Graduate thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences
Department of Neuromedicine and Movement Science

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Assistive technology for the physically impaired

Current and emerging trends in assistive technology and control mechanisms for patients with loss of motor function

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Supervisor: Tore Wergeland Meisingset
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1. Background

Neurological disorders are the leading cause of disability worldwide, accounting for between 247 million and 308 million disability-adjusted life years globally (1). The course of many of these disorders may involve partial or complete loss of voluntary motor function in one or several muscles. Thus, their manifestations range anywhere from localized muscle weakness in a single muscle to locked-in-syndrome. Patients with progressive neurological diseases such as amyotrophic lateral sclerosis (ALS), multiple sclerosis progressive type (MS) and spinal muscular atrophy (SMA) typically experience a gradual decline in such functions, whereas physical disability remains quite constant in disorders such as cerebral paresis (CP). In neurological disorders with an acute onset, such as traumatic brain injury (TBI), traumatic spinal cord injury (TCI) and stroke, one may even expect patients' motor function to improve in the months following initial hospitalization and later stabilize, particularly if adequate rehabilitation is provided. In other words, neurological disorders which cause motor impairments are a vastly heterogenous group in terms of initial presentation, course and prognosis, and these patients may require highly individualized disease management in order to maintain an acceptable quality of life throughout the course of their affliction.

The purpose of adaptive equipment is to compensate for a loss of function. A wide variety of adaptive equipment can be used by patients with physical impairments, including computer hardware and software, mobility aids and orthotic devices, and environment control solutions. Such equipment facilitates patient independence from caregivers when performing activities of daily living (ADL) like dressing, feeding and personal hygiene, as well as instrumental activities of daily living (IADL), such as communication with others, household management and transportation. In the World Health Organization's cross-cultural quality of life questionnaire WHOQOL-100, 4 out of the 100 questions deal with the performance of ADL (2). Several other questions are related to IADL either directly or indirectly, for instance "to what extent do you have problems with transport?" and "how satisfied are you with your opportunities to learn new information?", respectively. The inclusion of ADL in this quality of life assessment implies that assistive technology or the lack thereof may substantially affect the individual patient's quality of life.

In addition to serving a wide variety of purposes, adaptive equipment can be operated by means of various types of control mechanisms, depending on the extent of the user's disability. The input for such a control mechanism can in theory be obtained from any point in the chain of transmission between cerebral cortex and effector muscle. Most control mechanisms currently in use in assistive technology rely on the very endpoint of this chain of transmission, which is muscular force generation; examples include, but are not limited to pressure-activated switches, pedals, joysticks, air flow sensors, voice control, eye movement tracking and accelerometers. If adequately controlled force generation is not feasible, the options are limited to electrode-driven control mechanisms capable of translating muscular or neural action potentials into equipment input, such as a switch activated by electromyographic signals. A number of implantable brain-computer interfaces (BCI) have been or are being developed. These constitute a possible "last resort" in that they require no neuromuscular function beyond the generation of cortical activity. A large arsenal of available control mechanisms provides greater flexibility when tailoring adaptive equipment solutions to the needs and abilities of an individual patient.

Herein, we aim to review the current and near future state of control mechanisms in adaptive equipment for patients with neurological disorders which cause paresis or paralysis. The review will include a disability-oriented systematization of assistive technology and control mechanisms, and reflections around the utility, ease of use, cost and medical risk associated with currently or imminently available control mechanisms in assistive technology.

2. Materials and methods

A series of interviews was conducted with professionals involved in the production, sale and ordination of adaptive equipment for disabled patients in order to elucidate the current state of available adaptive equipment in our region (Table 1). These interviews were not conducted according a predetermined questionnaire, but in an open-ended, conversational fashion to highlight each professional's area of expertise and views on the current state of the assistive technology field.

Name	**Role/profession**	**Affiliation**
Mari-Anne Myrberget	Occupational therapist	St. Olav University Hospital
Alf Aksel Nøst	Technical advisor	NAV Assistive Technology Centre
Bjørnar Gjerde	Marketing representative	Picomed
Roy Staven	User representative	The Norwegian Association of Disabled
Henrik Hansson	Sales representative	Tobii Dynavox
Tobias Stærmose	Researcher	Aarhus University
Truls Johansen	Occupational therapist	Sunnaas Hospital
Jane Svartskuren	Special educator	Sunnaas Hospital
Laurie Paquet	Sales representative	Kinova

Table 1. Names of interview subjects working in the assistive technology field, along with their professional titles/roles and main institutional/industrial affiliation.

Three comprehensive literature searches were conducted. Two were performed in the multidisciplinary database SCOPUS, with the following search syntaxes:
"((KEY (*disease** OR *disability** OR *mobility** OR *paralysis**)) OR (TITLE (*disease** OR *disability** OR *mobility** OR *paralysis**))) AND ((KEY (*"assistive technology*"* OR *"adaptive equipment*"* OR *"self-help device*"*)) OR (TITLE (*"assistive technology*"* OR *"adaptive equipment*"* OR *"self-help device*"*))) AND *"nervous system disease*""*

((KEY (*disease** OR *disability** OR *mobility** OR *paralysis**)) OR (TITLE (*disease** OR *disability** OR *mobility** OR *paralysis**))) AND ((KEY (*"assistive technology*"* OR *"adaptive equipment*"* OR *"self-help device*"*)) OR (TITLE (*"assistive technology*"* OR *"adaptive equipment*"* OR *"self-help device*"*))) AND (LIMIT-TO (DOCTYPE , *"re"*))

A search was also performed in the medical database PubMed with the syntax "*(nervous system diseases[MeSH Terms]) AND (self-help devices[MeSH Terms])"* and filtered to only include review and systematic review articles. The search and article selection process is detailed in Figure 1. Ultimately, 30 papers were read in their entirety and used in this review; these are summarized in Table 2. Targeted literature searches in the aforementioned research databases were also conducted to elaborate on or corroborate information gathered during interviews.

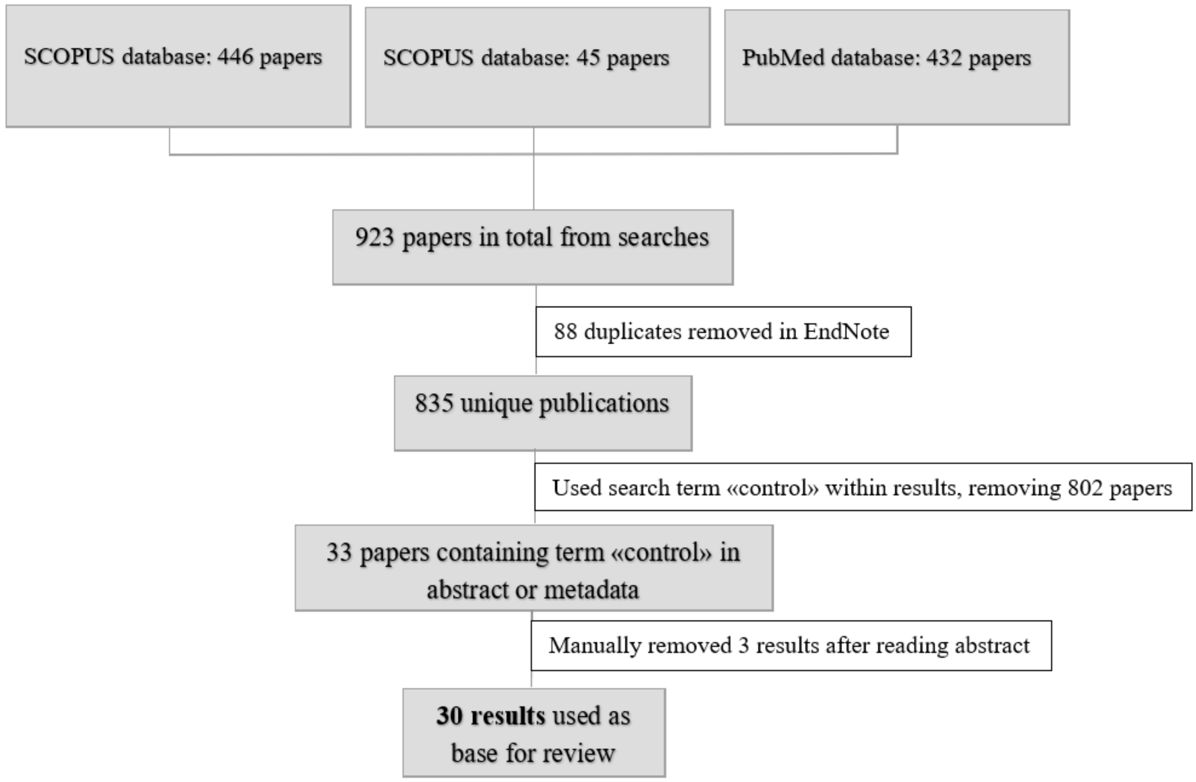

Figure 1. Visualized paper selection process from database search.

Title	Author	Year	Subject
Multiple control mechanisms			
Bioengineering and spinal cord injury: a perspective on the state of the science	Cooper, R.A.	2004	Bioengineering advances in assistive technology for spinal cord injury patients.
A review of emerging access technologies for individuals with severe motor impairments	Tai, K. et. al.	2008	Control mechanisms for assistive technology.
Trends in communicative access solutions for children with cerebral palsy	Myrden, A. et. al.	2014	Control systems for alternative and augmentative communication.
New and emerging access technologies for adults with complex communication needs and severe motor impairments: State of the science	Koch Fager, S. et. al.	2019	Control systems for assistive devices.
Integrated control and related technology of assistive devices	Ding, D. et. al.	2003	Utilization of a single control system for multiple devices.
Environment control			
The efficacy and benefits of environmental control systems for the severely disabled	Craig, A. Tran, Y. McIsaac, P. Boord, P.	2005	Environment control.
Assistive devices			
Review of control algorithms for robotic ankle systems in lower-limb orthoses, prostheses, and exoskeletons	Jiménez-Fabián, R. Verlinden, O.	2012	Algorithms mimicking human gait patterns in ankle-stabilizing assistive devices.
Assistive technologies: can they contribute to rehabilitation of the upper limb after stroke?	Farmer, S. E. et. al.	2014	The effect of assistive technology use on upper limb impairment after stroke.

A review in gait rehabilitation devices and applied control techniques	Chaparro-Cárdenas, S. L. et. al.	2018	Algorithms mimicking human gait patterns in powered lower-limb exoskeletons for rehabilitation.
Mechanical control mechanisms			
Further evaluation of microswitch clusters to enhance hand response and head control in persons with multiple disabilities	Lancioni et. al.	2005	Strategic positioning of paired mechanical switches for device control.
Vision based interface system for hands free control of an intelligent wheelchair	Ju, J. S. et. al.	2009	Device control utilizing facial and neck musculature.
Joystick Control for Powered Mobility: Current State of Technology and Future Directions	Dicianno, B. E. et. al.	2010	Joystick control in mobility aids.
Eye movement tracking			
Electrooculograms for Human-Computer Interaction: A Review	Chang, W. D.	2019	Electrophysiological eye movement tracking for computer access.
Brain-computer interfaces			
Applications of cortical signals to neuroprosthetic control: a critical review	Lauer, R. T. et. al.	2000	Brain-computer interfaces for assistive devices.
Brain-machine interfaces: past, present and future	Lebedev, M. A. Nicolelis, M. A.	2006	Potential and limitations of brain-computer interfaces.
Assistive technology and robotic control using motor cortex ensemble-based neural interface systems in humans with tetraplegia	Donoghue, J. P. et. al.	2007	Brain-computer interfaces for assistive devices.
Brain-computer interfaces as new brain output pathways	Wolpaw, J.R.	2007	Potential and limitations of brain-computer interfaces.
Brain-computer interfaces in the continuum of consciousness	Kübler, A. Kotchoubey, B.	2007	Utility of brain-computer interfaces in cognitively impaired patients.
Brain-computer interfaces: communication and restoration of movement in paralysis	Birbaumer, N. Cohen, L. G.	2007	Brain-computer interfaces for assistive devices.
Functional source separation and hand cortical representation for a brain-computer interface feature extraction	Tecchio, F. Porcaro, C. Barbati, G. Zappasodi, F.	2007	Adaptation of brain-computer interfaces for substituting hand movement.
Brain-computer interface in paralysis	Birbaumer, N. et. al.	2008	Brain-computer interfaces for assistive devices.
Brain-computer interfaces in neurological rehabilitation	Daly, J. J. Wolpaw, J. R.	2008	Brain-computer interfaces in rehabilitation devices.
EEG-based brain-computer interfaces: an overview of basic concepts and clinical applications in neurorehabilitation	Machado, S. et. al.	2010	Brain-computer interfaces in rehabilitation devices.
Review of wireless and wearable electroencephalogram systems and brain-computer interfaces--a mini-review	Lin, C. T. et. al.	2010	EEG-based brain computer interfaces and wireless technology.
An EEG-based brain computer interface for rehabilitation and restoration of hand control following stroke using ipsilateral cortical physiology	Fok, S. et. al.	2011	Presentation of a brain-computer interface which controls a hand orthosis using scalp-based EEG.

Brain-computer interfaces for neurorehabilitation	Sreedharan, S. et. al.	2013	Brain-computer interfaces in rehabilitation devices.
Application of BCI systems in neurorehabilitation: a scoping review	Bamdad, M. et. al.	2015	Brain-computer interfaces in rehabilitation devices.
Brain-computer interfaces for communication and rehabilitation	Chaudhary, U. et. al.	2016	Brain-computer interfaces in assistive technology.
Other			
Robotics and virtual reality: A perfect marriage for motor control research and rehabilitation	Patton, J. et. al.	2006	Virtual reality interfaces for device control.
Efficacy and usability of assistive technology for patients with cognitive deficits: a systematic review	de Joode, E. et. al.	2010	Assistive technology for compensating cognitive impairment.

Table 2. Papers selected from the literature search performed in SCOPUS and PubMed, ordered by topic: Control mechanisms (multiple), environment control, assistive devices, mechanical control, eye-movement control, brain-computer interfaces, other. Papers within each topic ordered by year.

3. Results

Neuromuscular disorder phenotypes

In assistive technology, the course of a neurological disorder carries important implications for its management. Service providers in our region reported that progressive neurological diseases warrant a proactive approach where control mechanisms are introduced long before they become a necessity, so that the patient may be as proficient as possible in using them when their disease progresses. Similarly, in a disease with unidirectional progression and a constant decline in function, anticipating and planning the management of further deterioration is more feasible than in disorders with bidirectional progression characterized by both remission and relapse phases. Among the non-progressive neurological disorders, a key distinction is whether the disorder is congenital or debuts in early childhood, or whether it is acquired later in life. Patients with stable congenital neurological deficits are arguably better equipped to cope with their disease than an adult acquiring a similar degree of disability, owing to a combination of childhood neuroplasticity and the early introduction of adaptive equipment. Additionally, the presence and severity of extramotor symptoms such and pain, sensory loss and cognitive deficits may complicate the management of paresis and paralysis in patients with neurological disorders, and disorders across all the aforementioned categories are associated with such symptoms to varying degrees.

Beyond the resources it takes to stay ahead of a progressive disease and introduce adaptive equipment at an early stage, such an approach may be psychologically unpleasant to some of these patients, as it promotes reflection around future function loss, and patients' preferences are paramount in this context. Efforts should be made, however, to build the patient's confidence in adaptive equipment they are likely to need later, particularly equipment pertaining to activities which are important to the individual patient, such as specially adapted vehicles for patients who appreciate activities outside of the home.

Assistive devices

In Table 3, manifestations of loss of motor function are presented along with assistive technology suited for compensating the respective disabilities, as well as control mechanisms which are not suitable in the same instances.

Lost/diminshed function	**Applicable assistive device(s)**	**Non-applicable control mechanism(s)**
Speech	Communication software	Speech commands

Neck musculature	Static/dynamic head restraints	Head-activated pressure sensors Head-mounted accelerometer/gyroscope steering Head-operated joysticks
Upper limb	Dynamic arm supports Specialized computer keyboards Orthoses Robotic exoskeletons Feeding robots Dressing robots Environment control	Touch screens Rope pull switches
Hand	Specialized utensil grips Grip-reinforcing gloves Orthoses Enhanced-accessibility computer interfaces	Conventional computer mice and keyboards Hand-operated buttons/switches Finger-operated joysticks
Lower limb	Wheelchairs/mobility scooters Orthoses Crutches Robotic exoskeletons Stair lifts Home automation solutions	Pedals
Oculomotor	-	Eye movement tracking
Breathing	-	Air flow sensors
Tongue	-	Tongue-activated pressure sensors
All mobility and communication, with cognitive impairment	Partner assisted scanning	All user-operated control mechanisms

Table 3. Functional categorization of motor disabilities with applicable assistive devices and non-applicable control mechanisms.

In patients with impaired speech, alternative means of communication may increase the quality of life (QoL) as perceived by the patient and provide opportunities for intimacy and interaction with others and the patients' environments (3). With ongoing global digitalization, alternative and augmentative communication (AAC) software is increasingly available. Common functions of such software is the conversion of typed text or selected icons or images to computer-generated speech, or screen display of selected icons or images. Software which allows the patient to take photographs and send or display them to others is used as assistive technology, and has recently found mainstream appeal through the popular social medium SnapChat.

Supporting the head at a natural, upright angle is as much a therapeutic goal as a replacement of lost function for the patients who cannot achieve this with their own muscle strength. A failure to do so will over time cause pain, skeletal deformities and increase the risk of cervical dislocation (4). Additionally, the reliability of eye-movement tracking sensors depends on the head being maintained in a constant position. Head restraints used for this purpose are normally fixed to a wheelchair or other seating used by the patient, and may be either static – allowing little to no movement – or dynamic, where the device facilitates controlled head rotation (5).

Loss of function of the upper limb, particularly the dominant one, significantly impacts a patient's independence in performing ADL. Technology which compensates upper limb paresis or paralysis is normally intended either to restore the limb's mobility or substitute its use entirely. Devices representing the former include dynamic arm supports which negate the strain of gravity, specialized computer keyboards with large keys separated by frames on which the patient may rest their hands (6, 7), and robotic exoskeletons which provide force beyond what the patient's muscles are able to generate (8). Orthoses, similarly to neck restraints, allow the patient to maintain their elbow and shoulder joints in positions they otherwise couldn't, and prevent complications from resting the upper limb at unnatural angles. The latter may be exemplified by specialized robots for individual activities such as dressing, feeding (9) and browsing through the pages of a book. One may also automate doors and curtains in the patient's home and provide them with remote control of lighting and thermostats, broadly referred to as environment control (10).

Barring cognition, humans largely owe their position as the most apical of apex predators to hand dexterity and opposable thumbs. The complexity of normal human hand function is difficult to fully mimic with man-made devices, and the current state of adaptive equipment for hand paresis and paralysis reflects this. Orthoses are used to stabilize finger and wrist joints, whereas writing or eating utensils may be fitted with specialized grips so that they can be held with greater ease (11). Motorized grip-reinforcing gloves are available (12), but these aids are currently limited to gross motor reinforcement, a limitation stemming from the lack of control mechanisms capable of registering user-generated input accurately enough to conduct mechanized fine motor hand movements. Computer accessibility is of key importance when utilizing other assistive technology such as AAC and environment control, and computer interfaces may be adapted to tolerate less precise button presses through the enlargement of click boxes – a function available by default in modern personal computers (7) – and a range of alternative control mechanisms can replace conventional computer mice and keyboards.

Locomotion is essential to independent living, and uncompensated loss of motor function in the lower limbs or feet is correspondingly debilitating. If such a loss is unilateral, crutches may be used to retain gait function, as may orthotic devices. Paraplegia and bilateral paresis of the lower limbs necessitate the use of wheelchairs or mobility scooters. Traditional arm-operated wheelchairs are demanding for the patient to use independently and thereby require a virtual absence of concomitant upper body paresis and paralysis, while a mobility scooter is a road vehicle suitable for prolonged outdoor use. The greater ease of use and independent locomotion offered by electrically powered wheelchairs (EPWs) and mobility scooters does come at a cost of reduced physical activity (13). Robotic lower limb exoskeletons have become increasingly feasible over the past decades. A major share of the development of such devices has been conducted for military purposes, but medical lower limb exoskeletons are also seeing increased interest in the scientific community. Generating useful input for such exoskeletons is a challenge in a medical setting, since the device cannot necessarily rely on amplifying mechanical force generated by a disabled user, as opposed to a soldier (14). In the home, stair lifts can be installed to ease transportation between floors, and as with upper arm disability, environment control could compensate the loss of physical range caused by lower limb disability.

Certain losses of motor function impact the range of control mechanisms which may be used by the patient. These functions tend to rely on muscles over which the patient can be expected to retain precise control for much of their disease course. A loss of voluntary oculomotor movement, voluntary breathing or tongue motility excludes the possibility of using eye movement tracking, air flow sensors or tongue-operated switches, respectively. Similarly, the patient's cognitive state is considered when ordinating self-help devices, as alternative control mechanisms may be demanding to learn and operate. For some patients, the only applicable auxiliary aid is assistance from another human, as is the case with partner assisted scanning (PAS) (15).

Control mechanisms

Control mechanisms applicable in assistive technology range from interfaces broadly used in the populace, such as touch screens, joysticks, computer mice and keyboards, to devices which would be highly impractical were it not for the fact that they are the only remaining means for the patient to interact with their surroundings, such as BCI. In general, control mechanisms that demand more refined motor function tend to rely less on the patient's cognitive skills and allow the patient to generate greater volumes of meaningful output over a shorter time span. Tai et. al. draw distinctions between those control mechanisms which require reliable motor control of at least one limb or of the neck, those which require fine motor control above the neck, and those that require no movement (16).

As implied earlier, a fully functional human hand grants ample opportunity for rapid and accurate interaction with technology, and control interfaces which rely on finger movements are widely implemented both within and beyond the field of assistive technology. Such interfaces include conventional computer mice and keyboards, handheld remote controls, joysticks and touch pads. Joysticks are a form of proportional control for which the input is a vector with a specific direction and magnitude. This makes them suitable for controlling EPWs and computer cursors, as the input translates directly to an output which is either experienced or visualized, respectively. The bulk of research conducted on joysticks has been concentrated on their use by unimpaired persons (17), and correction for involuntary movements remains an obstacle to their use by patients suffering from nervous system diseases (18). Touch pads and trackballs mice provide a similar degree of control (17).

A slew of variants of mechanical switches are available to users who retain gross motor limb movement, including plate, lever, mercury, tread, string and "jelly bean" switches , the latter of which is commonly used in access technology. Fancioni et. al. have published several papers on the use of "microswitches" – mechanical switches adapted to register highly specific stimuli, such as a series of chin movements within a predetermined time period - and "microswitch clusters", where one switch is activated in order for another switch/sensor to register the stimulus intended for device operation (19, 20). Switch clusters may be set up in a manner that leads the patient to correct their posture regularly, as opposed to using a single switch which may inadvertently cause the patient to "slouch" towards their access pathway (19). Microswitch clusters also offer the advantage of eliminating input from unintentional movements (20). Gross motor control retained in individual limbs can also be registered using infrared (IR) sensors which track changes in the skin's reflection of IR radiation emitted by the device, as demonstrated by Reilly and O'Malley. Although this study provided no quantitative effect measures, participants reported that they perceived the system as responsive (21).

Gross motor control of the head is often used in the absence of reliable limb motion, and such input may be registered using various technologies. A wearable device fitted with an accelerometer can function as a single-signal switch, triggered when head acceleration reaches a pre-specified threshold value (22). The further addition of a gyroscope allows for accurate measurement of the head's angular velocity, an input which may be used to control a computer cursor or EPW (23) with proportional control analogous to that of a joystick. A similar interface has been developed by Y.L. Chen (24), using tilt sensors instead of gyroscopes, thus relying on head inclination relative to a given baseline over time as an input rather than head acceleration. This is advantageous to patients with limited head movement speed or range. IR sensors may be used to indicate head position in real-time, with an infrared beam emitted or reflected from the head onto an IR-sensing surface essentially functioning as an electromagnetic pointing stick. A study by Y.L. Chen et. al. has shown that patients using a spectacle-mounted IR control system can type a 97-letter passage in 4.9 ± 2.0 minutes and achieving a typing accuracy approaching 95 % without the use of a selection switch (25). The efficiency of head-mounted cursor control devices can be further increased by incorporating a designated selection signal corresponding to a mouse click, as it eliminates the "linger time" otherwise needed to select the desired character or icon. An EPW control system proposed by Ju et. al. uses a combination of IR sensors and video cameras to detect the sagittal head inclination and mouth shape of the patient, which are used to regulate the direction and speed of the wheelchair, respectively. This design had the added benefit of disregarding unintended head rotation which the user may perform instinctively while examining their surroundings, and in comparisons with a headband-based tilt sensor system and a video-based system using head rotation as the “turn” command, the novel system was non-inferior to the comparators in terms of accuracy and processing speed, and required less training (26).

Signals for eye movement are mediated through cranial nerves III, IV and VI, and eye blinking relies on the function of cranial nerve VII. Eye movements and blinking may therefore be used as an access pathway for patients who have lost all motor control mediated through spinal nerves. Blinking can be reliably detected using IR or video camera technology, both of which are relatively inexpensive and widely available, and is primarily suitable for switch activation, requiring a series of blinks of a given duration within a given time frame and in order to eliminate “noise” from involuntary blinking (27). Gaze direction is most commonly monitored using IR sensors, which although relatively robust to ambient lighting may be subject to interference from IR radiation sources such as the sun, as well as blocked by most substances. Moreover, if one wishes to avoid a head-mounted device, wheelchair-mounted eye movement tracking devices are highly sensitive to deviations in head posture. Electrooculography (EOG), in which eye movement is registered by means of a two-electrode system measuring the electric potential between the retina and cornea is robust against environmental and postural disturbances (28). Electrophysiological impulses emitted while blinking or masticating may give rise to EOG artifacts, and EOG performance depends on signal processing to correct for such artifacts (28, 29). A range of different EOG electrode placements are feasible, and while placement in the orbitotemporal region of the face is the most reliable, electrodes integrated in ear buds offer acceptable accuracy as well (30). The latter method has the added benefit of resembling audio head sets. Currently, most EOG research has been performed using wet electrodes, but dry electrodes which may be integrated in eyeglasses and other headwear also appear to perform adequately (28). In the current literature, the computer output of EOG-based control systems is limited to incremental cursor movements in a pre-defined set of directions, often using blinks as a selection signal (31, 32), whereas interfaces with IR sensors allow for fluent real-time gaze tracking. Both modalities are suitable for eye-writing (33, 34), with EOG displaying superior accuracy in trials compared to IR, 87.38% computer recognition versus 69.4% human recognition, respectively. Video, IR and EOG eye tracking can all be utilized to perform simple, discrete gestures which may be used to control computer interfaces, environment control or other assistive technology (35, 36). As the eye has evolved to serve an exclusively sensory function, an issue shared by current eye tracking interfaces is the occurrence of inadvertent eye movement when the user observes their surroundings, resulting in unintended input, commonly dubbed the “Midas touch problem” (37).

Another access pathway which relies solely on cranial nerve transmission is the tongue, innervated by cranial nerves XII, and to some extent X; it utilizes an area of the motor cortex which approaches that of the hand, and is thus suited for sophisticated motor tasks (38). Nutt et. al. developed a tongue-mouse interface designed for computer and EPW control which uses a piezoceramic plate fitted to the palate and upper teeth for cursor control, with pressure sensors which register bites in three distinct locations (39). A key drawback of this sensor system is that it obstructs the mouth and occupies space below the palate, thereby hindering speech and feeding while the system is in use. An unobtrusive tongue control interface developed by Huo et. al. uses a magnetic element which may be attached to the tongue using tissue adhesive, worn as a tongue piercing or implanted beneath the glossal mucosa, the movement of which is registered by a sensor module integrated into externally worn headgear (40). This magnet-based system allowed study participants to operate an EPW at approximately one-third of the speed at which they were able to perform EPW operations using a finger-controlled joystick. A toggle option was included to allow users to switch between driving mode and an inactive mode during which tongue movement does not result in EPW output. The system may also be operated using either proportional or discrete control, with the latter essentially providing a “cruise control” option. Leung and Chau published a proof-of-concept paper for nonobtrusive, contactless capture of tongue protrusions using video cameras (41). This method only functioned as a single-signal switch, as opposed to the two aforementioned methods, and therefore needs to be combined with other control systems or a scanning system in order to provide computer access.

Speech recognition technology has seen rapid development over the past decades, and devices which combine artificial intelligence (AI) and speech recognition are pervasively present in high-income countries, as exemplified by Google Voice, Siri and Alexa, to a point where computer access by means of speech recognition can be considered mainstream technology. In a single-subject study by Havstam et. al., Dragon Dictate – a speech recognition system which fits spoken user input into existing templates and adapts to the individual user's speech through machine learning – was shown to accurately register three to four commands in two participants with severe dysarthria. The reliability of the system decreased as more words were added (42). Cunningham et. al. have developed an environment control system which may be operated using only voice commands and uses machine learning to adapt to dysarthric speech in the individual user. The system can also access input data from other users via an internet cloud in order to facilitate machine learning. A command learned by the system corresponds to a given environmental control output in the form of an IR signal, which may be programmed manually or learned by the system from existing IR remotes. Thus, the system is easily adaptable to the user's speech in one end, and to the user's environment in the other (43). A key weakness of speech recognition is interference from noise in the user's environment, an issue which can be amended through integration with other input modalities. Sahadat et. al. presented a system which combines speech recognition, a tongue switch and head movement tracking by means of accelerometer and gyroscope. These control mechanisms served as typing, mouse click and cursor movement functions, respectively, in order to grant computer access (44). In the severely disabled, vocalization may be used as an input for a microswitch or microswitch cluster, as described earlier in this paper (20). Microphone placement and variability in sensitivity between different microphones poses a potential problem, particularly for severely disabled users. Moreover, while AI provides increased sensitivity which may be useful to dysarthric patients, such algorithms may be prone to overfitting, resulting in "Midas touch" phenomena (42). In a survey conducted by Koester et. al., respondents reported that speed and ease of use were the two most important reasons for them to choose a non-speech input method over speech recognition. 54.2% of respondents were satisfied with the accuracy of their speech recognition system, versus 72.7% for non-speech input; speech input was favored in the other satisfaction parameters surveyed (45).

Surface electromyography (sEMG) is applicable as a control mechanism for patients who retain neuromuscular transmission, but are unable to generate enough force to successfully manipulate a switch. In a study by Gryfe et. al., myoelectric signals from the interosseous muscles of the hand were used by ALS patients for computer access, and upon the loss of reliable motor control of these muscles, electrodes were relocated to the foot, cheek or forehead (46). Similarly, Y. Cheng et. al. demonstrated that sEMG could be utilized by spinal chord injury patients for operating a telephone system (47). Barreto et. al. developed a computer access interface which combines facial cursor control and mouse clicks via facial sEMG with EEG, wherein the latter serves to engage and disengage the EMG electrodes in order avoid unintended input (48). The are several limitations and challenges which pertain to sEMG use as an access pathway. Severely disabled patients cannot necessarily rely on sEMG signals, as the method depends on an adequately high signal/noise-ratio, i.e. the monitored muscle needs to be sufficiently strong compared to surrounding muscles which may be involved in unrelated motions. Perspiration, variation in contact between electrodes and the skin, as well as dehydration of electrode gel over time also represent detriments in the method's robustness (49, 50)

Brain-computer interfaces

Brain-computer interfaces constitute an access pathway which does not require any motor function, and may thus be used by patients suffering from locked-in syndrome (LIS), in which only a few small voluntary motor responses are retained, typically vertical eye movement. BCI often rely on computer screens to provide visual feedback, although in the case of total locked-in syndrome (TLIS), in which no voluntary motor control remains whatsoever, the use of tactile or auditory stimuli to produce evoked potentials is necessary due to visual impairment caused by paralysis of the extraocular muscles (51, 52). The taxonomy of BCI is described in table 4.

Non-invasive		**Invasive**	
Signal acquisition method	**Signal detected**	**Signal acquisition method**	**Signal detected**
fMRI	Cerebral oxygenation (BOLD signal)	Extracortical microelectrode array - Epidural - Subdural - Intravascular	Electrocorticographic oscillations (ECoG)
NIRS			
PET	Cerebral metabolism		
MEG	Slow cortical potentials (SCP) Sensorimotor rhythms (SMR) P300 evoked potentials Steady-state visual evoked potentials (SSVEP) Error-related negative evoked potentials (ERNP)*		
EEG		Intracortical microelectrode array	Local Field Potentials Single-unit activity Multi-unit activity
		Two-photon calcium imaging	Calcium channel permeability

Table 4. Signal acquisition methods used in established BCI approaches along with the corresponding signal(s), categorized as either invasive or non-invasive. *Difficult to register using MEG.

In addition to the variables considered in Table 4, J. R. Wolpaw highlighted the importance of whether a BCI is goal-oriented or process-oriented; that is, whether the interface is designed to produce a certain output or range of outputs as efficiently as possible, or to allow the patient precise control of a virtual or physical movement. A process-oriented BCI, such as an interface for cursor control, may grant a greater degree of control, but the output will also be less reliable than with a goal-oriented BCI in which the input is a discrete signal. In general, invasive BCI tend to be process-oriented whereas non-invasive BCI tend to be goal-oriented(53).

Non-invasive approaches to acquiring brain signals include functional magnetic resonance imaging (fMRI), near infrared spectroscopy (NIRS), magnetoencephalography (MEG), positron emission tomography (PET) and scalp-based EEG. Of the aforementioned approaches, the response of fMRI, NIRS and PET is too slow for application in computer or device control. fMRI, PET and MEG in their current state may only be performed in a strictly controlled environment using heavy equipment and require expert personnel. Scalp-based EEG is therefore the most studied non-invasive approach (52, 54). Letter or word selection using SCP requires training using operant learning, where a positive stimulus such as a smiley face or pleasant sound is shown in response to the user successfully triggering a slow cortical potential (55). This learning appears to depend on prefrontal cortex function, and patients exhibiting impairment of prefrontal cortex function, such as those suffering from attention deficit disorder or schizophrenia seems to have difficulty in training to use this method (56). BCI which utilize SMR register a decrease in alpha activity (8-13 Hz) over the somatosensory or motor cortex which occurs while performing, preparing for or imagining a movement. Users of these BCI learn to do so by performing letter selection or cursor control through such mental activities. Additionally, SMR has been demonstrated to provide three-dimensional control of neuroprosthetic and robotic limbs with speed and precision non-inferior to invasive methods (52). The P300 evoked potential occurs in response to a surprising stimulus; if the BCI user concentrates on a letter on an on-screen keyboard and said letter flashes at random, it triggers the P300 evoked potential and will result in the selection of that letter. P300 is the most expensively studied BCI approach, as well as the one most commonly used for word processing (51), and systems using this signal approach word processing rates of 2-4 words/min when combined with word prediction software (52). BCI which use SSVEP record electric activity in the occipital cortex which is triggered by looking at icons flashing at specific frequencies of >6 Hz. The ERNP is triggered in a fashion similar to P300, although by a stimulus perceived by the user as erroneous rather than surprising, and it may thus be used to eliminate unintentional input when typing with a BCI (56, 57). Virtual reality environments may useful for patients training to use EEG-based BCI (52). Although of little utility in cursor control or letter selection, NIRS was shown in one study to provide patients suffering from TLIS with the ability to communicate “yes” or “no”, albeit with an accuracy of 70% (51).

In 2000, Lauer et. al. reviewed the feasibility of using cortical signals detected by EEG or intracortical electrodes to operate a neuroprosthetic device intended for spinal cord injury patients. In principle, the design favored by the authors would utilize somatomotor cortex signals using scalp-based EEG in order to electrically stimulate the muscles which were rendered paralyzed due to spinal cord injury (58). This was later demonstrated in 2005; using SMR, a patient was able to self-administer electric stimulation to their arm and hand in order to successfully grab a glass of water (59). In order to attain multiple types of output from a BCI, the user needs to be able to perform multiple mental activities which in turn need to be distinguishable based on cortical signal characteristics. Machado et. al. stated that EEG-based BCI were capable of generating discrete or continuous output which could be used for computer, EPW or prosthetic control. Key weaknesses of BCI in the context described in the same publication were reliability and the time interval between neural output and device response, which are particularly critical when using a BCI to assist gait (60). Fok et. al. presented a mechanized hand orthosis which utilizes scalp-based EEG with dry electrodes to distinguish between cortical activity corresponding to opening and closing the hand in an ipsilateral cortical region. The device is intended to aid in the rehabilitation of stroke patients by assisting the user in the opening and closing motions, thus generating tactile feedback and facilitating post-stroke neural reorganization. The device was tested on 4 healthy volunteers across 10 trials, and successfully registered hand position with an average accuracy of 81.3%. The acquisition of cortical signals from an ipsilateral cortical region is particularly useful in stroke patients, as limb impairment most often is a result of damage to the contralateral primary motor (56, 61). Studies on EEG-based BCI for restoration of communication in patients suffering from ALS have primarily used SCP, SMR and P300 signals, and for this purpose such BCI are mostly successful, with the notable exception of patients who suffer from TLIS upon beginning training (56). In combination with word suggestion software, 10 healthy subjects using a P300-based typing program were able to correctly type 10-word sets at an average speed of 1.67 min per set (62). Lin et. al. described methods of using Bluetooth and Wireless Local Area Networks (WLAN) to achieve wireless transmission for EEG-based brain-computer interfaces, all of which had been demonstrated in existing publications. Advantages attributed to wireless BCI in the review include greater ease of installation and troubleshooting as opposed to traditional, wired BCI, as well as greater freedom of movement for the user (63).

Invasive BCI, which involve surgical implantation of electrodes or microelectrode arrays, provide superior spatial resolution compared to noninvasive BCI (57). Despite these theoretical advantages of invasive BCI, Wolpaw et. al. reported that the totality of studies does not indicate that invasive approaches provide better performance (52, 53), and only a few studies with small numbers of participants have been published in which the efficacy of invasive BCI has been evaluated. ECoG refers to the recording of electrical activity along the cortical surface, and has currently only been performed experimentally on humans in conjunction with surgeries which warrant craniotomy (Daly 08). In addition to lower-frequency rhythms which may be attained non-invasively, ECoG may record gamma bands (30-200 Hz), and a study by Miller et. al has previously indicated that high-frequency data (>60 Hz) may be valuable in the interpretation of imagined movement (64). Another probable advantage held by ECoG over non-invasive BCI is the absence of electromyographic and electrooculographic noise (52). In addition to epidural and subdural implantation, which require craniotomy, ECoG has been performed on sheep using an endovascular stent with a microelectrode array inserted through the jugular vein, developed by T. Oxley. The signal quality using this method was comparable to that of the epidural or subdural approach (65, 66). This intravascular approach was recently also applied to two human subjects with flaccid upper limb paralysis due to ALS, and allowed them to type at speeds of 13-20 correct characters per minute with 92-93% accuracy. When used in tandem with an eye-tracking interface for cursor control, the intravascular ECoG method allowed the participants to independently compose a text, check their email, shop and manage their finances on the computer (67). In a separate human study, in which the participant achieved similar typing and IADL performance to the two aforementioned subjects, CT venography was performed 3 months after implantation and showed no signs of stenosis or thrombi resulting from device use (68). ECoG has been used by study participants suffering from ALS to gain three-dimensional control of a robotic arm with grasp function; these participants did have some residual head and arm mobility, and similar results have not been reported for more severely afflicted ALS patients. Intracortical signal acquisition, which primarily has been tested on monkeys, provides the potential to detect spikes from individual neurons (single unit activity, SUA) or small groups of neurons (multi-unit activity, MUA), as well as voltage gradients in a small group of neurons (local field potentials, LFP), which all require the insertion of microelectrodes into the cortical tissue (57). In a study on two participants with ALS who did not suffer from LIS, an intracortical microelectrode array allowed the participants sufficient control of a cursor to type up to 115 words over a 19 min period (69). A concern with all invasive BCI is their safety, both with regard to infection risk and tissue reaction. Additionally, there is still uncertainty about the long-term signal stability of invasive BCI (52). In the case of spinal cord injury patients using BCI for movement restoration, concern has been expressed over whether post-injury neuroplasticity may induce change in which neuron groups are used for the restored movement, thereby necessitating relocation of an eventual intracortical electrode array.

4. Discussion

The purpose of this thesis was to provide an overview of existing and emerging assistive devices and control mechanisms for patients with loss of motor function resulting from nervous system disease. To our knowledge, no such review has been published since 2008 (16). It is reasonable to assume that assistive technology and adjacent scientific fields have seen significant advances in 12 years, and this assumption warrants an updated review. One fundamental challenge with reviewing current assistive technology is that the topic is not clearly demarcated from general consumer technology. As certain technology costs have decreased over time, some of the access technologies reviewed, such as speech recognition and mechanical switches, have become so widely available that their use occurs primarily outside of an assistive technology context. Industry research and development is, inevitably, to a large extent driven by the market. When products fall into mainstream usage, it often leads to producers further adapting that product to suit the needs of the general public, effectively sidelining the smaller group of disabled users. Another aspect of this normalization of assistive technologies is that it may make it more difficult for disabled persons to receive state funding for devices; for instance, personal computers were previously considered assistive devices in Norway, but have now become so ubiquitous that users are required to obtain them at their own expense.

On the other hand, access technologies intended for severely disabled persons, such as BCI, generate output at such slow rates that they have little mainstream appeal in their current state. However, such profound physical disability is rare, and studies on the efficacy of BCI in locked-in or total locked-in patients are usually case studies or limited to small sample sizes, which is not strong evidence. This is especially the case for invasive BCI, which are usually tested in the context of planned surgery. It is possible that the minimally invasive stent electrode developed by Oxley et. al. could be tested more extensively. Non-invasive BCI trials often use healthy study participants, and it is unclear whether similar efficacy can be expected in severely disabled patients, particularly those suffering from disorders which involve cortical degeneration. Another issue with the documentation on the efficacy of novel assistive devices and control systems is that clinical trials are often performed in a laboratory setting. Assistive technology is intended for everyday use, and needs to perform well over time and in a variety of situations. Therefore, efforts should be made to test devices in the user’s home and investigate user satisfaction in assistive technology trials.

When attempted, the combination of multiple input modalities appeared to increase accuracy and operation speed, as exemplified by microswitch clusters (20) and the combination of eye tracking and a non-invasive BCI (62). This approach should be attempted more often, as control mechanisms which do not perform adequately on their own may do so when used to complement each other.

Based on the search results, BCI-related publications appear to be overrepresented in research on control mechanisms for assistive technology, particularly when compared to the reality described by the people who were interviewed for this review. Tai et. al. postulated a need for more research to be conducted on non-invasive, EEG-based BCI, and the publications resulting from our literature search did indeed tend to emphasize EEG-based BCI. Interestingly, there are relatively few differences between the reviews published about BCI in the mid-2000s and the most recent review by Chaudhary et. al., despite BCI being by far the most common subject among the articles we found on control mechanisms. This may be suggestive of the fact that although a subject of much ongoing research, progress in the development of invasive BCI is hampered by limited access to human subjects on which it would be ethically acceptable to experiment.

The topic of BCI warrants some ethical reflection. This technology may allow a locked-in patient with ALS to communicate with loved ones and caregivers for a prolonged period of time, thereby increasing quality of life during late stages of the disease's course. However, it is known that cognitive decline is a feature of ALS (70), and equipping a patient whose cognitive function is gradually declining with a cognitively demanding communications system may place an added burden on both the patient and their next of kin. When possible, a will should be prepared by the patient before such issues arise, stating when treatment should be discontinued. Information provided by the patient on their perceived quality of life is likely to influence caregiver decisions on whether to initiate or terminate life-prolonging tracheostomy-assisted ventilation, and in late stages of ALS it could prove difficult to assess the reliability of such information. Additionally, having a means of communication beyond the point where the patient enters the locked-in state could make decision-making pertaining to the continuation of tracheostomy-assisted ventilation more difficult, since entering the locked-in state could lose its role as a marker for when it is appropriate to cease treatment (71). On the contrary, prolonging the time during which the patient can communicate will allow that patient to retain their autonomy for longer, which is of intrinsic value. However, as formerly implied, the possibility of cognitive decline would raise doubt over whether the patient's consent is informed. Current European guidelines for diagnosing disorders of consciousness involve clinical tests, EEG and functional neuroimaging (72); these tests do not provide satisfactory distinction between vegetative state and conditions with some extant consciousness, and it has been proposed that around 40% of patients diagnosed as being in a permanent vegetative state may be misdiagnosed (73). Not only could BCI be used by some of these patients for communication, but novel BCI could aid in diagnosing disorders of consciousness with greater accuracy, thus providing a path towards optimal treatment. The utilization of BCI has the potential to increase the risk of overtreating locked-in patients whose quality of life is poor, thereby exerting a heavy emotional toll on them and their loved ones. It ought to also be mentioned that BCI in their current state are relatively expensive equipment, and their use would unquestionably be unevenly distributed between patients in countries with high and low levels of income.

The scope of this review as defined in the introduction was most likely too wide. In particular, reflections around cost, ease of use and medical risks associated with the various control mechanisms are aspects which in many cases were redundant or on which no information was available in the literature which was retrieved. Most of the literature used in this review provides little information beyond potentially describing a given technology as "low cost", and the types of technology detailed herein are so heterogenous it makes little sense to compare their ease of use. It also became apparent through the interviews conducted that equipment ordination is based primarily on the individual user's needs, as well as preferences if these can be accommodated to at a reasonable price. Methodologically, one could criticize the inclusion of interviews which were not conducted in a structured fashion and therefore are not reproducible. Indeed, most of the subject matter from the interviews was not included directly in this review. However, information gathered from the interviews advised the emphasis placed on each paper, and barring the overrepresentation of BCI-related material, this review provides an accurate description of the assistive technologies and control systems used in restoration of movement and communication today.

5. Conclusion

In the present review, currently available adaptive devices for patients with loss of motor function, control systems for assistive technology, as well as frontier research within the field from the year 2000 until 2020 has been summarized and systematized. While the most commonly used technological solutions are not currently undergoing further development, cybernetic approaches to movement restoration and brain-computer interfaces have seen persistent interest from the research community throughout this period, and AI and machine learning play an increasingly important role in the assistive technology field. Clinical data on the efficacy of brain-computer interfaces as an access technology for the most severely disabled patients is still sparse, as are comparative studies on different signal acquisition methods for such interfaces. Integration of multiple input modalities and wireless compatibility present possibilities for the future improvement of established access technologies.

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