Patients with ALS can use sensorimotor rhythms to operate a brain-computer interface

Abstract—People with severe motor disabilities can maintain an acceptable quality of life if they can communicate. Brain-computer interfaces (BCIs), which do not depend on muscle control, can provide communication. Four people severely disabled by ALS learned to operate a BCI with EEG rhythms recorded over sensorimotor cortex. These results suggest that a sensorimotor rhythm–based BCI could help maintain quality of life for people with ALS.

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ALS, brainstem stroke, and other severe neuromuscular disorders may leave patients with little or no voluntary muscle control, so that they are nearly or totally locked-in to their bodies, with minimal or no means of communication. While home ventilators and other life support technology now enable these patients to live for many years, many elect to die as their disease progresses and they approach the locked-in state.[1] Their physicians and other caregivers often concur in this decision and, depending on legal restrictions, may even assist in effecting it.[2,3]

Nevertheless, severely paralyzed patients may evince little or no depression and can lead pleasant and productive lives.[4] Furthermore, the capacity to communicate with family members and other caregivers is a critical component in maintaining their quality of life.[5] Thus, these patients need communication technologies that do not require neuromuscular function.[6]

Brain-computer interfaces (BCIs) use EEG or other measures of brain activity as alternative, nonmuscular channels for conveying the user's intent to devices such as simple word-processing programs. People with ALS can learn to produce positive or negative shifts in slow cortical potentials (SCPs) and use that control to select among letters or icons.[7,8] However, some patients cannot master SCP control, and for those who can, communication is slow (e.g., two letters per minute). Thus, we are evaluating other BCI methods for patients with ALS.

People without disabilities or with disabilities such as spinal cord injuries can learn to control the amplitudes of mu (8 to 12 Hz) or beta (18 to 26 Hz) rhythms recorded over sensorimotor cortex to move a cursor in one or two dimensions.[9] This study evaluated the possibility that a sensorimotor rhythm–based BCI method might provide patients with ALS with communication that could be faster than that attainable with SCPs or accessible to those unable to use SCPs.

Methods. Four adults who had ALS and were severely disabled (table 1) participated. All gave informed consent for the study, which had been reviewed and approved by the Ethics Committee of the Medical Faculty of the University of Tübingen and the New York State Department of Health Institutional Review Board.

After initial evaluation defined the frequencies and scalp locations of each person's spontaneous mu and beta rhythms, he or she learned cursor control over 3 to 7 months (1 to 2 sessions per week). Table 2 shows the locations and frequencies of the rhythms that patients used for cursor control at the end of training, and the motor imagery they employed to modify rhythm amplitude. The training protocol has been described previously[6,9] and is summarized here.

The patient faced a 43-cm video screen (while reclining in bed or sitting in a wheelchair or normal chair) while scalp electrodes (in a cap) recorded 16 EEG channels (Fp1, Fp2, F3, Fz, F4, T7, T8, C3, Cz, C4, Cp3, Cp4, P3, Pz, P4, Oz[9]) (right-ear reference; bandpass 0.01 to 70 Hz; sampling rate 160 Hz). Each session had eight to fifteen 2- to 3-minute runs separated by 1- to 5-minute breaks. Thus, a typical session lasted 30 to 70 minutes. Each run had 20 to 35 trials. During each trial, the patient was presented with a target consisting of a red vertical bar that occupied the top or bottom half of the right edge of the screen and a cursor on the left edge. The cursor moved steadily across the screen with its vertical movement controlled by sensorimotor rhythm amplitude. Motor imagery (see table 2) reduced rhythm amplitude and thus moved the cursor down, while the no-imagery state did the opposite. The patient's task was to move the cursor to the height of the target so that it hit the target when it reached the right edge. Each trial consisted of a 1-second period from target appearance to the beginning of cursor movement, a 2-second period of cursor movement, a 1-second postmovement reward period during which the target flashed yellow if it had been hit, and a 1-second intertrial interval.

To control vertical cursor movement, one EEG channel over sensorimotor cortex (see table 2) was derived from the digitized data according to a common average reference.[6,9] Every 50 milliseconds, the most recent 400-millisecond segment from this channel was analyzed by an autoregressive algorithm to determine the amplitude in a 3- or 6-Hz wide mu- or beta-frequency band, and this amplitude was used in a linear equation that specified a vertical cursor movement.[6,9] Thus, a vertical cursor movement occurred 20 times per second. Complete data were stored from each trial for offline analysis.

Cranial muscle EMG, which often occurs early in training in healthy people, contaminated several sessions in two patients. It disappeared when they were asked to relax during performance, and the contaminated sessions were omitted from performance analysis.

†Deceased.

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Table 1 *Patient description*

Patient	Age, y	Sex	ALS type	Time since diagnosis	Artificial nutrition	Artificial ventilation	Limb function	Speech
A	65	M	Bulbar	17 mo	Yes	No	Yes	No
B	46	F	Spinal	2 y	Yes	Yes	Minimal	Slow
C	56	M	Spinal	9 mo	Yes	Yes	Minimal	Slow
D	53	M	Spinal	2 y	No	No	Weak	Yes

Each patient's performance was assessed by accuracy (i.e., percentage of trials in which the target was hit) and by r^2 (i.e., the proportion of the total variance of the sensorimotor rhythm amplitude accounted for by target position). Improvement with training was evaluated by linear regression of accuracy over sessions.

Results. Over the initial 20 sessions of training, all four patients acquired sensorimotor rhythm control.[6,9] Table 2 shows the average accuracy for the final three of these 20 sessions for each patient. Every patient far exceeded the 50% accuracy expected by chance ($p < 0.001$ by χ^2). Furthermore, each patient showed significant improvement in accuracy by linear regression ($F > 14.4$, $p < 0.01$).

The figure shows the improvement over training sessions for Patient A and also shows for a session near the end of training the scalp topography of r^2 at the frequency used for cursor control and the voltage and r^2 spectra at the scalp location used for control. Accuracy improves steadily over training, and the sensorimotor rhythm control acquired is focused both topographically and spectrally.

Discussion. All four patients acquired sensorimotor rhythm control. Furthermore, while cortical imaging studies were not available, at least three showed hyperreflexia during the course of their disease, suggestive of cortical involvement.[10] Nevertheless, they were still able to develop control at normal scalp locations and at mu or beta frequencies that were normal or slightly below normal. Although these patients were already severely disabled (see table 1), it remains possible that their control will wane as their disease continues to progress. It also remains to be determined whether people who are already totally locked-in before BCI training can acquire sensorimotor rhythm control.

The performance achieved over 20 sessions by every patient exceeded the 70% accuracy sufficient for using a language support program.[8] Furthermore, the regression analysis (e.g., figure) and previous studies[6,8,9] suggest that performance will continue to improve with further training. Thus, this study indicates that a sensorimotor rhythm–based BCI might help patients with ALS to maintain an acceptable quality of life despite severe disability. For example,

Table 2 *Sensorimotor rhythm control location and frequency band, motor imagery used, and average accuracy for last three sessions for each patient*

Patient	Location	Frequency	Imagery	Accuracy, %
A	CP3	19.5–25.5	Right hand	78
B	CP3	17.5–20.5	Right hand	81
C	CP4	8.5–11.5	Left hand	77
D	Cz	18.5–24.5	Feet	76

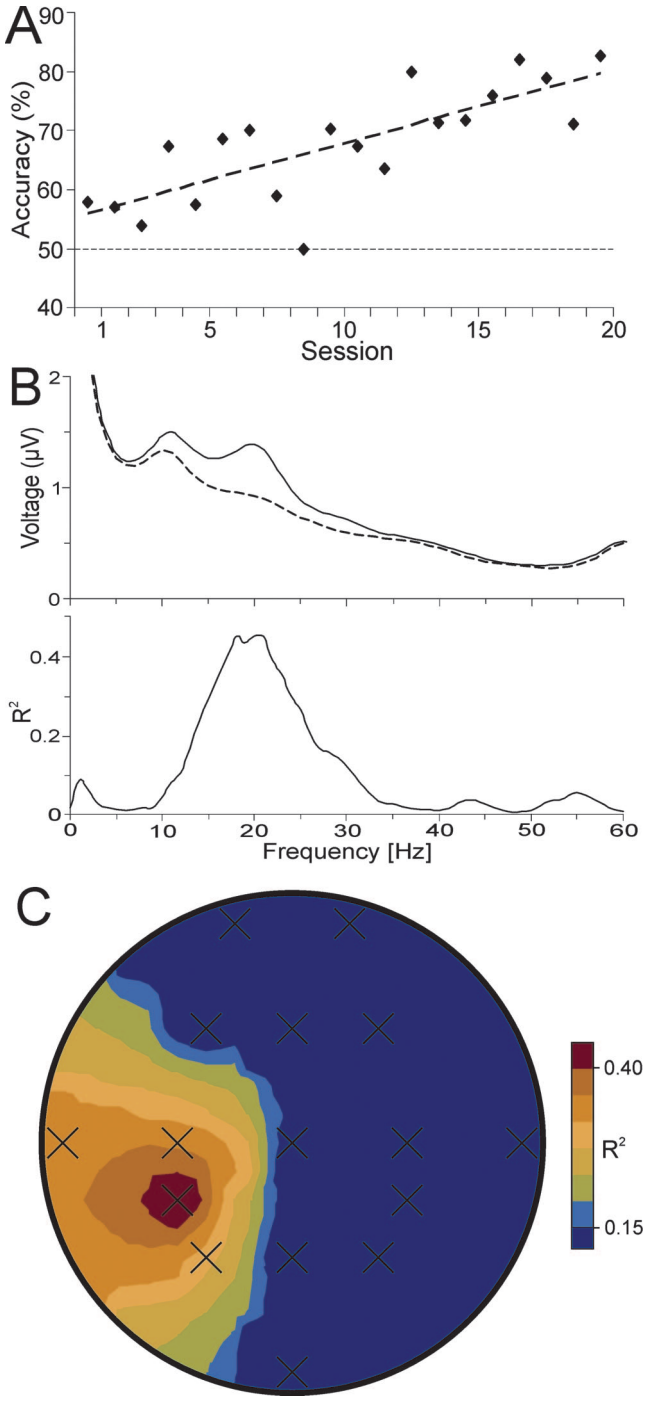

Figure. Representative data from Patient A. (A) Development of control over 20 training sessions. The dashed line shows the significant linear regression (see text). The dotted line is the 50% accuracy expected by chance. (B) Voltage spectra from a session from the control location (CP3) for top (solid) and bottom (dashed) targets and the corresponding r^2 *spectrum. Control is focused in the beta rhythm frequency band. (C) Scalp topography (nose at top) from a session for the 19.5- to 25.5-frequency band. Control is focused at CP3 over left sensorimotor cortex.*

it could enable them to operate an environmental control system or a simple word-processing system more rapidly than usually possible with an SCP-based BCI. Furthermore, it could provide an alternative communication solution for those who cannot master SCP control.

Current studies, which take place principally in patients' homes, are focusing on two goals critical to the eventual clinical significance of BCI communication technology. The first goal is to increase the speed and accuracy of operation, implement initial applications, and demonstrate that they can significantly improve the lives of people with severe motor disabilities. The second goal is to reduce the dependence of BCI training and long-term use on continuing expert oversight and to thereby increase the practicality and reduce the cost of widespread clinical use.

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