a TCP/IP connection) and the subject was asked to utilize its button interface using BCI control.

III. RESULTS

A. *System prototype and robotic platform implementation*

The core unit of the prototype received the logical signals from the input devices and converted them into commands that could be used to drive the output devices. Its operation was organized as a hierarchical structure of possible actions, whose relationship could be static or dynamic. The user could select the commands and monitor the system behavior through a graphical interface (Fig. 2). The prototype system allowed the user to operate remotely electric devices (e.g. TV, telephone, lights, motorized bed, alarm, and a front door opener), as well as monitoring the environment with remotely controlled video cameras and the robotic platform (AIBO). The input and feedback signals were carried over a wireless communication.

B. *Clinical validation*

Each of the 14 able-bodied subjects tested the successive releases of the system for 8-12 sessions. The purpose of the use of the system by able-bodied subjects was to validate system security and safety. The system input devices were all functionally effective in controlling the domotic appliances and the small robotic device (AIBO). Patients were able to master the final release of the system within 5 sessions, performed once or twice a week. Because of the high level of muscular impairment, patients affected by DMD (n=6) had the best access to the system via joystick, which required minimal efficiency of the residual muscular contraction at the distal muscular segments of the upper limbs (minimal flexion-extension of the hand fingers). The 8 type I/II SMA patients had optimum access to the system via a joystick (3 patients), touchpad (2 patients), keyboard (1 patient), and button (2 patients). The variety in the access devices in this class of patients was related to a still functionally effective residual motor abilities of the upper limbs (mainly proximal muscles), both in terms of muscular strength and range of movements preserved. None of the patients was comfortable in accessing the system via head-tracker because of the weakness of the neck muscles. According to the early results of the questionnaire, all patients were independent in the use of the system at the end of the training. A schematic evaluation of the degree of the system acceptance by the users revealed that amongst the several system outputs, the front door opener was the most accepted controlled device (mean score 4.93 in a range 1-5) whereas the robotic platform (AIBO) received the lowest score (mean 3.64). Four of the motor impaired users had interacted with the system via BCI (see below).

Fig. 2 Appearance of the feedback screen. The Feedback application has been instructed to divide the window into three panels. In the top panel, the available selections (commands) appear as icons. In the bottom right panel, a feedback stimulus by the BCI (matching the one the subject has been training with) is provided; the user uses his learnt modulation of brain activity to move the cursor at the center to hit either the left or the right bars – in order to focus the previous or following icon in the top panel – or to hit the top bar – to select the current icon. In the bottom left panel, the Feedback module displays the video stream from the video camera that was chosen beforehand in the operation.

C. *Brain Computer Interface (BCI) application*

Over the 8-12 sessions of training, subjects acquired brain control with an average accuracy higher than 75% (accuracy expected by chance alone was 50%) in a binary selection task. Four patients out of 14 underwent a standard BCI training. Similarly to healthy subjects, all these patients acquired brain control that supported accuracies above 60% in the standard binary decision task. The patients employed imagery of foot or hand movements. Brain signal changes associated with these imagery tasks were mainly located at midline centro-parietal electrode positions. Figure 3 shows for one representative patient in a session near the end of training, the scalp topography of r^2 at the frequency used to control the cursor with an average accuracy of 80%. In this case, control was focused at Cz (i.e., the vertex of the head).

When BCI training was performed in the system environment, healthy subjects could control the interface by using two targets to scroll through the icons and to select the current icon, respectively. One more icon was added to disable selection of commands (turn off BCI input) and a combination of BCI targets was programmed to re-establish BCI control of the system. All 4 patients were able to successfully control the system. However, system performance achieved in these patients using the BCI input was lower than that for muscle-based input.

IV. DISCUSSION

Even the most advanced assistive device can currently not provide the level of assistance that can be provided by a human. Nevertheless, it can contribute to relieve the caregiver from continuous presence in the patient's room since the patient can perform some simple activities on his/her own. In this respect, the preliminary findings we reported would innovate the concept of assistive technology device and they may bring it to a system level. In fact rather than providing the

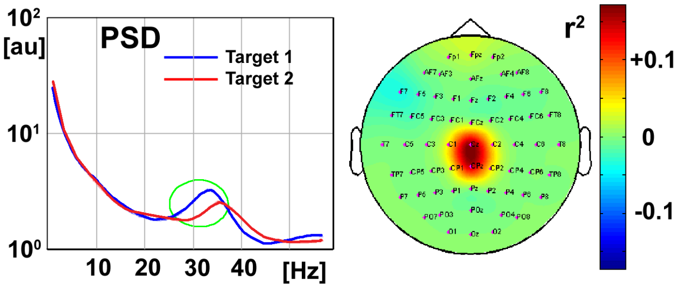

Fig.3 EEG patterns related to the intentional brain control in a SMA patient. *Left panel:* spectral power density of the EEG of the most responsive channel. Red and blue lines correspond to the subset of trials in which the user tried to hit the top and the bottom target, respectively. *Right Panel:* Topographical distributions of r^2 values at the most responsive frequency (33Hz). The red colored region corresponds to those regions of the brain that exhibited brain control.

patient with separate devices to help him with a nimber of activities, the proposed system provides unified (though flexible) access to all controllable appliances.

From a clinical perspective, the perception of the patient, as revealed by the analysis of questionnaires, is that he/she does not have to rely on the caregiver for all tasks. Although further studies are needed in which a larger cohort of patients is confronted with the system and a systematic categorization of the system impact on the quality of life should take into account a range of outcomes (e.g., mood, motivation, caregiver burden, employability, satisfaction) [14][15][16], the results obtained from this pilot study are encouraging for the establishment of a solid link between the field of human machine interaction and neurorehabilitation strategy [17].

Exploration of potential impact of BCI on the users' interaction with the environment is peculiar to this work when compared to the previous studies on the usefulness of the BCI-based interfaces, i.e. [3][5][7]. Although the improvement of quality-of-life brought by such an interface is expected to be relevant only for those patients who are not able to perform any voluntarily controlled movement, the advances in the BCI field are expected to increase the performance of this communication channel, thus making it effective for a broader population of individuals. Upon training, the able-bodied subjects enrolled in this study were able to control a standard application of the BCI (i.e., a cursor moving on a screen as implemented in the BCI2000 framework) by modulating their brain activity recorded over the scalp centro-parietal regions, with an overall accuracy above 70%. Similar levels of performance were achieved by the patients who underwent BCI training with standard cursor control application. All patients displayed brain signal modulations over the expected centro-parietal scalp positions. This confirms findings in [3][5][7] and extends them to other neurological disorders (DMD and SMA).

V. CONCLUSION

In conclusion, in this pilot study, we integrated an EEG-based BCI and a robotic platform in an environmental control system. This provides a first application of this integrated technology platform towards its eventual clinical significance. In particular, the BCI application is promising in enabling people to operate an environmental control system, including those who are severely disabled and have difficulty using conventional devices that rely on muscle control. Integration of several different assistive technologies including a BCI system, can potentially facilitate the translation from pre-clinical demonstrations to a clinical useful BCI.

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