A Decision Tree for Brain–Computer Interface Devices

P. R. Kennedy and K. D. Adams

***Abstract*—This paper is a first attempt to present a "decision tree" to assist in choosing a brain–computer interface device for patients who are nearly or completely "locked-in" (cognitively intact but unable to move or communicate.) The first step is to assess any remaining function. There are six inflexion points in the decision-making process. These depend on the functional status of the patient: 1) some residual movement; 2) no movement, but some residual electromyographic (EMG) activity; 3) fully locked-in with no EMG activity or movements but with conjugate eye movements; 4) same as 3 but with disconjugate eye movements; 5) same as 4 but with inadequate assistance from the available EEG-based systems; 6) same as 5 and accepting of an invasive system.**

***Index Terms*—Amyotrophic lateral sclerosis (ALS), brain–computer interface (BCI), beta rhythm, brainstem stroke, electroencephalogram (EEG), electromyogram (EMG), event-related potentials (ERPs), intracortical electrodes, local field potentials (LFPs), locked-in patients, mu rhythm, neurotrophic electrode, slow waves, visual-evoked potentials (VEPs).**

I. INTRODUCTION

Brain–computer interface (BCI) devices provide a communication channel between the brain's activity and a computer, without requiring the usual motor output. BCIs are being developed in order to provide people who are nearly or completely "locked-in" (cognitively intact, but unable to move or communicate) with a method to type text, produce synthetic speech, control their environment, restore movement, or engage in recreational activities. It can be difficult to decide which BCI device is suitable for functional rehabilitation of a severely physically impaired person. In this paper, we consider devices that are now, or soon will be, available for the nearly or completely locked-in person such as those with amyotrophic lateral sclerosis (ALS or Lou Gehrig's Disease) or brainstem stroke. The features of such a decision tree are not necessarily obvious simply from knowledge of the various devices available and their capabilities. Nor is any decision necessarily obvious from a patient's clinical diagnosis. Thus, a decision to choose the most suitable device may best be made based on a functional assessment in combination with an individual patient's preference.

The key step in making a useful functional assessment is to focus on what the patient can do rather than on what the patient cannot do. This is important because functional state may change. In some disorders, such as ALS, abilities may deteriorate quickly over the course of months, or they may remain stable (as in the case of well-known scientist Stephen Hawking.) In other disorders, such as, for example, brainstem stroke in some patients, they may improve. Choosing the optimal BCI depends on functional status. If a patient's function improves, the chosen access device may require less functionality.

The decision tree proposed here applies to static or slowly progressive conditions. We show examples of how to apply this decision tree to ALS and brainstem-stroke patients. Typical alternative access devices include switches (Piezo electric, mechanical, etc.), head pointer systems (infrared, mechanical), speech synthesizer keyboards, and others. This decision tree is not intended for users of alternative computer access devices as described by Anson [1].

TABLE I
DEVICES IN CURRENT USE AND UNDER DEVELOPMENT

Single Unit Recordings	Neurotrophic Electrode, Utah Array, Microwire Bundles
Local Field Potential Recordings	Sub cortical or extra cortical, Subdural or extradural
EEG Based Devices	SCP, Mu, Beta, ERP (P300), VEPs
Muscle Computer Interface	Accepts single fiber, normal or hyperactive EMG

II. DEVICE CATEGORIZATION

If a patient can make isotonic voluntary movements, but cannot use a keyboard, a typical alternative access device such as a switch may be adequate for his/her needs. In this discussion, we focus, instead, on patients who have minimal or no isotonic movement, those with isometric contractions, and those with no muscle electrical activity at all. We have identified six inflexion points that relate to the degree of remaining function. Our decision tree is based on knowledge of a patient's remaining function and on BCI devices that currently exist or are in development [23]. The device categories are described in Table I. They are presented with the highest bandwidth (or high resolution of neural output) devices in the upper rows.

Single unit recording devices are currently being implanted in monkey [2]–[4], rat [5], and human cortices using the neurotrophic electrode [6]. These provide long-lasting recordings of stable robust multiunit activity with high signal-to-noise ratios (SNRs). In humans, they have been used for as long as over 3 yrs. The Utah array, a 10×10 array of tines, is plugged onto the cortical surface to record single units with adequate SNRs, for variable lengths of time [2]. Microwire bundles are inserted along the length of the cortex and single units with adequate SNRs are recorded for variable lengths of time [4]. Devices of this type provide the highest bandwidth because they record from multiple neurons. They are the basis for the electrical potential changes that constitute the electroencephalograpic (EEG) signal recorded over the scalp and the local-field potentials (LFPs).

LFPs are recorded from the cortical surface subdurally [7] or extradurally. These are intermediate bandwidth devices. Subdural devices ought to have a somewhat higher bandwidth than extradural devices inserted through the skull.

EEG-based devices are one of the traditional pursuits of BCI researchers. These devices can be categorized into those that interpret spontaneous EEG rhythms in the frequency domain and those that interpret event-related potentials (ERPs) in the time domain. Examples of the former include the slow-cortical potentials of Birbaumer and colleagues [8], the mu-rhythm detector of the Wadsworth BCI [9], beta detection of the Graz BCI that operates using single-trial imagined movements [10], [11], and others [12], [13]. ERPs include the P300 event detection system [14], [15] and the visual-evoked potentials (VEPs) that receive frequency-specific visual input from icons [16]–[18]. To date, the disadvantage of all these EEG systems is that they can only be used as binary choice systems and not as mouse emulators. Nevertheless, with the speed of single trial EEG, faster access is assured and binary limitations may be mitigated.

Muscle–computer interface devices, including the Muscle Communicator (MC) [19] and the CyberLink, record from a variety of muscle states such as those found in virtually paralyzed muscles or in hyperactive spastic muscle. They are mouse emulators, but can be used as a binary system for scanning or Morse code.

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TABLE II
CLINICAL CONDITIONS ASSOCIATED WITH THE LOCKED-IN SYNDROME

Condition	Locked-in onset	Prevalence USA	Incidence USA	Ventilator
ALS and variants	Gradual	30,000*	4-6/100k**	10%
Brainstem Stroke	Sudden	50,000 approx***	0.8/100k	Usually
Muscular Dystrophy	Gradual	10,000**	1.9-3.4/100k**	Usually not
Cerebral Palsy	Gradual	400,000**	Unknown****	Usually not
Axonal GBS, neuropathies	Sudden	Unknown, low	Unknown	Usually

Sources: *ALS Association, **Eisenberg et al 1999, ***Barnett et al 1998. ****Cerebral Palsy Association figures not forthcoming

III. CLINICAL CONDITIONS

The clinical conditions relevant to the discussion here include ALS and variants (such as spinal muscular atrophy), brainstem stroke, muscular dystrophy, cerebral palsy, axonal neuropathies, axonal Guillian Barre Syndrome (GBS) [20]–[22]. Some properties of these conditions are summarized in Table II. We do not include Multiple Sclerosis because there is usually significant cognitive decline by the time the patients are almost fully paralyzed.

IV. DECISION TREE

The following decision tree incorporates devices published as of June 2002. There are six inflexion points in this process (as shown in Fig. 1).

1) If there is discernible movement of one to three distinct muscles, then typical alternative access devices that require some muscle activity can be used. Note that the MC or EEG could also be used instead or in addition. If three movement (or muscle) sites are available, a mouse-emulating device such as the Mouse Mover can be used. If only two movement (or muscle) sites are available, dual-switch scan or dual-switch Morse code can be used. If only one movement (or muscle) site is available, a single switch (such as a Piezo-electric switch) for scanning or Morse Code can be used. Single or double EMG switches could also be used.[1]
2) If EMG is detectable but there is no discernible movement, the MC can be used. If two muscles are available, the MC with dwell or the double EMG switch in scanning mode can be used. If only one muscle is available, the MC switch can be used. An alternative at each level is an EEG system.
3) If a person has coordinated eye movement, but no discernible movement or EMG activity, an eye gaze system or an EEG system can be used.
4) If there is inadequate eye control and the patient prefers a noninvasive system, EEG should be used.
5) If the EEG system is inadequate and an invasive system is acceptable to the patient, LFP recording systems from extradural or subdural locations can be used. However, these must be implanted before the patient loses all movement, since EMG activity is needed for correlation with the recorded LFPs.
6) If the EEG system is inadequate and the invasive option is acceptable to the patient, and the patient has reached the stage of total paralysis, implanted electrodes, such as the neurotrophic electrode can be used.

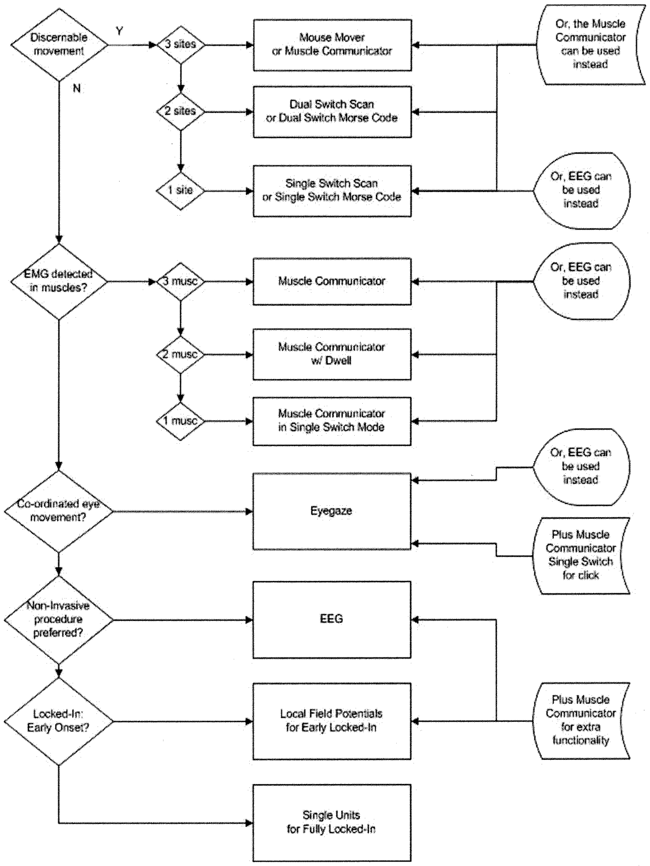

Fig. 1. Decision tree for application of brain–computer interfaces to locked-in patients.

V. CLINICAL EXAMPLES

To examine a typical application of this decision tree, an ALS patient can be used as a first example. According to the ALS Association of America [20] and others [21], there are 30 000 ALS patients in the United States, with an annual incidence of about 6000 per year, and a life expectancy of five years from time of diagnosis. Ninety percent of these patients refuse a ventilator at this stage and elect to die. Those with bulbar ALS (moving limbs but paralyzed respiration, speech and swallowing) more often accept a ventilator (the percentage who make this choice is not known.) With modern medical care, ALS is not a terminal disease. Patients have been kept alive on ventilators for decades (again, Stephen Hawking is an example).

The decision tree for a BCI for an ALS patient is as follows.

1) While the patient can still move, choose the MC or another access device.
2) At this time the patient needs to decide for or against a ventilator.
3) If the decision is against, a device like the MC will suffice until death. If binary mode is acceptable, an EEG system may suffice.
4) If the patient decides in favor of a ventilator, a noninvasive EEG system should be considered if adequate and available for the patient's needs. Alternatively, the MC is considered.
5) If an EEG system is not desired or available, a system for recording LFPs is implanted extra- or subdurally while movements remain available for correlation with the LFPs. Prior to implantation, the patient is trained on the MC using available muscle activity. This activity is correlated with the recorded LFPs after implantation.
6) If the patient is fully paralyzed, LFPs probably cannot be adequately set up. An implanted electrode such as the neurotrophic electrode can then be chosen to provide communication channels.

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[1] EMG Switch, single or double, from Neural Signals Inc., Atlanta, GA 30318.

The brainstem-stroke patient provides a second example. Brainstem strokes constitute a small percentage of all strokes in the U.S., with an annual incidence of about 2500 [22]. The patient is suddenly and completely locked-in. Occasionally, there are dramatic histories of patients assumed to be in a coma, exposed only by the blink of an eye. The pathology of a brainstem stroke is a lesion in the ventral pons or upper medulla that transects the pyramidal motor pathway. This leaves the sensory pathways intact along with intact ascending reticular activating system and, usually, respiratory center. Thus, sleep cycles are normal, sensation is normal, alertness is preserved, and cognition is intact. Most patients either die or recover to a point of using augmentative communication devices. Some walk again. A minority (number is not definitively known) remain locked-in, perhaps as many as 50 000 in the U.S. Fully locked-in patients would benefit from an EEG system or, if binary control is not sufficient, from an implanted electrode. Patients who have slight recovery of EMG activity, with or without slight movement, might be able to use an MC device to provide mouse emulation functions. Another alternative might be eye-gaze system, except that eye movements are rarely conjugate, and nystagmus is common in these patients.

VI. CONCLUSION

This paper presents an initial attempt to define candidacy for the various BCI devices. Although the clinical conditions described here are not likely to change significantly in the near future (although, hopefully, a cure for at least some of them may be possible at some time), there is tremendous potential for dramatic improvements in device capabilities in the near future. For example, it may be possible for single-trial EEG to drive a cursor and not operate solely in the binary mode. Thus, future noninvasive systems may be more efficacious and, therefore, the device of choice. The decision tree described here will have to be modified as device capabilities develop and improve. It will need constant updating as technologies change. It does, however, provide a useful guide based on current knowledge.

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