Artificial Intelligence in Medicine 59 (2013) 133–142

Contents lists available at ScienceDirect

Artificial Intelligence in Medicine

journal homepage: www.elsevier.com/locate/aiim

Hybrid brain–computer interfaces and hybrid neuroprostheses for restoration of upper limb functions in individuals with high-level spinal cord injury

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ARTICLE INFO

Article history:
Received 9 November 2012
Received in revised form 17 July 2013
Accepted 23 July 2013

Keywords:
Functional electrical stimulation
Hybrid neuroprosthesis
EEG
Hybrid brain–computer interface (BCI)
Motor imagery
BCI training
Spinal cord injury
Tetraplegia

ABSTRACT

Background: The bilateral loss of the grasp function associated with a lesion of the cervical spinal cord severely limits the affected individuals' ability to live independently and return to gainful employment after sustaining a spinal cord injury (SCI). Any improvement in lost or limited grasp function is highly desirable. With current neuroprostheses, relevant improvements can be achieved in end users with preserved shoulder and elbow, but missing hand function.
Objective: The aim of this single case study is to show that (1) with the support of hybrid neuroprostheses combining functional electrical stimulation (FES) with orthoses, restoration of hand, finger and elbow function is possible in users with high-level SCI and (2) shared control principles can be effectively used to allow for a brain–computer interface (BCI) control, even if only moderate BCI performance is achieved after extensive training.
Patient and methods: The individual in this study is a right-handed 41-year-old man who sustained a traumatic SCI in 2009 and has a complete motor and sensory lesion at the level of C4. He is unable to generate functionally relevant movements of the elbow, hand and fingers on either side. He underwent extensive FES training (30–45 min, 2–3 times per week for 6 months) and motor imagery (MI) BCI training (415 runs in 43 sessions over 12 months). To meet individual needs, the system was designed in a modular fashion including an intelligent control approach encompassing two input modalities, namely an MI-BCI and shoulder movements.
Results: After one year of training, the end user's MI-BCI performance ranged from 50% to 93% (average: 70.5%). The performance of the hybrid system was evaluated with different functional assessments. The user was able to transfer objects of the grasp-and-release-test and he succeeded in eating a pretzel stick, signing a document and eating an ice cream cone, which he was unable to do without the system.
Conclusion: This proof-of-concept study has demonstrated that with the support of hybrid FES systems consisting of FES and a semiactive orthosis, restoring hand, finger and elbow function is possible in a tetraplegic end-user. Remarkably, even after one year of training and 415 MI-BCI runs, the end user's average BCI performance remained at about 70%. This supports the view that in high-level tetraplegic subjects, an initially moderate BCI performance cannot be improved by extensive training. However, this aspect has to be validated in future studies with a larger population.

1. Introduction

The bilateral loss of the grasp function associated with a motor complete or nearly complete lesion of the cervical spinal cord severely limits the affected individuals' ability to live independently and return to gainful employment post injury, which severely compromises their quality of life. Any improvement in lost or limited grasp function is highly desirable not only from the patients' point of view [1,2], but also for economic reasons [3]. Together with the fact that individuals with tetraplegia are often young people who have been injured in sporting and diving accidents, rehabilitation specialists have always focused on finding ways to improve an impaired or lost upper extremity function. Since to date none of the neuroprotective or

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http://dx.doi.org/10.1016/j.artmed.2013.07.004

neuroregenerative treatments has led to relevant improvements in humans, specialists' endeavors have primarily resulted in methods for compensating for individual functional deficits. Among those are surgical procedures, in which tendons of strong muscles are rerouted from their original attachment to a new one to restore the action that has been lost [4].

However, surgical functional rehabilitation is only possible if a sufficient number of muscles are still under voluntary control. This is not the case in patients with lesions above C5, who constitute about 20% of the entire European spinal cord injury (SCI) population. In this subgroup of SCI individuals, a handful of technological solutions for restoration of the upper extremity function are available. Among them are motor-driven orthoses, which due to their costs, complexity and size are intended to be used as training devices rather than as personalized support systems [5,6]. Thus, today the only clinically applicable possibility for restoring a permanently lost upper extremity function – at least to a certain extent – is the application of neuroprostheses based on functional electrical stimulation (FES). Over the last 20 years, several FES systems with different levels of complexity have been developed and introduced to end users. These FES systems deliver short current impulses to efferent nerves that cause paralyzed muscles to contract [7]. On this basis, FES artificially compensates for the loss of voluntary muscle control. When using FES for motor substitution, the easiest and least expensive way of improving a very weak or lost function is the application of non-invasive neuroprostheses that use multiple surface electrodes [8–10]. Before meaningful movements are possible, individuals with a chronic SCI need to undergo extensive muscle training. This low-frequency FES training can reverse the profound disuse atrophy of the paralyzed muscles even many years after the SCI. The time required to achieve sufficient fatigue resistance and force depends on the individual status of the muscles and ranges from weeks to months [11].

Most of the current neuroprostheses for the upper extremity can be used for grasp restoration only in SCI individuals with preserved voluntary shoulder function and active elbow flexion. Even with the most sophisticated device, namely the implantable Freehand® grasp neuroprosthesis, only a restoration of finger, thumb and wrist movements was possible [12]. Only a few experimental studies with implantable devices demonstrated the feasibility of supporting the elbow function in very selected subjects with high-level SCI [13]. One of the main challenges in restoring elbow flexion is the rapid muscle fatigue that occurs due to the substantial weight of the forearm and the non-physiological synchronous activation of the paralyzed muscles through external electrical pulses. Additionally, the main elbow flexor (biceps) muscle is often denervated, since its associated motor neurons are destroyed due to the spinal trauma [14].

The fact that in individuals with high-level SCI only a few residual functions are preserved also has an impact on the selection and setup of an appropriate user interface for autonomous control of a grasp neuroprosthesis. User interfaces that rely on either the movement or the underlying muscle activation from a non-paralyzed body part can hardly be applied in this patient group [15,16]. A general problem in the selection of the appropriate user interface is the interference of an assistive device (AD) with the natural body functions. For example, people with tetraplegia often wish to eat without extensive support from caregivers. If a neuroprosthesis is to be used for eating and drinking, control movements involving the mouth cannot be applied. The same holds true if gaze or head movements are intended to be used for neuroprosthesis control [17].

Brain–computer interfaces (BCIs) are technical systems that provide a direct connection between the human brain and a computer [18]. Such systems are able to detect thought-modulated changes in electrophysiological brain activity and transform such changes into control signals. Most of the BCI systems rely on brain signals that are recorded non-invasively through placement of electrodes on the scalp. At present, these electroencephalogram (EEG)-based BCI systems can function in most environments with relatively inexpensive equipment and therefore offer the possibility for practical BCIs to gain relevance in the rehabilitation field. One type of EEG-based BCI exploits the modulation of sensorimotor rhythms (SMRs). These rhythms are oscillations in the EEG occurring in the alpha (8–12 Hz) and beta (18–26 Hz) bands and can be recorded over the sensorimotor areas. Their amplitude typically decreases during actual movement and similarly during mental rehearsal of movements (motor imagery (MI)) [19,20]. Several studies have shown that people can learn to modulate their SMR amplitude by practicing MI of simple movements e.g., hand/foot movements [21]. This process occurs in a closed loop where the system recognizes the SMR amplitude changes evoked by MI and these changes are instantaneously fed back to the users. This neurofeedback procedure based on operant conditioning enables BCI users to control their SMR activity and thus that of an AD.

These observations suggest that a BCI may be a valuable component in a neuroprosthetic user interface. A major advantage over other user interfaces is that it can be operated independently from residual motor functions. Furthermore, MI-based BCIs have enormous implications for providing natural control of grasping and reaching neuroprostheses in particular in individuals with high-level SCI since they rely on volitional signals recorded from the brain directly involved in upper extremity movements.

The feasibility of MI-based BCI systems for control of neuroprostheses using surface [22] as well as implantable [23] electrodes was shown in tetraplegic SCI users with a loss of hand and finger function. One of the major limitations of studies involving humans in this field is that the results were obtained in selected users with high BCI performances [24]. This raises the question as to what extent the published results can be generalized to a user population of non-selected persons. The results of a recent study involving a small group of individuals with paraplegia and tetraplegia show that motor imagery-induced EEG patterns can be discriminated in the first training session in only half of the participants. However, it is unclear whether extensive training sessions will lead to a sufficient BCI performance in at least some of the individuals with SCI with initially low or moderate performance [25]. Subjects with SCI also show a diffuse and broadly distributed event-related desynchronization (ERD)/synchronization (ERS) pattern during attempted foot movements in contrast to the focal beta ERD/ERS pattern during foot movement attempted by healthy subjects [26]. This shows that tetraplegic BCI users in general may not achieve the high performance of paraplegic or healthy individuals, although they have the greatest need for this type of system.

Therefore, the aim of this work is to show that (1) with the support of hybrid FES systems consisting of an FES system and semiactive orthosis, restoration of not only hand and finger, but also elbow function is possible in users with tetraplegia and (2) shared control principles can be effectively used to allow for adequate BCI control of this hybrid FES system in end users in whom only a moderate BCI performance is achieved even after extensive training.

2. Patients and methods

2.1. Characteristics of the end user

The individual in this single case study is a right-handed 41-year-old man with a traumatic SCI sustained in August 2009. He is affected by a complete motor and sensory lesion (American Spinal Injury Association (ASIA) Impairment Scale A [27]) with a