Brain-Computer Interfacing for Users with Cerebral Palsy, Challenges and Opportunities

Ian Daly, Martin Billinger, Reinhold Scherer, and Gernot Müller-Putz

Laboratory of Brain-Computer Interfaces, Institute for Knowledge Discovery,
Graz University of Technology, 8010, Graz, Austria

Abstract. It has been proposed that hybrid Brain-computer interfaces (hBCIs) could benefit individuals with Cerebral palsy (CP). To this end we review the results of two BCI studies undertaken with a total of 20 individuals with CP to determine if individuals in this user group can achieve BCI control.

Large performance differences are found between individuals. These are investigated to determine their possible causes. Differences in subject characteristics are observed to significantly relate to BCI performance accuracy. Additionally, significant relationships are also found between some subject characteristics and EEG components that are important for BCI control. Therefore, it is suggested that knowledge of individual users may guide development towards overcoming the challenges involved in providing BCIs that work well for individuals with CP.

1 Introduction

Cerebral palsy (CP) is an umbrella term used to describe a group of disorders of the nervous system, which result in functional disorders to movement and posture [1]. CP is commonly caused by injury or damage to the fetal or infant brain, such as, for example, hypoic ischemic brain injury. Although CP is non-progressive specific symptoms may change over time as the individual grows [2]. Additionally, motor disturbances in individuals with CP are often accompanied by disturbances to perception, cognition, communication, and behaviour.

Motor control impairments exhibited in individuals with CP can include problems with executing intended movements, posture, and muscle tone regulation. In some instances individuals may be unable to control a wide range of muscles and may, hence, exhibit near complete paralysis. Additionally, lack of muscle tone regulation may lead to spasticity [3].

As a result, individuals with CP may experience a range of challenges in their lives. As muscle control over the face and vocal cords may be impaired communication may be restricted. Such problems may place a number of restrictions on the daily lives of individuals with CP and result in them relying on care-givers for many of their day-to-day needs [2].

C. Stephanidis and M. Antona (Eds.): UAHCI/HCII 2013, Part I, LNCS 8009, pp. 623–632, 2013.

Brain-computer interfaces (BCIs) have been proposed as a potential tool to help meet some of the needs of individuals with CP [4]. BCIs have been proposed as an assistive device to aid with communication (for example by providing speller to speech applications) and help with movement control (for example by providing wheelchair control). BCIs have also been proposed to assist with rehabilitation efforts (for example by providing positive reinforcement to the desired neurological activation patterns associated with desirable movement). Specific applications envisioned for individuals with CP include applications for emotional management, facilitation of learning, improvement of rehabilitation therapies, improvement of health management, enablement of play, and improvement of users' abilities to express decisions.

A BCI device is an example of an assistive human-computer interface (HCI) technology which attempts to allow control of a computer by modulating neurophysiological processes [5]. BCIs, therefore, may allow severely disabled individuals the possibility to control a computer, and hence communicate and interact, without having to rely on efferent nervous system activation. As such, individuals with no other communication pathways, or those with severe challenges to their ability to produce precise or reliable motor control (such as individuals with CP), may potentially be able to benefit from use of a BCI.

BCIs have been proposed as an assistive device to help with, for example, communication [6] and wheelchair control [7]. They have also been shown to allow control of computers and devices by a number of different patient populations - such as patients with spinal cord injuries [8] and patients after incidence of stroke [9] - as well as healthy individuals.

One of the most popular methods for acquiring signals from the brain for use in BCI control is the electroencephalogram (EEG). This is a non-invasive and relatively cheap method for acquiring potential differences in electrical activity recorded from different places on the surface of the scalp. Such potential differences result from summed post-synaptic potentials arising from electrical activity concentrated mainly in cortical neurons.

However, the broad range of symptoms apparent in individuals with CP, coupled with the cause of the condition, damage to the fetal or infant brain, makes it unclear whether BCI devices are usable by such a population.

To attempt to address this issue it has been further proposed that hybrid BCIs (hBCIs) may be of some benefit to such individuals [10]. hBCIs combine two or more types of BCI or a BCI and control based upon some other physiological signal(s) with the aim of thereby improving performance over that achievable with a single BCI [11]. However, prior to attempting to provide hBCIs to users with CP it is important to first asses to what extent users with CP can gain control of a BCI and which types of BCI can be controlled by users in this group.

To this end we review two studies from our group to demonstrate whether, in some cases, BCI control is possible by individuals with CP. Differences in subject characteristics are also compared to BCI performance and EEG component strengths over both studies to determine if subject performance is determined by any of their characteristics (e.g. age, gender etc.). If some subject characteristics are determined to significantly relate to performance this has the potential to allow identification of whether other individuals with CP who share those characteristics could potentially control those BCIs.

There are a very wide range of differences between individuals with CP. Symptoms may range from very mild to very severe, may involve one, or both, sides of the body, and may involve different body parts more or less severely [12]. Symptoms may include torsion spasm, dystonia, athetosis etc. These may occur in isolation or in combination at varying levels of severity [13]. Additionally, spasticity may also be exhibited by individuals with CP [14]. Dependent upon the symptoms exhibited there may be specific challenges presented in attempting to obtain clean EEG signals from specific individuals with CP.

BCIs rely on the detection of patterns of neurological activity, which can be modulated by the users to attempt to achieve control. However, it is unclear how brain damage in individuals with CP affects these neurological responses.

Two brain responses frequently used for BCI control are the steady state evoked potential (SSEP) and the sensorimotor rhythm (SMR).

SSEPs are changes in relative band-power over baseline in response to the user attending to a regular stimulus such as a flashing light or a vibrating tactile stimulus [15]. The EEG band-power at the same frequency as the stimulus exhibits an increase over baseline in response to attendance to the stimulus. A popular choice of SSEP for BCI control is the steady state visual evoked potential (SSVEP) in which a visual stimulus, such as a light, is used [15].

SMRs are observed as changes in relative band-power over the sensorimotor cortex, and relate to planning and execution of movement and a number of other cognitive tasks such as mental rotation, spatial navigation, word-letter association etc [16]. Particular cognitive tasks exhibit different patterns of SMR changes over different cortical regions and at different frequency bands.

All these brain responses have been shown to differ between subjects and within subjects over different recording sessions. It is unclear whether we are able to measure equivalent responses in individuals with CP, when compared to other patient groups or healthy subjects, due to the various neurological factors associated with CP.

2 Methods

Two studies have been conducted by our group to determine, firstly, whether we can detect steady state visual-evoked potentials (SSVEPs) or sensorimotor rhythms (SMRs) from individuals with CP and, secondly, whether those changes may be used to produce effective online BCI control.

2.1 Measurements without Feedback

Offline measurements were conducted to determine if we are able to detect the necessary brain patterns for BCI control from individuals with CP. Two BCI types were investigated SSVEP BCIs and SMR BCIs.

Subjects. Six individuals with CP participated in this measurement session. Details of the subjects for these measurements and the measurements with feedback are both listed in table 1. Institutional review board (IRB) ethical approval was obtained for all measurements.

Table 1. Subject details for both measurements conducted with and without feedback. GMFCS denotes the Gross motor function classification system score [17], Orthopaedic disorders are denoted by codes which indicate lower limb disorders (MMII) or upper limb disorders (MMSS). The subjects' dominant hand is either, left (L), right (R), bilateral (B), or unknown (-). Subject codes indicate subjects who participated in offline studies without feedback (N-) or in online studies with feedback (F-).

User	Sex	Age	GMFCS	Orthopaedic disorders	CP type	Sensory disturbances	Hand
N-01	M	36	IV	MMII	Spastic Hemiplegic	-	R
N-02	M	30	V	MMII, MMSS	Dystonic-spastic	-	L
N-03	M	34	V	MMII	Athetosis	-	R
N-04	F	38	IV	MMII	Dystonic	Myopia	R
N-05	F	62	IV	MSI	Spastic Hemiplegic	-	R
N-06	M	38	V	MMII, MMSS	Dystoni-spastic	-	L
F-01	M	53	V	MMII, MMSS	Dystonic	-	L
F-02	M	36	V	MMII, MMSS	Dystonic-spastic	-	L
F-03	F	52	IV	MMII	Spastic diplegia	Myopia	R
F-04	M	22	IV	MMSS, MMII	Acquired cerebral damage	-	R
F-05	M	32	V	MMII	Acquired cerebral damage	Blind, left. Deaf, left.	B
F-06	F	20	-	MMII, MMSS	Dystonic	-	-
F-07	M	34	IV	MMSS, MMII	Athetosic	-	L
F-08	F	58	IV	MMII	Spastic diplegia	Myopia	R
F-09	F	32	IV	MMII	Spastic	-	L
F-10	F	36	V	MMII, MMSS	Spastic	-	L
F-11	M	38	V	MMII, MMSS	Dystonic-spastic	-	L
F-12	F	36	V	MMII, MMSS	Dystonic	Myopia	L
F-13	M	37	IV	MMII, MMSS	Spastic	-	-
F-14	F	31	IV	MMII, MMSS	Spastic	-	-

Recording. EEG was recorded at 512 Hz using a g.USBamp system (g.tec, Austria) from electrodes FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, Pz, O1, and O2. Electrodes were grounded at the right mastoid and referenced to the left.

SSVEP Paradigms. Two stimuli were presented on screen (one to the left and one to the right). The user was cued to attend to one or the other for 10 seconds via an arrow appearing in the centre of the screen and remaining in place for 2 s followed by an 8 s period of attention to the appropriate stimuli. This is repeated 10 times (either left or right) per session. After each session the user was asked if they would like to continue or stop.

SMR Paradigm. The user was asked to attempt to kinaesthetically imagine either hand or foot movement. Each movement was visually cued by presenting pictures of either the hand or the foot. Pictures were presented in the centre of the screen for 2 seconds and the user was instructed to perform the cued action for 6 seconds. Each action was cued 10 times per run, with different numbers of runs per user dependent upon when the user elected to stop.

2.2 Measurements with Feedback

Subjects. Fourteen individuals with CP voluntarily participated in this study (seven male, age range 20 to 58 with a median age of 36, SD = 10.97). IRB ethical approval was obtained for all measurements. Details of these participants are also listed in table 1.

Recording. EEG was recorded from 16 electrode channels via the g.tec GAMMAsys system with g.LADYbird active electrodes. The following channels were used; AFz, FC3, FCz, FC4, C3, Cz, C4, CP3, CPz, CP4, PO3, POz, PO4, O1, Oz, and O2. The reference electrode was placed on either the right or left ear and the ground electrode was placed at either TP7, TP9, or at FPz. EEG data was sampled at a frequency of 512 Hz and saved to file.

SSVEP. The SSVEP paradigm consisted of four square targets in the form of four red boxes arranged in a quadrangle. Stimuli were rapidly changed between red and black at frequencies of (clockwise from top left) 6.66 Hz, 8.57 Hz, 12 Hz, and 15 Hz. Users were cued to attend to one of the targets via an arrow which remained in place for 6 s. Additionally, a fifth null condition was cued by a cross. Feedback was provided by highlighting a selection frame around the target. Inter-trial intervals were uniformly distributed between 3 – 5 s. Each SSVEP run consisted of 20 trials with equal numbers of trials for each class.

Classification was performed via canonical correlation analysis (CCA) described in [18]. Thresholds were initially set to 0.2 for each stimulation frequency.

CCA was applied in a sliding window to segments of the EEG of length 2 s and a step size of 0.0625 s. Feedback was presented to the user if the output of the CCA method exceeded the threshold for 0.5 s consecutively.

Sensorimotor Rhythms. The SMR paradigm consisted of an initial calibration phase followed by an online feedback phase.

During the calibration phase the user was asked to perform four different mental tasks in response to a cue. The tasks were to kinaesthetically imagine movement of either hand, kinaesthetically imagine movement of the feet, perform mental arithmetic, or perform mental word-letter association.

The timing of individual trials was as follows. Second 0: a fixation cross appears in the centre of the screen and remains for the duration of the trial. Second 1.5: a cue appears on screen indicating which task to perform. This cue remains until second 3.5. Remaining time: this was the imagery period and the user was instructed to perform the cued task, halting when the cross disappeared.

During the imaginary period a bar was used to display the LDA classifier distance from the users ERD/S. Increased classifier distance caused the bar to fill from left to right. An individual run in both the training and feedback phases contained 32 trials. For further details the reader is referred to [19].

2.3 Performance Differences

Relationships between the subject characteristics, average performance at each BCI and strength of EEG components were investigated to attempt to determine the reasons for performance differences between subjects. Stepwise multi-linear regressions were performed with subject details as predictors and either BCI accuracies or component strengths as criterions. The following characteristics were used as predictors; age, gender, GMFCS score, Orthopaedic disorder, CP type, Sensory disturbance, handedness, heart rate, head movement, EEG signal quality index (SQI) [20], and finally the type of measurement performed (with or without feedback). Separate regression analyses were performed for SSVEP band-powers, ERD/S strengths, and accuracies at SSVEP- and SMR-BCIs.

Adjusting for multiple comparisons (2 BCI types and 2 criterion; component strength and performance) is done via Bonferroni correction. Thus, the significance level is adjusted from $p = 0.05$ to $p = 0.0125$.

2.4 Signal Quality

The quality of the EEG recorded is assessed in two ways. First, a detailed visual inspection is conducted of the signals to identify the distribution of artifact contaminated epochs and the types of artifacts. Second, the signal quality index (SQI) is adopted from [20] to provide an analytical measure of the signal quality.

Visual inspection labels portions of the EEG as clean of artifacts, containing blinks, containing Electromyographic (EMG) artifacts, containing movement artifacts, or containing slow EOG artifacts.

3 Results

SSVEPs. SSVEPs are first passively evoked during offline measurements. Doing so produces clear peaks in the spectrogram relating to SSVEP stimulation frequencies below 15 Hz in 3 of the 6 investigated subjects. Classification of SSVEP was attempted in 2 of the 6 users with a statistically significant classification accuracy of 0.75 ($p < 0.05$) achieved with one (subject N-01).

SSVEPs are also used during measurements with feedback with a further 14 subjects. Doing so produces, as reported elsewhere [19], significant online classification accuracies ($p < 0.05$) in 5 of the 14 users.

Sensorimotor Rhythms. During offline measurements SMR responses are visible in 4 of the 6 investigated subjects and classification is significant ($p < 0.05$) in 4 of the 6 subjects. The EEG in the 2 of the 6 subjects without discernible SMRs are heavily contaminated with artifacts.

During attempted online BCI control clear sensorimotor rhythms are visible in 12 of the 14 users with artifacts contaminating the spectra in the remainder. The online classifier identifies enough trials to be trained with 10 of the 14 users and online classification is statistically significant ($p < 0.05$) in 6 of those users. Of those users one user exhibits significant correlations between the classifier output and the artifacts present in the signal. Thus, of the 14 users who attempted online BCI control via SMR modulation, 5 were successful.

3.1 Performance Differences

User performance accuracies at the SMR BCI are found to significantly relate to age ($r^2 = 0.455$, $p = 0.010$, significant) and mean SQI values ($r^2 = 0.812$, $p = 0.029$, insignificant after Bonferroni correction).

User performance accuracies at the SSVEP BCI are not found to significantly relate to any of the users' characteristics.

3.2 Component Difference

ERD/S strength is found to significantly relate to the subjects CP type ($r^2 = 0.376$, $p = 0.007$, significant) and mean SQI values ($r^2 = 0.654$, $p = 0.015$, insignificant after Bonferroni correction). Note, subjects with Dystonic and Spastic diplegia exhibit larger ERD/S effects than other CP types. However, it's very important to note that the number of types of CP in the study population means each of the six CP types is only represented by a few subjects (see table 1). Thus, only very low confidence can be given to the generalizability of this result. The SSVEP component strength is found to significantly relate to the mean SQI values ($r^2 = 0.723$, $p = 0.037$, insignificant after Bonferroni correction).

Mean SQI values are found to relate to subject gender ($r^2 = 0.323$, $p = 0.006$, significant) and orthopaedic impairment type ($r^2 = 0.564$, $p = 0.038$, insignificant after Bonferroni correction).

3.3 Signal Quality

Table 2 lists the percentage of the measurement contaminated by each type of artifact and clean EEG in the recording from each subject. Note that the EMG contamination is the most prevalent of the artifact types.

Table 2. Percentage occurrence of each type of artifact over subjects with feedback. Note, artifact labels are not available for subject F-06 due to occasional periods of ground electrode detachment.

Subject	Percentage of recording					
	Blink	EMG	Movement	Failing electrode	Slow EOG	Clean EEG
F-01	10.11	21.61	6.71	0.18	6.91	54.93
F-02	4.75	50.63	1.55	0	0.27	42.79
F-03	6.76	11.19	3.58	0	0.13	78.35
F-04	3.67	33.45	0.59	0	0	62.35
F-05	2.10	17.53	0	0	0	80.37
F-07	0.73	39.12	12.63	0	0	47.89
F-08	4.03	14.67	0	0	0	81.29
F-09	9.20	20.83	1.09	0	0	68.87
F-10	6.58	40.77	2.84	0	0	50.07
F-11	1.48	2.89	5.27	0	0.17	90.20
F-12	0.16	42.18	0	0	0	57.66
F-13	1.95	7.83	1.94	0	4.64	83.65
F-14	3.34	48.22	1.53	0	0	46.98
Mean (± STD)	4.22 (3.15)	26.99 (16.14)	2.90 (3.58)	0.01 (0.04)	0.93 (2.20)	65.03 (16.26)

4 Discussion

This work demonstrates that BCIs could be suitable assistive devices for individuals with CP. It is seen that the electrophysiological processes SSVEPs and SMRs may be observed in EEG recorded from individuals with CP. Significant BCI classification accuracies are also achieved with both paradigms.

The results suggest that the key characteristics relating to BCI performance are users' age, CP type, and EEG quality. Subject age exhibits a positive correlation with SMR BCI performance. Thus, older subjects perform better at BCI control. SQI is seen to significantly relate to the subjects' gender and orthopaedic type. Male subjects are observed to produce worse SQI measures. Note, that the numbers of male (11) and female (9) subjects are insignificantly different.

Taken together the key characteristics which determine performance in this group of subjects are gender, age, and measures of their CP diagnosis (CP type and orthopaedic type). This finding may help guide the customization of specific BCIs to specific individuals with CP. For example younger users with CP may require more repetitions or longer trials before an ERD response can be significantly identified. Alternatively, these findings may indicate cases when BCI control is not feasible for some users, or would require a customized design.

It is observed that there is no significant relationship between SSVEP band-power changes and any measures of impairment. However, there is a significant relationship ($p < 0.05$) observed between the strength of the ERD/S in the frequency range 8 - 13 Hz and the subjects' age. The ERD/S strength increases with age. As CP is a lifelong condition this suggests that ERD/S strength is increasing with time the subjects have lived with the condition. We suggest that the older the individuals with CP the more practised they are at movement and hence the better able they are to produce strong ERD/S effects.

Some of the relationships identified between BCI performance and user characteristics are non-significant after correction for multiple comparisons. However, Bonferroni correction may be overly conservative and erroneously identify results as insignificant. Therefore, future work will aim to expand the number of subjects to see how well these results generalize.

Large amounts of artifact, in particular EMG, are observed in EEG from this user group. EMG artifacts are particularly prevalent on occipital electrodes impacting SSVEP accuracy. As the amount of artifact contamination is very high - over 50 % in some subjects - it is crucial to remove artifacts in such a way that the EEG may still be used for BCI. We, therefore, suggest artifact removal methods should focus on EMG. A proposed method for this is described in [21].

5 Conclusion

Control of either an SMR or an SSVEP BCI is possible by some users with CP. Some user characteristics are seen to significantly correlate with performance and/or EEG component strength. However, many challenges remain in providing BCIs that work effectively for a large number of users with CP.

Acknowledgments. This work was supported by the FP7 Framework EU Research Project ABC (No. 287774).

References

1. Krigger, K.W.: Cerebral palsy: an overview. Am. Fam. Physician 73, 91–100 (2006)
2. Panteliadis, C.P., Strassburg, H.-M.: Cerebral palsy: principles and management. Thieme (2004)
3. Miller, F.: Cerebral palsy. Springer (2005)
4. Neuper, C., Müller, G.R., Kübler, A., Birbaumer, N., Pfurtscheller, G.: Clinical application of an EEG-based brain-computer interface: a case study in a patient with severe motor impairment. Clin. Neurophysiol. 114, 399–409 (2003)
5. Wolpaw, J.R., Birbaumer, N., McFarland, D.J., Pfurtscheller, G., Vaughan, T.M.: Brain-computer interfaces for communication and control. Clin. Neurophysiol. 113, 767–791 (2002)
6. Kalcher, J.: Graz brain-computer interface II: towards communication between humans and computers based on online classification of three different EEG patterns. Medical and biological engineering and computing 34, 382–388 (1996)

7. Leeb, R., Friedman, D., Müller-Putz, G.R., Scherer, R., Slater, M., Pfurtscheller, G.: Self-paced (asynchronous) BCI control of a wheelchair in virtual environments: a case study with a tetraplegic. In: Computational Intelligence and Neuroscience (2007)
8. Pfurtscheller, G., Müller-Putz, G.R., Pfurtscheller, J., Rupp, R., Hoffmann, U.: EEG-Based Asynchronous BCI Controls Functional Electrical Stimulation in a Tetraplegic Patient. EURASIP Journal on Advances in Signal Processing 2005, 3152–3155 (2005)
9. Kaiser, V., Daly, I., Pichiorri, F., Mattia, D., Müller-Putz, G., Neuper, C.: On the relationship between electrical brain responses to motor imagery and motor impairment in stroke. In: Stroke (2012)
10. Daly, I., Aloise, F., Arico, P., Belda, J., Billinger, M., Bolinger, E., Cincotti, F., Hettich, D., Iosa, M., Laparra, J., Scherer, R., Mueller-Putz, G.: Rapid prototyping for hBCI users with Cerebral palsy. In: Proceedings of BCI Meeting (2013)
11. Allison, B.Z., Brunner, C., Kaiser, V., Müller-Putz, G.R., Neuper, C., Pfurtscheller, G.: Toward a hybrid brain computer interface based on imagined movement and visual attention. J. Neural. Eng. 7, 26007–26016 (2010)
12. Wojciech, K., Wojciech, S.: Comparisons of right and left hemiparetic cerebral palsy. Pediatric Neurology 31(2), 101–108 (2004)
13. Odding, E., Roebroeck, M.E., Stam, H.J.: The epidemiology of cerebral palsy: incidence, impairments and risk factors. Disabil Rehabil 28, 183–191 (2006)
14. Tilton, A.: Management of spasticity in children with cerebral palsy. Semin. Pediatr. Neurol. 11(1), 58–65 (2004)
15. Ming, C., Shangkai, G.: An EEG-based cursor control system. In: BMES/EMBS Conference, vol. 1, p. 669. IEEE (1999)
16. Pfurtscheller, G., McFarland, D.: BCIs that use sensorimotor rhythms. In: Brain-Computer Interfaces: Principles and Practice, pp. 227–240. Oxford University Press (2012)
17. Wood, E., Peter, R.: The Gross Motor Function Classification System for Cerebral Palsy: a study of reliability and stability over time. Developmental Medicine and Child Neurology 42(5), 292–296 (2007)
18. Seber, G.: Multivariate observations. Wiley-Interscience (1984)
19. Daly, I., Billinger, M., Laparra-Hernándex, J., Aloise, F., Garcìa, M., Müller-Putz, G., Scherer, R.: Brain-computer interfaces as a potential assistive tool for cerebral palsy patients. Clinical Neurophysiology (2012) (in review)
20. Daly, I., Pichiorri, F., Faller, J., Kaiser, V., Kreilinger, A., Scherer, R., Mueller-Putz, G.: What does clean EEG look like? In: Conf. Proc. IEEE Eng. Med. Biol. Soc. (2012)
21. Daly, I., Billinger, M., Scherer, R., Mueller-Putz, G.: On the automated removal of artifacts related to head movement from the EEG. In: IEEE Transactions on neural systems and rehabilitation engineering (2013)