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Brain-Computer Interface Controlled Robotic Gait Orthosis

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Abstract. An able-bodied individual utilized walking motor imagery to operate a brain-computer interface (BCI) controlled robotic gait orthosis. This provides preliminary evidence that restoring brain-controlled ambulation is feasible, and it may lead to future BCI-controlled lower extremity prostheses for those with spinal cord injury.

Keywords: BCI, EEG, SCI, Robotic Gait Orthosis, Ambulation, Walking, Gait

1. Introduction

Excessive reliance on wheelchairs in individuals with tetraplegia or paraplegia due to spinal cord injury (SCI) leads to many medical co-morbidities such as cardiovascular disease, metabolic derangements, osteoporosis, and pressure ulcers. Treatment of these conditions contributes to the majority of SCI health care costs. Therefore, in addition to increasing independence and quality of life, restoring able-bodied-like ambulation in this patient population can potentially reduce the incidence of these medical co-morbidities. However, no biomedical solution exists that can accomplish this goal, and hence novel methods are required. A brain-computer interface (BCI) controlled lower extremity prosthesis may constitute one such novel approach.

This concept was first explored in the authors' prior work [Wang et al., 2012; King et al., 2012] in which able-bodied and SCI subjects used an electroencephalogram (EEG) based BCI to successfully control the ambulation of an avatar within a virtual reality environment. This motivated the current study, which integrates a BCI with a lower extremity prosthesis (Lokomat, Hocoma, Switzerland). For safety reasons, the feasibility of this system was first tested in an able-bodied individual.

2. Materials and Methods

A 41 year old, able-bodied male underwent a 64-channel EEG recording (256 Hz sampling rate, 0.1-40 Hz bandpass filter) while engaged in alternating epochs of idling and walking kinesthetic motor imagery (KMI). These data were analyzed using a combination of classwise principal components analysis (CPCA) [Das and Nenadic, 2009] and approximate information discriminant analysis (AIDA) [Das and Nenadic, 2008] for dimensional reduction, followed by Bayesian classification. This generated an EEG prediction model for online BCI operation. A treadmill-suspended robotic gait orthosis (RoGO) system (Lokomat) was then interfaced with the BCI (Fig. 1A). In 5 online tests, the subject utilized walking KMI/idling to ambulate/idle with the BCI-RoGO system as prompted by 1-min alternating walk/idle cues over a 5 min period. The online performance was assessed with cross-correlation analysis, omission, and false alarm rates.

Electromyogram (EMG) was measured to rule out BCI control by voluntary leg movements. To this end, lower extremity EMG were measured under 3 baseline conditions: active walking (subject voluntarily walked while the RoGO servos were turned off); cooperative walking (subject walked synergistically with the RoGO); and passive walking (the subject was fully relaxed while the RoGO made walking movements). Pairs of surface EMG electrodes were placed over the left quadriceps, tibialis anterior (TA), and gastrocnemius muscles (Fig. 1A), and signals were acquired with a bioamplifier (MP150, Biopac, Goleta, CA), bandpass filtered (0.1–1000 Hz), and sampled at 4 kHz. In addition, a gyroscope (Wii Motion Plus, Nintendo, Kyoto, Japan) with a custom wristwatch-like enclosure was strapped to the distal left lower leg (proximal to the ankle), and was used to measure leg movements (Fig. 1A).

3. Results

The offline accuracy of the EEG prediction model was 94.8 ± 0.8% (10-fold cross validation, chance: 50%). The CPCA-AIDA EEG feature extraction maps are shown in Fig. 1B. The subject's salient features during walking KMI were dominated by bilateral arm, likely due to arm swing KMI, and medial frontal areas. The cross-correlation between instructional cues and the BCI-RoGO walking epochs averaged over the 5 online sessions was

0.809 ± 0.056 ($p < 10^{-5}$). Also, there were on average 0.8 false alarms and no omissions per session; results for each session are shown in Table 1. A video of an online session can be found at http://youtu.be/W97Z8fEAQ7g.

The analysis of EMG and gyroscope data indicated that no movement occurred prior to the initiation of the BCI decoded "walking" states (Fig. 1C). When compared to the 3 baseline conditions, the EMG during online BCI-RoGO walking in all 3 muscle groups were statistically different from those of active or cooperative walking conditions ($p < 10^{-13}$), and were not different from passive walking ($p = 0.37$). Since passive walking generates some EMG activity [Mazzoleni et al., 2009], these results confirm that the BCI-RoGO system was wholly BCI controlled.

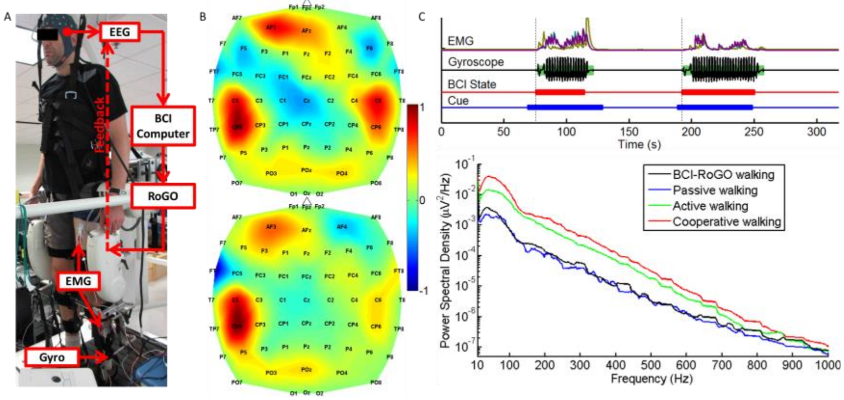

Figure 1. *(A) Subject suspended in the RoGO. A monitor presented instructional cues. (B) The CPCA-AIDA feature extraction maps at the 8-10 Hz bin (one map for each of the 2 classes). (C) Top: A representative online session showing epochs of idling and BCI-RoGO walking (red: decoded BCI states; blue: instructional cues). The thick/thin blocks indicate walking/idling. Corresponding EMG (gold: quadriceps; teal: TA; purple: gastrocnemius) and BCI-RoGO walking as detected by the gyroscope. (C) Bottom: Quadriceps EMG PSD similar to passive condition.*

***Table 1**. Cross-correlation between BCI-RoGO walking and cues at specific lags, number of omissions and false alarms.*

Trial	X-Corr. (lag in sec)	Omissions	False Alarms (duration in sec)
1	0.771 (10.25)	0	1 (12.0)
2	0.741 (4.50)	0	2 (5.5, 5.5)
3	0.804 (3.50)	0	1 (5.3)
4	0.861 (4.50)	0	0
5	0.870 (12.00)	0	0

4. Discussion

These results provide preliminary evidence that restoring brain-controlled ambulation is feasible, and justifies further investigation in individuals with SCI. If successful, this may lead to the future development of BCI-controlled lower extremity prostheses for free overground walking. Furthermore, this system can also be applied to incomplete motor SCI, where it could lead to improved neurological outcomes beyond standard physiotherapy.

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