Assistive Technology: The Official Journal of RESNA
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uaty20

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Published online: 22 Oct 2010.

To cite this article: Kelly Tai MASc , Stefanie Blain BASc & Tom Chau PEng (2008) A Review of Emerging Access Technologies for Individuals With Severe Motor Impairments, Assistive Technology: The Official Journal of RESNA, 20:4, 204-221, DOI: 10.1080/10400435.2008.10131947

To link to this article: http://dx.doi.org/10.1080/10400435.2008.10131947

Asst Technol 2008;20:204–219

A Review of Emerging Access Technologies for Individuals With Severe Motor Impairments

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Research and development in the field of access technologies for individuals with severe motor impairments has accelerated over the past 10 years. Many emergent alternatives to conventional mechanical switches, such as infrared sensing, electromyography, oculography, and computer vision, have been investigated for those retaining some limited volitional motor ability. At the same time, electroencephalography, electrocorticography, intracortical recordings, and electrodermal activity have been explored for those presenting as locked in. The relevant literature is scattered across many disciplines, obfuscating the strength of the clinical evidence in support of the different access technologies currently in development. This article systematically organizes the literature on the aforementioned access technologies, summarizing their underlying operational mechanisms while reviewing the clinical evidence reported between 1996 and 2006. Research evidence within this period is generally found to be at the case study or uncontrolled study level, with very modest sample sizes. Novel mechanical switches and electroencephalography-based access systems dominate the literature, whereas many other movement-based access modalities have emerged with promising early findings. Access methods for those without extant physical movement constitute a critical direction for future and ongoing research efforts.

Key Words: Access technology—Locked-in syndrome—Human-computer interface—Rehabilitation.

Historically, individuals with severe and multiple physical disabilities, whether congenital, traumatic, or disease induced, have had limited independence due in large part to a lack of alternative means of interacting with the surrounding world. Technologies that translate the intentions of the user with profound physical impairments into functional interactions such as communication or environmental control are often referred to as access technologies. In the past century, access technologies have emerged in response to demographic changes subsequent to a number of key historical events (Hobson, 2002), including the polio epidemic of the 1950s and 1960s that paralyzed tens of thousands of individuals and the thalidomide tragedy in which an estimated 10,000 children worldwide were born with severe birth defects (von Moos, Stolz, Cerny, & Gillessen, 2003). At present, the need for access technologies has not waned. Improved care of low-birth-weight infants has increased the number of survivors with severe impairments (Tudehope et al., 1995; Watts & Saigal, 2006), many of whom eventually require access technologies for communication, mobility, and education. The expanding population of older adults is accompanied by a growing burden of disability (Guralnik, Fried, & Salive, 1996) and heightened demand for alternative access strategies. In addition, it is recognized that individuals with locked-in syndrome, most of whom are dependent on access technologies for communication, can survive for many decades (Doble, Haig, Anderson, & Katz, 2003). This article surveys recent developments in the area of access technologies. We focus specifically on technology-mediated solutions for individuals with severe motor impairments, who are often nonverbal. Our attention is further limited to emerging technologies, that is, those that are in the research-and-development stage and, for the most part, not yet commercially available.

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ACCESS TECHNOLOGIES

Because the term *access technology* is used by many disciplines in a multitude of different con-

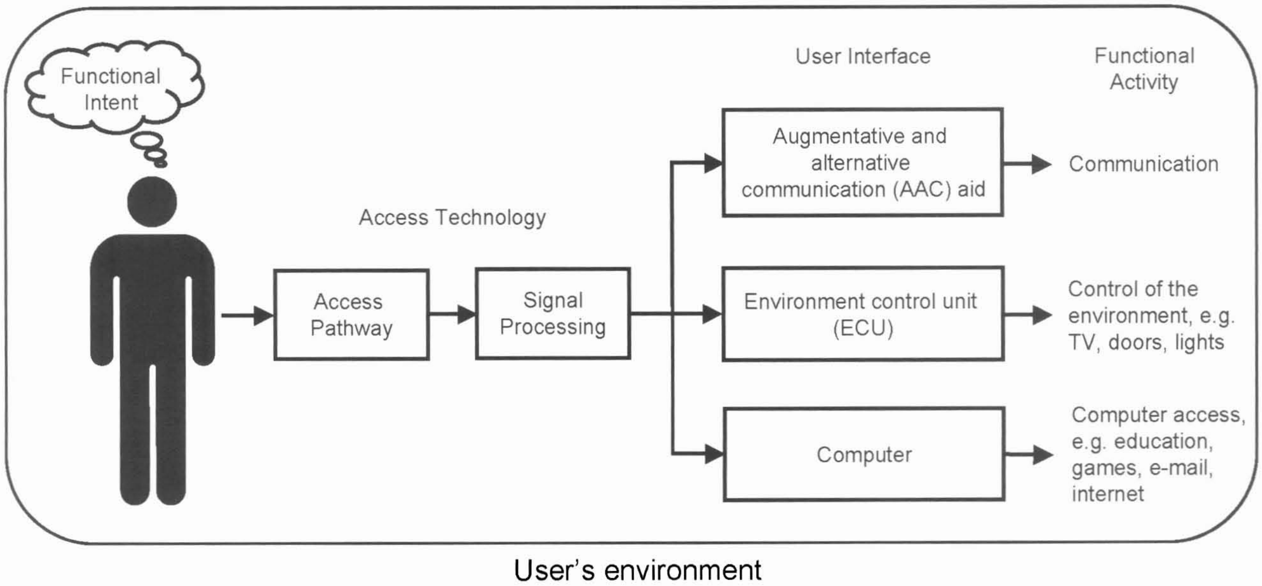

FIG. 1. An access solution: The functional intent of the user is manifested as physical movements and/or physiological changes that are acquired and processed by an access technology; the processed signal is used to drive a user interface, which in turn triggers the execution of an appropriate functional activity within a specific user environment.

texts, we begin by clarifying the definition adopted in this article. As depicted in Figure 1, the technical components of an access solution include an access technology and a user interface technology. The access technology is further composed of (a) an access pathway, that is, the actual sensors or input devices by which an expression of functional intent (e.g., a movement or physiological change) is transduced into an electrical signal, and (b) a signal-processing unit that analyzes (e.g., filtering and pattern classification) the input signal and generates a corresponding control signal. The control signal in turn drives a user interface, which may be an iconic display for an electronic communication aid, a front panel for an environmental control unit, or an on-screen keyboard running on a computer.

As shown in Figure 1, in the broadest sense, an access solution encompasses not only the technology being used but also the user of that technology, the activity being performed, and the surrounding environment (Cook & Hussey, 1995). These four components interact dynamically and should thus be considered when evaluating the effectiveness of an access solution. Causes of severe physical disability necessitating deployment of alternative access solutions include brain-stem injury, spinal cord injury (Beukelman & Mirenda, 1998), spastic quadriplegic cerebral palsy, or progressive motor neuron disease such as amyotrophic lateral sclerosis (ALS), among others.

In this review, we will focus exclusively on access technologies, which, according to Figure 1, constitute the technological front end of an access solution. To structure our review, we classify access technologies according to the physical or physiological abilities to which they cater (Fig. 2). This organization is not unique, nor are the categories necessarily exclusive, and other taxonomies are clearly possible. However, the present classification may be clinically useful in the initial assessment of potential access solutions for a given client. In the present context, a reliable access site is a location in the body where a movement or physiological change can be repeatedly generated at will and is discernible from baseline resting activity.

LITERATURE SELECTION

A preliminary search of the ACM Digital Library, ISI Web of Science, OVID (MEDLINE, CINAHL, EBM Reviews, EMBASE, and Ovid Healthstar), and PubMed using the phrases *brain-computer interfaces, human-computer interfaces,* and *human-machine interfaces* was conducted. We scanned through the key-word lists of articles relating to access technologies and derived the following set of principal key words: *microswitch, head-computer mouse, SEMG (surface electromyography), eye tracking, eye-gaze, face tracking, feature tracking,* and *galvanic skin response* as well as *mechanical switch, infrared sensing, EMG (electromyography), oculography, computer vision, EEG (electroencephalography), ECoG*

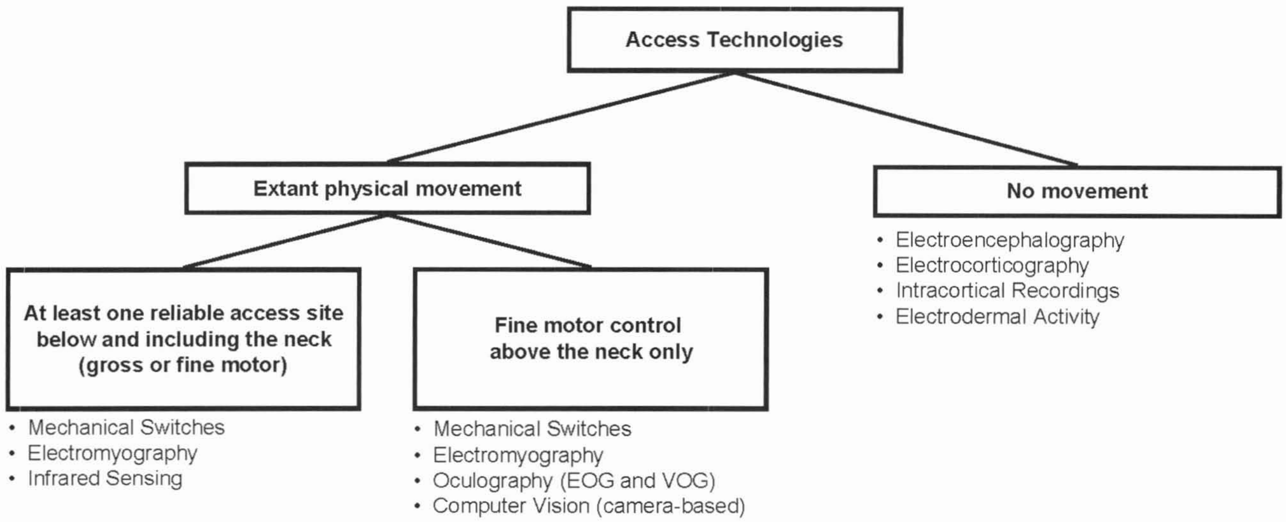

FIG. 2. Categorization of access technologies by the level of physical movement exhibited by the user.

(*electrocorticography*), *intracortical recording,* and *electrodermal activity.* Using these principal key words along with a list of qualifying terms, namely, *locked-in syndrome, assistive technology, rehabilitation,* and *disability,* we searched the aforementioned databases, retrieving 3,462 articles.

For inclusion in the present review, articles must have appeared in peer-reviewed journals dating from 1996 to 2006 that (a) reported specifically on the development of a novel access technology in the communication, computer access, or environmental control domains; (b) incorporated real-time testing with online feedback; and (c) performed clinical testing involving individuals with severe motor disabilities. There was no preference for a specific application domain. In the context of this article, individuals with severe motor disabilities are defined as those whose mobility is limited to residual fine motor control above the neck or movement below the neck sufficient only for single-switch operation. Based on these criteria, 52 articles were extracted for review once overlap between databases was removed.

The ensuing review will roughly adhere to the organization presented in Figure 2. Here, access technologies have been categorized according to the level of extant physical movement achievable by the end user. Options that harness extant movement (left branch of Fig. 2) are further subcategorized on the basis of access site location and movement either above or below the neck. Technologies that accommodate users with no controllable movements (right branch of Fig. 2) are grouped according to their underlying physiological measurement. For each access technology, we will explain the technological principle of operation, review recent studies deploying the technology, and discuss its merits and limitations.

We start with technologies aimed at individuals with the highest level of extant physical movement, that is, those with at least one reliable movement below and including the neck. For this level of physical ability, mechanical switches, electromyography, and infrared sensing have been demonstrated as possible access solutions.

MECHANICAL SWITCHES

In the simplest case, a mechanical switch consists of two or more contacts and an actuator that connects or disconnects the contacts to close or open the switch, respectively. The actuation mechanism may respond to a specific mechanical stimulus, including changes in displacement, tilt, air pressure (e.g., sip and puff), or force. These switches are controlled with an explicit physical movement. A host of mechanical switches are already available for individuals capable of some volitional movement; examples include plate, lever, mercury, tread, string, pillow, and "Jelly Bean" switches (A. Wilson, 1998). However, a number of novel switches and switch-combination strategies have been proposed for those with severe motor impairments.

Lancioni and his collaborators have developed custom switches using position and vibration sensors to target chin (Lancioni, O'Reilly, Sigafoos, et al., 2004; Lancioni, O'Reilly, Singh, Sigafoos, Tota, et al., 2006; Lancioni, Singh, O'Reilly, Oliva, Montironi, et al., 2004) and hand movements (Lancioni, O'Reilly, Singh, Stasolla, et al., 2004; Lancioni, Singh, O'Reilly, & Oliva, 2002; Lancioni, Singh, O'Reilly, Oliva, Baccani, et al., 2002), thereby facilitating access for children with severe disabilities. They have also demonstrated the use of switch clusters, logical combinations of multiple switches (e.g., pressure and tilt) located at different body sites (Antonucci et al., 2006; Lancioni, O'Reilly, Oliva, & Coppa, 2001b; Lancioni, O'Reilly, Singh, Campodonico, et al., 2004; Lancioni, O'Reilly, Singh, Oliva, et al., 2006; Lancioni, Singh, O'Reilly, & Oliva, 2003). Such clusters can be used, for example, to filter out inadvertent switch activations due to inappropriate body positions or involuntary movements.

On a separate front, Perring, Summers, Jones, Bowen, and Hart (2003) developed and exemplified the operation of a self-adjusting accelerometer-based head switch with two patients, one with degenerative motor neuron disease and the other locked-in as a result of traumatic brain injury. Other scientists have employed mechanical switches to design head-operated computer mice. Y. L. Chen (2001) implemented a mouse using tilt sensors to direct cursor movement and a touch switch to generate mouse clicks and found that differences in performance between able-bodied and tetraplegic individuals were not statistically significant. Using gyro sensors to detect angular velocity, Kim and Cho (2002) introduced a hybrid operation mode incorporating both absolute and relative pointing analogous to that of a joystick. Five individuals with disabilities operated the system after 10 min of training.

Generally, the merits of mechanical switches lie in their widespread availability, robustness to everyday wear and tear, and operational simplicity. However, their deployment can be a challenging endeavor as the user may require elaborate positioning aids or mounting systems to secure the switch at the identified access site (A. Wilson, 1998). One major disadvantage of mechanical solutions is that they are designed to harness consistent motor activity of one body part or area. In reality, access site reliability for many users fluctuates over time because of mental (Kennedy, Bakay, Moore, Adams, & Goldwaithe, 2000; Krausz, Scherer, Korisek, & Pfurtscheller, 2003) and physical fatigue (Evans, Drew, & Blenkhorn, 2000; Lancioni & Lems, 2001) or changes in functional abilities (Borasio & Miller, 2001; Ditunno & Formal, 1994). Despite these limitations, mechanical switches remain a promising and relatively inexpensive access technology for those with at least one reliable voluntary movement.

INFRARED SENSING

Infrared (IR) sensing involves the transmission of light in the IR band of the electromagnetic spectrum from a source to a detector. Short-range wireless IR transmission typically employs simple light-emitting diodes to emit IR radiation. Photodiode-based receivers in the line of sight of the transmitter detect radiation and generate a proportional output voltage. A switching mechanism that compares receiver output to a detection threshold voltage may therefore be established. Alternatively, IR reflection can be detected with a single transceiver. Access technologies based on IR sensing commonly require the user to mount a transmission module onto his or her head. The user then aims the emitted beam onto devices designed or modified to receive IR signals.

Y. L. Chen et al. (1999) developed an eyeglass-mounted IR system. Using only head movements, three spinal cord–injured participants with quadriplegia required an average 4.9 $\pm$ 2.0 min to type a short, 97-letter passage with an average accuracy of 94.6%. In a subsequent study, S. C. Chen et al. (2004) tested their IR device with a communication board with six nonverbal individuals with tetraplegia. The average accuracy for a series of selections was 89.7% $\pm$ 5.5%. In both cases, participants received only 10 min of training prior to testing, and performance was deemed comparable to that of able-bodied participants using the same instrument.

On a separate front, Evans et al. (2000) created an IR head-operated joystick that was informally evaluated on nine individuals with disabilities. No quantitative user evaluations were presented. Reilly and O'Malley (1999) implemented a movement detection system using two laser diodes and two charge-coupled device arrays as detectors. Movement of a body part was sensed as changes in the skin speckle reflection of the targeted access site, and hence, the user was not required to wear any accessories. With this system, six participants with tetraplegia completed computer navigation and selection tasks using head or residual movements of certain limbs. Accuracies were not reported, but qualitative feedback from users suggested that the system was responsive and generally comparable to commercial head-mounted access technologies.

More recently, IR sensing has been used with children with severe disabilities as a single-switch access technology to detect eye blinks (Lancioni, O'Reilly, Singh, Oliva, Coppa, et al., 2005) and eyelid movements via an eyeglass-mounted transceiver (Lancioni, Singh, et al., 2006) and chin movements using a transceiver suspended from a hat and positioned just under the chin (Lancioni, O'Reilly, Singh, Sigafoos, Tota, et al., 2006). In all cases, participants maintained a high level of switch activation 2 months following switch introduction.

IR technology can be used to produce relatively low-cost interfaces (Evans et al., 2000). However, there are some noteworthy challenges associated with IR sensing, such as its short range of transmission and blockage by common materials (Lindstrom & Souri, 1998). In addition to requiring a direct line of sight between light source and detector, performance can be affected by ambient IR sources such as sunlight (Kahn & Barry, 1997).

ELECTROMYOGRAPHY

Surface electromyographic (EMG) electrodes record electrical activity generated by muscles at rest and during contraction. Silver/silver chloride (Ag/AgCl) wet electrodes are most commonly used for recording, and they require the application of an electrolytic gel to form a conducting path between electrode and skin.

Gryfe, Kurtz, Gutmann, and Laiken (1996) reported that patients with ALS could control a myoelectric switch using a range of reliable motor activation sites including the interosseus muscles in the hand. In a later study, an EMG-based telephone system was controlled by a spinal cord injury patient via trapezius muscle contraction and relaxation after 30 min of training (Y. Chen, Lai, Luh, & Kuo, 2002). Several groups have also designed and tested human-computer mouse interfaces with able-bodied individuals, using EMG patterns associated with voluntary facial movements (Barreto, Scargle, & Adjouadi, 1999, 2000; Huang, Chen, & Chung, 2006) as well as a combination of facial EMG and eye tracking (Surakka, Illi, & Isokoski, 2004). These systems may be extensible to any patient with adequate facial muscle control, but such remains to be demonstrated.

In principle, a user with a single voluntary muscle contraction could be outfitted with an EMG-based access channel. In practice, the feasibility of such a solution depends largely on the signal-to-noise ratio and, hence, the strength of the muscle contraction (Merletti & Parker, 2004). The integrity of the EMG signal is also affected by motion artifact, muscle cross-talk, perspiration, and variations in electrode/skin contact impedance between electrode applications (Clancy, Morin, & Merletti, 2002). More issues arise when considering long-term usage. Electrolytic gels are cumbersome to apply and dehydrate over time, leading to a reduction in signal quality (Searle & Kirkup, 2000).

For nonverbal individuals limited to fine motor control above the neck, eye trackers or computer vision–based face-tracking systems may facilitate communication and environmental control.

OCULOGRAPHY

Gaze-based communication systems map eye movement or point-of-gaze to cursor position. Video-oculography (VOG) and electro-oculography (EOG) are the dominant technologies incorporated into commercially available eye trackers (Bates, Istance, Oosthuizen, Majaranta, 2005). VOG-based approaches (Lankford, 2000; Rasmusson, Chappell, & Trego, 1999) typically consist of an IR light source and a camera mounted to a computer. Gaze direction is calculated by computing the offset between corneal reflection and pupil centre. VOG's market dominance is likely due to its noninvasiveness and high accuracy (Bates et al., 2005). In systems using EOG (Di Mattia, Curran, & Gips, 2001), electrodes around the eyes measure shifts in potential difference between the cornea and retina that occur when the user changes gaze direction.

There is a paucity of clinical studies on oculography in refereed journals. The majority of the literature identified from our search consisted of conference papers comprising case studies or anecdotal evidence. Based on our evaluation of available literature, the current state of eye-tracking technology is unclear. However, one might argue that its clinical relevance is demonstrated by its growing commercial availability. The increasing prominence of eye tracking in the access technology field is perhaps best illustrated by the formation of Communication by Gaze Interaction (COGAIN) in 2004, an international consortium whose mandate is to promote the use of eye-tracking technology to individuals with severe motor disabilities.

Although eye tracking can facilitate control at speeds comparable to a hand mouse, productivity rates for computer tasks are lower in practice. Input modalities that share one channel for control and observation suffer from the "Midas touch" complex (Jacob, 1991). Such modalities have no intuitive means of differentiating between an input command and other user activity, and errors arise when the system incorrectly interprets user input. Anecdotal reports have cited calibration drift (Majaranta & Raiha, 2002), user fatigue (Bates & Istance, 2003), and insufficient range of motion of the eye as additional factors limiting the usability of eye-tracking devices. Furthermore, EOG is susceptible to the same artifacts and impedance issues as EMG and other surface biopotential measurements (Heckenlively & Arden, 2006).

COMPUTER VISION

A computer vision–based access system tracks the location of a user-identified facial landmark (e.g., nose or pupil) via a camera and translates position changes into cursor movements on a computer screen.

Using a CCD camera, Betke, Gips, and Fleming (2002) developed the Camera Mouse, capable of tracking a number of facial features (nose, lips) as well as other body parts. The system was tested on 12 individuals with severe cerebral palsy and traumatic brain injury; 9 individuals reportedly established control, although additional details on training protocol and evaluation methods were not disclosed. The FaceMouse (Perini, Soria, Prati, & Cucchiara, 2006) used a Web camera to capture images, and a comparative evaluation was conducted on 10 individuals with disabilities. After several hours of training on a virtual speller, the average spelling rate for users was more than two times faster than that achieved on a traditional scanning system. Eleven individuals were qualitatively evaluated on two systems developed by Mauri, Granollers, Lores, and Garcia (2006) based on face and color tracking, respectively. The color tracker operated by detecting the position of a marker attached to a user's access site.

Computer vision has also been employed on able-bodied individuals to detect fine movements, such as eyebrow raises and eye blinks (Grauman, Betke, Lombardi, Gips, & Bradski, 2003; Morris, Blenkhorn, & Zaidi, 2002), that can theoretically act as switches in the target population. Computer vision–based approaches have recently been extended to inexpensive USB Web cameras. The trend toward decreasing hardware costs suggests that computer vision–based solutions may become an affordable access alternative for those with some repeatable neck or facial movements. The robustness of current feature-tracking systems is primarily limited by challenges associated with recovering lost features, which may be caused by changes in user orientation relative to the camera, involuntary movements from the user, feature occlusion, or variations in ambient lighting (Yilmaz, Javed, & Shah, 2006).

When an individual does not have any measurable extant physical movement, there exists the possibility of decoding functional intent through the analysis of various biopotentials.

ELECTROENCEPHALOGRAPHY

EEG is a measure of brain activity recorded from the scalp using surface electrodes and, in principle, encodes functional intent. This nonmuscular access channel is often described as a brain-computer interface (BCI). EEG-based BCIs are currently used in the target population on an isolated case-by-case basis, and its clinical availability is not yet widespread. For a comprehensive review of BCIs using electrophysiological signal features, the reader is referred to Birbaumer (2006).

Present-day BCIs can be categorized on the basis of the signal type extracted, evoked potentials, or consciously modulated spontaneous rhythms. The evoked potential group relies on elicited responses to external stimuli. This genre of BCI does not require extensive user training but significantly constrains user interaction. An example is a BCI based on the steady-state visual evoked potential (SSVEP) capable of detecting one's point of gaze (Wang, Wang, Gao, Hong, & Gao, 2006). The user is presented with a frequency-coded flashing matrix on a computer display, in which each cell flashes at different repetition rates. Visually targeting a specific cell induces an SSVEP at the corresponding frequency. Point of gaze is thus determined by detecting peaks in the amplitude spectrum of the evoked response. Another example is a BCI based on the detection of the P300 event-related potential in response to sequentially flashing arrows for object navigation (Piccione et al., 2006) and flashing rows and columns of letters for spelling (Sellers, Kübler, & Donchin, 2006). Flash visual-evoked potentials (Lee, Wu, Hsieh, & Wu, 2005) and steady-state somatosensory evoked potentials (Müller-Putz, Scherer, Neuper, & Pfurtscheller, 2006) have been proposed as alternative evoked potentials for those with visual deficits.

The second category of BCIs uses potentials that one can intentionally modulate with adequate training. Individuals with severe motor disabilities can be trained to control the amplitude of their slow cortical potentials (Birbaumer et al., 1999; Kaiser, Kübler, Hinterberger, Neumann, & Birbaumer, 2002; Karim et al., 2006; Kübler et al., 1999; Kübler et al., 2001; Kübler, Neumann, Wilhelm, Hinterberger, & Birbaumer, 2004; Neumann & Birbaumer, 2003), that is, low-frequency shifts in EEG activity elicited by external or internal events (Birbaumer, Elbert, Canavan, & Rockstroh, 1990). Individuals with motor impairments can also learn to modulate their sensorimotor rhythms (SMRs; Krausz et al., 2003; Kübler et al., 2005; Miner, McFarland, & Wolpaw, 1998; Neuper, Müller, Kübler, Birbaumer, & Pfurtscheller, 2003; Wolpaw & McFarland, 2004). Remarkably, similar SMR patterns are generated whether a specific movement is executed or simply imagined (Neuper & Pfurtscheller, 2001); the Graz-BCI harnesses this property, decoding changes in SMRs due to motor imagery (Pfurtscheller et al., 2006). Individuals with severe motor impairments have learned to regulate their SMR amplitudes to control cursor movement in one and two dimensions (Miner et al., 1998; Wolpaw & McFarland, 2004). Expanding the area of measurement, the Adaptive Brain Interface (Millán, Renkens, Mourino, & Gerstner, 2004) is controlled by activity in multiple cortical locations correlating to various cognitive tasks, such as mental arithmetic and object visualization. A low-frequency asynchronous design switch developed by the Neil Squire Society (Birch, Bozorgzadeh, & Mason, 2002; Mason, Bohringer, Borisoff, & Birch, 2004) is activated by detecting imagined voluntary movement-related potentials. High-level spinal cord–injured individuals activated the switch using imagined finger flexion, achieving classification accuracies exceeding 94%.

EEG has been popular in BCI research because of its noninvasiveness and high temporal resolution; however, its spatial resolution (Sitaram et al., 2007) and signal bandwidth (Birbaumer, 2006) are limited. BCIs based on spontaneously modulated potentials also have a steep learning curve. Users may require months or years to learn to consciously regulate certain brain activity (Neumann & Kübler, 2003). Physiological factors such as circadian rhythms, hormone levels, and body temperature have been found to affect the variability of electrophysiological signals (Sannita, 2006). Performance deterioration over the course of one session has been reported in several studies (Kennedy, Kirby, Moore, King, & Mallory, 2004; Millán et al., 2004; Shenoy, Krauledat, Blankertz, Rao, & Müller, 2006). Lastly, EEG is susceptible to electrical interference from environmental sources as well as EMG and EOG artifacts (Sanei & Chambers, 2007).

ELECTROCORTICOGRAPHY

Venturing directly to the brain surface, electrocorticographic (ECoG) activity can be recorded from surgically implanted epidural or subdural electrodes. Because ECoG is used to localize epileptic lesions in clinical practice, participants in these types of BCI studies have been limited to individuals in epilepsy surgery programs. In the area of alternative access, Leuthardt, Miller, Schalk, Rao, and Ojemann (2006) demonstrated that one-dimensional cursor control can be achieved by epilepsy patients after brief training, whereas auditory and motor imagery modulation during a cursor-control task (J. A. Wilson, Felton, Garell, Schalk, & Williams, 2006) suggested the possibility of a multimodal ECoG-based BCI.

Advantages of ECoG over EEG include a broader signal bandwidth, a higher spatial resolution, and less susceptibility to artifacts (Crone, Sinai, & Korzeniewska, 2006). However, patients are required to undergo a craniotomy for electrode implantation. Although long-term electrode implantation has not been tested in humans, studies on motor cortex stimulation suggest that chronic implantation is possible without serious side effects (Osenbach, Brewer, & Davis, 2003; Rasche, Ruppolt, Stippich, Unterberg, & Tronnier, 2006).

INTRACORTICAL RECORDINGS

Penetrating beyond the surface of the brain, another class of BCIs harnesses direct neural recordings by way of electrodes chronically implanted in the cortex. One approach consists of obtaining a large-scale recording corresponding to a summation of activity from a population of neurons (Buzsaki, 2004), often referred to in literature as a local field potential (LFP). A more recent development involves the extraction of single-cell activity from the motor cortex for input to prosthetic devices (Schwartz, 2004).

Neurotrophic recording electrodes that detect LFPs were tested by Kennedy et al. (2000, 2004) on three individuals with neuromuscular disorders. One individual demonstrated long-term two-dimensional control of a computer cursor (Kennedy et al., 2000) and a computer-simulated digit (Kennedy et al., 2004). Pilot clinical trials of a neuromotor prostheses system based on the detection of neuronal ensemble activity have produced encouraging results (Hochberg et al., 2006). The first trial participant manipulated a cursor to open simulated e-mail, play video games, and control a television set. Cursor control speed and accuracy were also evaluated, with the participant achieving an accuracy of 73% to 95% at speeds comparable to that of able-bodied individuals using a computer mouse.

Although earlier studies on intracortical approaches did not report significant improvements in performance over noninvasive BCIs (Birbaumer et al., 1999), recent studies suggest that intracortical recordings can support BCIs that (a) provide greater degrees of freedom than EEG and ECoG-based BCIs and (b) facilitate voluntary control while the user is performing other motor or cognitive tasks (Hochberg et al., 2006). However, reliable multielectrode recording systems are still at an early stage of development, and accessing the action potentials of individual neurons presents formidable challenges (Donoghue, 2002). Electrode tips must be placed proximal to the signal source and maintain long-term contact. Safety of the implantation procedure and postoperative risks such as tissue infection and scar tissue encapsulation remain important considerations.

ELECTRODERMAL ACTIVITY

Electrodermal activity (EDA) refers to changes in skin conductivity mediated by the autonomic nervous system. The most established measurement technique involves passing an external DC current between a pair of electrodes placed on the skin's surface and recording conductance changes in the skin. The recorded signal can be subdivided into a baseline signal modulated by circadian rhythms (Hot, Naveteur, Leconte, & Sequeira, 1999) and transient changes (electrodermal responses [EDRs]) associated with sweat gland hydration elicited by sympathetic nervous activity (Fowles, 1986).

Both components of the EDA signal have been evaluated as a potential method of access for locked-in individuals. Tsukuhara and Aoki (2002) examined the possibility of using event-related EDRs in a cue-based interface. EDA was recorded in individuals with cerebral palsy as they were asked to focus on a target letter while presented with a scanning sequence of single letters. Based on the hypothesis that the target letter would generate the largest EDR, the investigators correctly predicted 47% of the letters selected by the participants. Moore and Dua (2004) conducted a series of long-term characterization studies on a locked-in patient and reported that with training, baseline EDA signals can be consciously raised and lowered as a means of communication. The patient generated a binary response every 45 s with an accuracy of 61.78%.

Although EDA can potentially be a reliable access channel for locked-in individuals, it is unconsciously generated in response to a range of activities such as affective processes (Boucsein, 1992), memory recall (Homma, Matsunami, Han, & Deguichi, 2001), and startling and threatening stimuli (Edelberg, 1973). Habituation has been cited as another limiting factor (Seto-Poon et al., 2005).

DISCUSSION

Strength of Evidence

We identified 52 articles published from 1996 to 2006 that reported some level of clinical evidence relating to technological advances in access technologies. Owing to the small segment of the general population who exhibit severe motor disabilities, the majority of studies had small sample sizes, as shown in Table 1. Of the articles that reported the number of participants tested, 56.5% (26 of 46 articles) recruited no more than two individuals with severe motor impairments. Meaningful comparisons across genres of access technologies are inherently difficult to draw with such modestly sized studies. Further exacerbating the issue, performance with an access technology depends on multiple personal and environmental factors besides the technology being used (Cook & Hussey, 1995), and each research group tends to employ a different evaluation method. On a positive note, Figure 3 indicates that the number of published clinical studies has increased significantly over the past 10 years. However, as shown in Table 2, the overall strength of evidence (Oxman, 1994) regarding the clinical efficacy of different access modalities remains low, with the majority of studies presenting Level IV (nonrandomized study without concurrent control group) or Level V (single case study) evidence.

From Table 2, we further note that, at the time of writing, there is very little research documenting clinical testing of oculography and electrocorticography with patients. This is particularly surprising in the case of oculography, given that some commercial systems have already surfaced. In any case, more controlled studies of the different access technologies are required to guide clinical decision making and policy formulation around device funding.

Research Challenges

Noninvasive options most studied for individuals lacking extant physical movement are by and large limited to EEG-based BCIs (Fig. 4). The dearth of literature on alternative noninvasive approaches suggests that increased research efforts in this direction are needed. Near-IR spectroscopy (Coyle, Ward, & Markham, 2007; Sitaram et al., 2007) and salivary pH (Wilhelm, Jordan, & Bir-

TABLE 1. **Summary of reviewed articles with clinical evidence reported between 1996 and 2006**

Access technology	Scientific principle/mechanism	Number of studies	Number of subjects (average)	Duration of evaluation (range)
Mechanical switches	Two or more contacts and an actuator that connects or disconnects the contacts in response to a mechanical stimulus	13	2	1 session–4.5 months
IR Sensing	Transmission of IR light from a source to a detector; switching mechanisms can be established by comparing detector output to a detection threshold	7	4	1 session to 2 months
EMG[a]	Electrical activity generated by muscles at rest and during contraction recorded through the skin	5	1	1 session
Oculography[b]	Detection of eye movement via computation of offset between corneal reflection and pupil center (VOG) or changes in potential difference between the pupil and cornea (EOG)	NA	NA	NA
Computer vision	Location of user-identified landmark tracked and translated into computer cursor movement	3	11	1 to 8 sessions
EEG	Electrical activity generated by neuronal firing in the brain recorded through the scalp	18	4	1 session to 7 months
ECoG[c]	Electrical activity generated by neuronal firing in the brain recorded through epidural or subdural electrodes placed on the brain surface	2	NA	NA
Intracortical recordings	Neuronal firing in the brain recorded through electrodes implanted in the cortex	3	1	9 to 17 months
EDA	Fluctuations in skin resistance modulated by the autonomic nervous system	1	5	1 session

Note: EMG = electromyography; VOG = video-oculography; EOG = electro-oculography; NA = not applicable; EEG = electroencephalography; ECoG = electrocorticography; EDA = electrodermal activity.

[a]Four studies with an undefined number of subjects were excluded from summary statistics.

[b]Studies returned in the literature search were limited to case studies or anecdotal evidence in conference proceedings.

[c]Studies returned in the literature search were limited to patients in epilepsy surgery programs.

baumer, 2006) have shown early promise as access channels for locked-in individuals and may help to fill this void. With the exception of Wilhelm et al. (2006), who tested on one participant with locked-in syndrome, at the time of writing, there have been no other reported trials using these technologies with individuals with disabilities. The large number of published studies on mechanical switches is due in part to one research group, Lancioni and colleagues. Other reviewed modalities do not have sufficient evidence to encourage clinical adoption. Our literature search yielded seven or fewer studies for each of these modalities in the past 10 years.

Several common technical shortcomings were identified across genres of access technologies. The challenge of distinguishing between voluntary and involuntary activity is prevalent in modalities that require extant user movement, as well as those that share one access channel for control and observation. One strategy for circumventing inadvertent activation is to increase the number of independent control signals available to the user by incorporating multiple access channels into a single interface. Such multimodal interfaces may also be better equipped to accommodate the dynamic needs of the user. Environmental sources of signal interference remain a design challenge for many access technologies. The inability to accommodate fluctuations in user input—whether mediated by instrumentation or physiological factors—is a drawback of access technologies based on surface biopotentials and manifests itself as calibration drift in IR sensing and eye/facial feature tracking.

Limitations and Context of the Review

Because this review is restricted to access technologies that harness physical movements or phys-

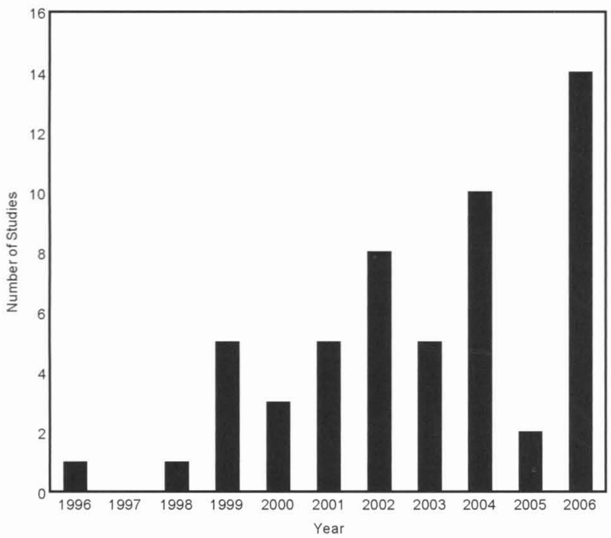

FIG. 3. Number of studies by year.

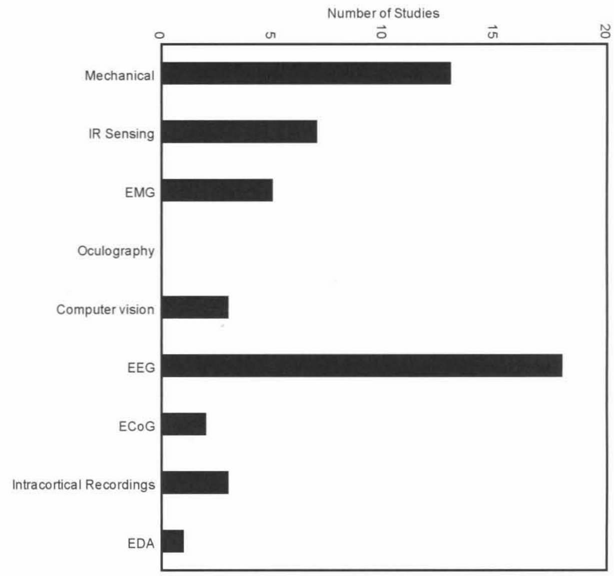

FIG. 4. Number of reviewed studies by genre of access technology.

iological changes in a manner suitable for nonverbal individuals with severe motor impairments, only a subset of technologies falling under the conventional umbrella classification of access technologies has been considered. For example, literature on innovations around voice-activated switches for individuals with severe dysarthria (Lancioni & Lems, 2001; Lancioni, O'Reilly, Oliva, & Coppa, 2001a; Lancioni, Singh, O'Reilly, Oliva, Piazza, et al., 2004; Lancioni, Singh, O'Reilly, Sigafoos, et al., 2004) and evaluations of speech recognition–based access (Havstam, Buchholz, & Hartelius, 2003; Koester, 2004) have not been included in this review. In addition, the experimental methods in a number of reviewed articles were not comprehensively documented and were therefore excluded from the compilation of summary statistics shown in Table 1. It is also important to note that the statistics for several genres of access technologies are biased by the high publication count of one or few research groups. Although this review is limited to journal articles, it is recognized that clinical evidence in the access technologies field often resides in non–peer-reviewed conference papers and commercial literature, neither of which were included.

In the grand scheme of an access solution, we reiterate that the present review has focused only on the access technology component, the front end of an access solution, as depicted in Figure 1. The reader is alerted to the important, complementary advances in user interface technologies for access solutions, including innovations in scanning strategies (Lesher, Moulton, & Higginbotham, 1999), automatic correction of input errors (Trewin, 2002), and pattern recognition–based switch processing (Yang, Luo, Yang, & Chuang, 2004). Additional insight into readily available access solutions can be gleaned from studies comparing commercial access technologies and interface elements such as head-tracking systems (DeVries, Deitz, & Anson, 1998) and off-the-shelf graphic symbol sets (Alant, Life, & Harty, 2005). Furthermore, the success of an access solution not only requires suitable technology but hinges on appropriate user training (Jones & Stewart, 2004), for example, by contingent stimulation (Lancioni, Comes, et al., 2005; Lancioni, O'Reilly, et al., 2002; Lancioni, O'Reilly, Singh, Oliva, Scalini, & Groeneweg, 2005; Lancioni, O'Reilly, Singh, Oliva, Scalini, Vigo, et al., 2005; Lancioni, O'Reilly, Singh, Sigafoos, Oliva, et al., 2006; Lancioni, O'Reilly, Singh, Scalini, et al., 2005; Lancioni, Singh, Oliva, Scalini, & Groeneweg, 2003). Meticulous documentation of technology usage, often facilitated by language activity monitoring in augmentative and alternative communication (AAC) systems (Hill & Romich, 2001), is also instrumental to evidence-based intervention. Clearly, reviewing all these complementary areas is beyond the scope of a single paper. Nonetheless, the reader is encouraged to survey these related topics to obtain a comprehensive perspective of contemporary access solutions.

CONCLUSION

The present article has systematically appraised the diffuse literature on access technologies for individuals with severe motor disabilities spanning

TABLE 2. Summary of key findings on access technologies

Access technology	Key findings	Limitations	Maximum level of available evidence[a]
Mechanical switches	Subtle chin and eye movements can be harnessed effectively using position and vibration switches (e.g., Lancioni, O'Reilly, Sigafoos, et al., 2004; Lancioni, Singh, O'Reilly, Oliva, 2002)	Positioning aids or mounting systems required for securing switch at identified access site (A. Wilson, 1998)	Level III
	Switch clusters can be exploited to filter out involuntary movements of certain body parts (e.g,. Lancioni et al., 2001b)	Access site reliability for many users fluctuates because of fatigue or changes in functional abilities over time (e.g., Borasio & Miller, 2001; Evans et al., 2000; Kennedy et al., 2000)	
	Tilt and gyroscopic sensors can be used for computer access (Y. L. Chen, 2001; Kim & Cho, 2002)		
IR sensing	IR sensors can serve as absolute and relative pointing devices, noninvasive motion detection systems, and optical switches (e.g., S. C. Chen et al., 2004; Evans et al., 2000)	Requires direct line of sight between source and detector (Lindstrom & Souri, 1998)	Level III
		Performance affected by ambient light sources (Kahn & Barry, 1997)	
EMG	Interosseus (Gryfe et al., 1996), trapezius (Y. Chen et al., 2002), and facial (Barreto et al., 2000) muscles have served as successful myoelectric access sites	Signal integrity affected by motion artifacts, cross-talk, perspiration, and variations in electrode/skin contact impedance between electrode applications (Clancy et al., 2002)	Level V
		Electrolytic gel dehydrates over time, leading to a reduction in signal quality (Searle & Kirkup, 2000)	
Oculography	Paucity of clinical studies using VOG- and EOG-based eye trackers	Inability to distinguish input commands from other user activity, resulting in unintended cursor movement (Majaranta & Raiha, 2002)	NA[b]
		Calibration drift, user fatigue, and insufficient range of motion cited in anecdotal reports (Bates & Istance, 2003; Majaranta & Raiha, 2002)	
Computer vision	Mouse emulation can be achieved via facial feature tracking using low-cost cameras (Betke et al., 2002; Perini et al., 2006)	Difficulty recovering lost features caused by changes in user orientation and ambient lighting and involuntary user movement (Yilmaz et al., 2006)	Level IV
EEG	Evoked potentials relying on elicited responses to visual stimuli demonstrated as access channel for individuals with severe motor disabilities (e.g., Wang et al., 2006)	Conscious regulation of brain activity may take months/years to acquire (Neumann & Kübler, 2003)	Level III

TABLE 2. Continued

Access technology	Key findings	Limitations	Maximum level of available evidence[a]
	Spontaneous EEG using self-modulated potentials deployed to locked-in individuals (e.g., Neumann & Kübler, 2003)	Physiological factors influence electrophysiological signal variability (Sannita, 2006) Signals susceptible to electrical interference from environment and motor artifacts (Sanei & Chambers, 2007)	
ECoG	One-dimensional cursor control achievable by epilepsy patients (Leuthardt et al., 2006)	Electrode implantation in humans demonstrated for only short-term use (e.g., J. A. Wilson et al., 2006)	NA[c]
Intracortical recordings	Long-term two-dimensional control demonstrated by one individual with neuromuscular disorder using neurotrophic recording electrodes implanted in the motor cortex (Kennedy et al., 2000) One individual demonstrated cursor control using neuroprosthesis (Hochberg et al., 2006)	Multielectrode recording systems at an early stage of development; safety of implantation procedure safety and postoperative risks remain important considerations (Donoghue, 2002)	Level V
EDA	Long-term control of baseline EDA signals achievable by an individual with locked-in syndrome (Moore & Dua, 2004)	Confounded by involuntary responses to affective processes, memory recall (Homma et al., 2001), and habituation (Seto-Poon et al., 2005)	Level III

Note: IR = infrared; EMG = electromyography; VOG = video-oculography; EOG = electro-oculography; NA = not applicable; EEG = electroencephalography; ECoG = electrocorticography; EDA = electrodermal activity.
[a]Based on clinical practice guidelines as defined by Oxman (1994).
[b]Studies returned in the literature search were limited to case studies or anecdotal evidence in conference proceedings.
[c]Studies returned in the literature search were limited to patients in epilepsy surgery programs.

the 10-year interval from 1996 to 2006. We find that mechanical switches are well established clinically, and recent switch innovations continue to harbor supportive evidence. With a significant volume of research, EEG-based access methods continue to advance, making clinical inroads incrementally. Generally, research on access technologies such as electrocorticography and intracortical measurement for those without volitional motor control has been steadily expanding. Overall, clinical evidence for different access technologies is presently based on case studies and uncontrolled experiments. More studies invoking emerging access technologies for those without extant physical movement, such as near-IR spectroscopy or electrodermal activity, are needed to fully ascertain their potential.

Acknowledgments: This work was supported in part by Bloorview Children's Hospital Foundation, the Natural Sciences and Engineering Research Council of Canada, the REMAD Foundation, and the Canada Research Chairs Program.

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Quiz 20.4a

Name______________________________

Quiz 20.4a A Review of Emerging Access Technologies for Individuals with Severe Motor Impairments

1. Technologies that translate the intentions of the user with profound physical impairments into functional interactions such as communication or environmental control are often referred to as ______________ technologies.
   A. intuitive
   B. novel
   C. access

2. These mechanical switches are controlled with _____________________________ movement.
   A. explicit physical
   B. subtle physical
   C. implicit internal
   D. explicit emotional

3. True/False. The deployment of mechanical switches can be a challenging endeavor as the user may require elaborate positioning aids or mounting systems to secure the switch at the identified access site.

4. True/False. Because of several significant limitations, in addition to being more expensive than some other viable alternatives, mechanical switches have become a less popular access technology alternative for those with at least one reliable voluntary movement.

5. Infrared (IR) reflection can be detected with:_____________________________
   A. a single transceiver
   B. no transceiver
   C. multiple transceivers

6. True/False. IR technology can be used to produce relatively low-cost interfaces. However, some challenges associated with IR sensing present themselves, such as its short range of transmission and blockage by common materials.

7. The following were cited as factors limiting the usability of eye-tracking devices:
   A. user fatigue
   B. calibration drift
   C. insufficient range of motion of the eye
   D. all of the above
   E. A and B only

8. True/False. A computer vision-based access system tracks the location of a user-identified facial landmark (e.g., nose or pupil) via a camera and translates position changes into cursor movements on a computer screen.

9. The __________________ was developed and is capable of tracking numerous facial features (nose, lips, etc.) as well as other body parts.
   A. the Motion Moose
   B. the Camera Mouse
   C. the Photo Tracker

10. True/False. EEG has been popular in BCI research because of its noninvasiveness and high temporal resolution; however, its spatial resolution and signal bandwidth are very limited.

11. _________________________ refers to changes in skin conductivity mediated by the autonomic nervous system.
    A. Electrothermal activity (ETA)
    B. Hypodermal activity (HDA)
    C. Electrodermal activity (EDA)
    D. Electromagnetic activity (EMA)

12. True/False. The success of an access solution not only requires suitable technology, but also hinges on appropriate user training, for example, by contingent stimulation.