REVIEWS

Adv Clin Exp Med 2012, **21**, 2, 263–272
ISSN 1899–5276

Emilia Mikołajewska[1], Dariusz Mikołajewski[2]

Neuroprostheses for Increasing Disabled Patients' Mobility and Control

Neuroprotezy wykorzystywane do zwiększenia możliwości osób niepełnosprawnych z zakresu mobilności i sterowania

[1]Rehabilitation Clinic, Military Clinical Hospital No. 10 and Polyclinic, Bydgoszcz, Poland
[2]Division of Applied Informatics, Department of Physics, Astronomy and Applied Informatics, Nicolaus Copernicus University in Toruń, Poland

Abstract

Neuroprostheses are electronic devices using electrophysiological signals to stimulate muscles, electronic/mechanical devices such as substitutes for limbs or parts of limbs, or computers. The development of neuroprostheses was possible thanks to advances in understanding of the physiology of the human brain and in the capabilities of hardware and software. Recent progress in the area of neuroprosthetics may offer important breakthroughs in therapy and rehabilitation. New dedicated solutions for disabled people can lead to their increased participation in social, educational and professional areas. It is worth focussing particular attention on new solutions for people with paralysis, people with communication disorders and amputees. This article aims at investigating the extent to which the available opportunities are being exploited, including current and potential future applications of brain-computer interfaces (**Adv Clin Exp Med 2012, 21, 2, 263–272**).

Key words: rehabilitation, neuroprosthesis, brain-computer inteface, disabled people.

Streszczenie

Neuroproteza jest urządzeniem elektronicznym wykorzystującym sygnały elektrofizjologiczne do stymulacji efektorów, takich jak mięśnie lub urządzenia elektroniczne i/lub mechaniczne, zastępujące kończyny lub ich części oraz sterowania komputerami i ich oprogramowaniem. Rozwój neuroprotez był możliwy dzięki postępowi w zrozumieniu neurofizjologii mózgu człowieka oraz zwiększeniu możliwości sprzętu komputerowego i oprogramowania. Postęp w omawianej dziedzinie może ustanowić nowe kamienie milowe w leczeniu i rehabilitacji. Nowe rozwiązania dedykowane osobom niepełnosprawnym mogą spowodować wzrost ich uczestnictwa w różnych obszarach życia: od społecznego przez edukację aż po obszar zawodowy. Szczególną uwagę warto zwrócić na stworzenie nowych rozwiązań dla pacjentów z porażeniem, brakiem możliwości komunikacji werbalnej oraz osób po amputacjach. Artykuł jest próbą oceny, w jakim stopniu wykorzystuje się możliwości z omawianego zakresu, w tym obecne i potencjalne przyszłe zastosowania interfejsów mózg–komputer (**Adv Clin Exp Med 2012, 21, 2, 263–272**).

Słowa kluczowe: rehabilitacja, neuroproteza, interfejs mózg–komputer, osoby niepełnosprawne.

Recent progress in neuroprosthetics may offer important breakthroughs in the rehabilitation of disabled people. Neuroprostheses are electronic devices that substitute motor, sensory or cognitive functions damaged as a result of an injury or a disease. In motor-disabled patients, neuroprostheses use electrophysiological signals to stimulate effectors like muscles or mechanical devices (substitutes for limbs or parts of limbs, powered wheelchairs, exoskeletons, etc.). Neuroprostheses can increase these individuals' mobility and radically improve their quality of life.

The development of neuroprostheses was possible thanks to advances in understanding of the physiology of the human brain and in the capabilities of hardware and software. Particular attention has been paid to neuroprosteheses for patients with paralysis, those with communication disorders and amputees [1–3].

The word "neuroprosthesis" should not be directly associated with “prosthesis” in the sense of an artificial extension that replaces a missing body part. The meaning of “neuroprosthesis” is much wider.

Review

A critical appraisal of the publications listed in the PubMed database was made (Figure 1).

The keywords “neuroprosthesis” and “brain computer interface” do not appear in the MeSH thesaurus. In the PubMed database, starting in 2003 a significant increase can be seen in the number of articles with the keyword “brain computer interface” and a moderate increase of number of artticles with keyword “neuroprosthesis”, which indicates where research is concentrated now.

A brain-computer interface (BCI) records cortical signals with the objective of interaction with the surrounding world, for example to control an artificial limb, a robotic artifact or a user interface for communication purposes [6, 7]. A BCI is a key part of a neuroprosthesis. One kind of neuroprosthesis is designed to increase disabled patients’ mobility and control. Despite the rapid development of BCIs there can be problems with their use in neuroprostheses in clinical practice. Extracting reliable information from the available neural signals is very important, and the produced output signal has to be suitable for real-life applications.

Three main kinds of neuroprostheses for increasing disabled patients’ mobility and control can be distinguished (Figure 3a):

1. Neuroprostheses that control paralyzed muscles, substituting for injured parts of the nervous system. The neuroprosthesis assigns the role of the spinal cord’s motoneurons to neurons of the motor cortex in the selected area(s) [9]. Because this process of control differs from the physiological process, each user/patient has to learn it from the beginning, relying on the brain’s neuroplasticity. The key points in this relearning are training the user to imagine the accomplishment of a specific motor activity, and the actual execution of the intent using the neuroprosthesis.

2. Neuroprostheses that control mechanical prostheses. These neuroprostheses can be useful for amputees whose spinal cord functions are preserved. Electrophysiological signals representing the intent to perform a specific motor activity are used to control electromechanical robotic devices that replace the missing body parts. This type of neuroprosthesis also entails the patient learning new abilities.

3. Interfaces using electrophysiological signals to control devices (communication devices, per-

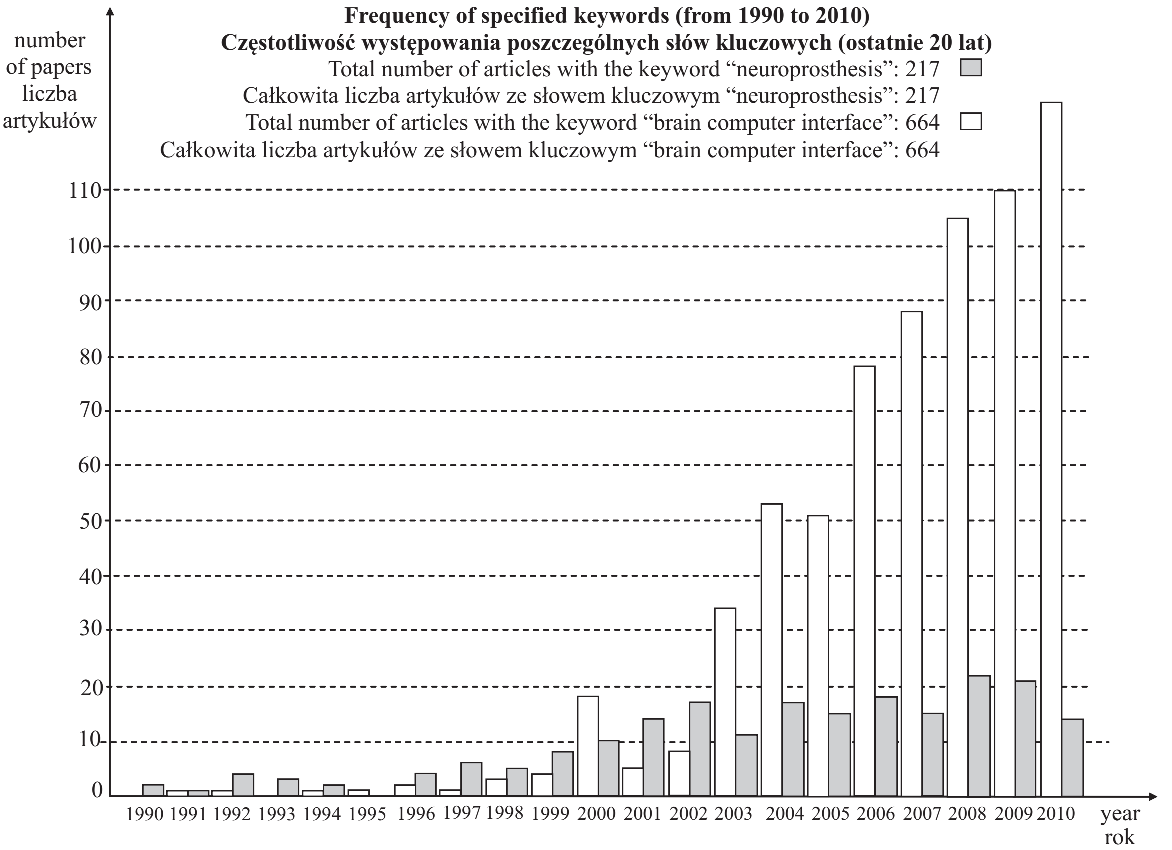

Fig. 1. Results of the authors’ investigation of the PubMed database (U.S. National Library of Medicine) [8]

Ryc. 1. Wyniki przeszukiwania bazy danych PubMed (U.S. National Library of Medicine) [8]

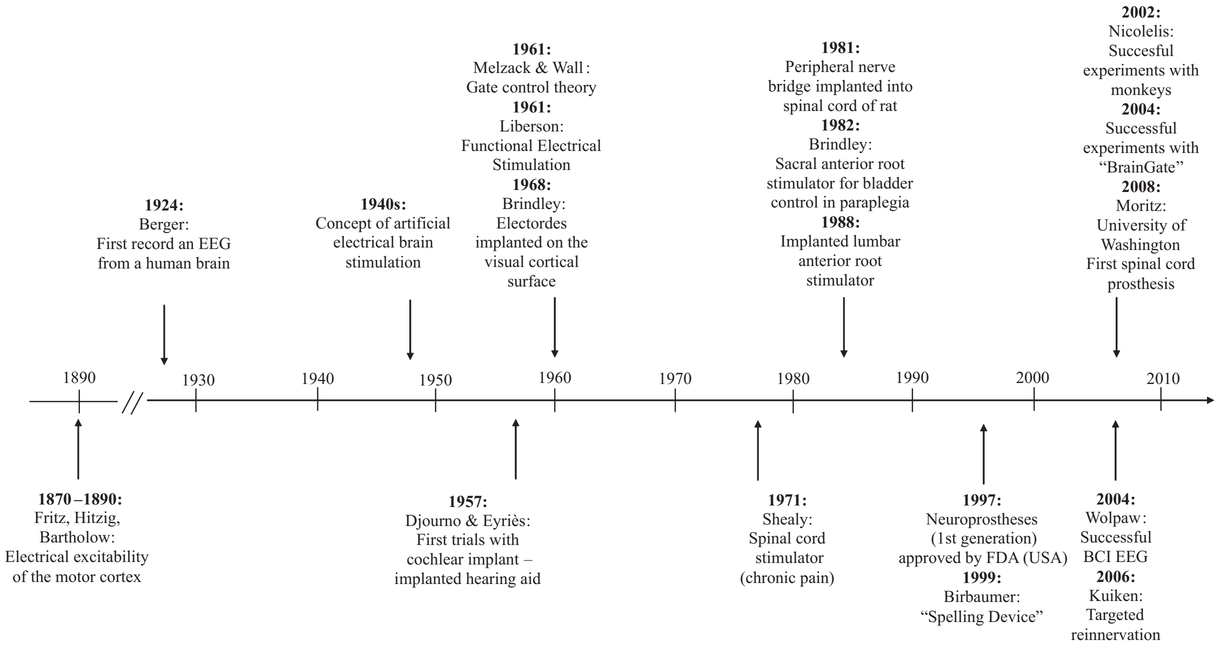

Fig. 2. Milestones in the history of brain-computer interfaces (BCIs) and neuroprostheses [4, 5]. Electrical brain stimulation in Parkinson's disease, dystonia, chronic pain and other disorders was used before BCI development

Ryc. 2. Kamienie milowe w historii interefejsów mózg–komputer i wszystkich rodzajów neuroprotez [4, 5]. Elektryczna stymulacja mózgu w terapii pacjentów z chorobą Parkinsona, dystonią, chronicznym bólem itp. były używane przed rozwojem BCI

sonal computers and whole systems controlled by them, such as smart homes). This kind of neuroprosthesis is designed for people with no or nearly no preserved motor functions. In this case electrophysiological signals are transformed into commands for the controlled devices, allowing the user to:

– communicate using simple devices and/or software like word processors;

– control the environment: desk assistants,

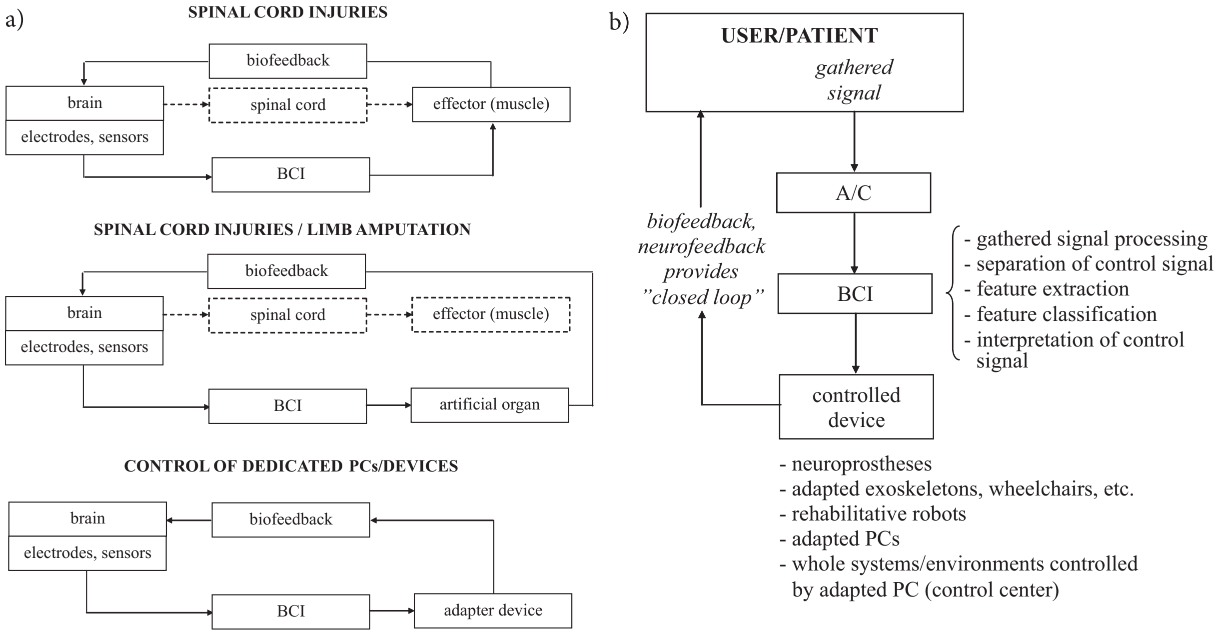

Fig. 3. Conceptual schema for a) common cases of neuroprostheses for mobility and control; and b) brain-computer interfaces [4, 5]

Ryc. 3. Idea: a) neuroprotez wykorzystywanych do zwiększenia możliwości osób niepełnosprawnych z zakresu mobilności i sterowania – najczęściej spotykane przypadki, b) interfejs mózg–komputer [4, 5] smart home systems, i-wear systems, telemedical systems, robotic manipulators or other rehabilitative robots [10, 11];

– control other computer-run systems for increasing user mobility, such as powered wheelchairs and exoskeletons.

Technical Solutions

The main element of all the neuroprostheses described above is the BCI (Figure 3b). The BCI is the "linking device" between the human brain and the computer: It records signals originating from the brain and transforms them into messages or commands for the controlled devices. Neuromuscular activity is not used to carry the message/commands [1–3, 12]. The signals gathered by a BCI depend on the neuro-technical interface itself, which can be divided into:

– non-invasive electrodes placed on the scalp, mainly based on EEG P300, steady-state visual evoked potentials (SSVEP) or event-related desynchronization/synchronization (ERD/ERS);

– electrode arrays implanted directly in the brain [1, 9, 13].

A lot of of bioelectrical, magnetic, metabolic and other signals are generated during brain activity. Some of the main records of bioelectrical signals are electrocardiograms (ECG), electroencephalograms (EEG, including P300, SSVEP, ERD/ERS), magnetoencephalograms (MEG), electrocorticograms (ECoG), electromyograms (EMG), averaged operant potentials (AOP), contingent negative variations (CNV), electroneurograms (ENG), electrooculograms (EOG), electroretinograms (ERG), electrocochleograms (ECochG), His bundle electrograms (HBE), surface His bundle electrograms (SHBE), visual evoked potentials (VEP/VER), auditory evoked responses (AER), olfactory evoked responses (OER) and somatosensory evoked responses (SER). These techniques are used on different parts of the body and entail various different modes of signal gathering, amplitude, frequency, duration, rhythm and other parameters, and are not always easy to interpret and to implement. In devices for practical use, the signal needs to be:

– easy to acquire (despite very low amplitudes, measured in μV, distortions, non-linearity and multistability);

– easy to implement in real-time device control;

– insensitive to errors and distortions, including changes in the user's health or emotional state;

– in commercial solutions, it needs to be simple, cheap and safe for common use – so far, computed tomography (CT), functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) are too complicated, and the most promising solution seems to be the Near InfraRed Spectroscopy (NIRS) BCI.

The user's adaptation to the BCI/neuroprosthesis entails at least two stages: the system learning phase and the adjustment (finetuning) of human-device interaction. Both stages can take a long time for unskilled users. Every user has to learn how to function with the BCI, providing accurate transmission of the intended meaning [1, 2, 9, 13, 14]. Another problem can be ensuring high effectivity of the whole system using low bit rates: 10–25 bits per minute in the case of EEGs [1]. On the other hand, BCIs based on EEGs are well known, safe and relatively cheap. In terms of transmission speed and time required for learning, a better alternative can be a MEG-based BCI. German research has shown a significant reduction in the time needed for the adjustment stage for new users: up to very good results in 32 minutes, while much worse results were obtained in the USA with an EEG-based BCI [15]. Artifacts in EEG signals make preliminary filtration and signal analysis necessary. These artifacts can distort the meaning of the EEG signal and decelerate the user's learning process [16]. Speed and accuracy in using a BCI increases with the effort and time the user devotes to learning, and depends on the whole system being adjusted to the particular user's possibilities and preferences [17–19, 20].

Effective control of neuroprostheses usually requires multi-channel control and a higher bit rate than BCIs for communcation purposes. In terms of control, problems with using neuroprostheses include dispersion of motor control; and the fact that motor learning and the further use of motor functions depends on the continuous adaptive neuroplasticity of the nervous system optimizing control of motoneurons in the spinal cord [13]. With a BCI, the control process can proceed in two possible ways:

– as process control: the BCI manages all the interactions connected with the execution of each move, but this can overload both the BCI and cerebral cortex.

– as goal selection: the BCI only mediates in transmitting user intent (e.g. to move) to the control unit and software of the neuroprosthesis. The neuroprosthesis executes all the necessary procedures on its own, relieving the BCI and cerebral cortex of this task. In the system hierarchy, part of the function of motor control is turned over to lower level(s), equivalent to the spinal cord's motoneurons [13].

Table 1. Selected BCI and neuroprosthetic solutions currently being developed or easily adaptable for neuroprosthetic use

Tabela 1. Wybrane rozwijane obecnie rozwiązania interfejsów mózg–komputer i neuroprotez lub mające możliwość łatwej adaptacji do tych zastosowań

Name (Nazwa)	Researcher/Producer (Producent)	Short description (Krótki opis)
BrainGate2 Neural Interface System [22]	Cyberkinetics Neurotechnology Systems, Brown University, USA	technologies to restore the communication abilities, mobility and independence of people with neurologic disorders, injury or limb loss
Wadsworth BCI System	Laboratory of Neural Injury and Repair, Wadsworth Center, USA	new generation of brain-based communication devices providing communication and control functions to people who have lost muscle control
Cyberhand	Cyberhand Project, Scuola Superiore Sant'Anna, Italy	five-fingered prosthetic hand activated by 6 DC motors, one for each finger (flexion/extension) + one for thumb positioning (adduction/abduction)
WALK! cooperative patient driven neuroprosthetic system [23]	Center of Automation and Autonomous Systems, Technical University of Munich, Germany	cooperative patient-driven neuroprosthetic system (gait neuroprosthesis)
NESS H200 Hand Rehabilitation System [24]	Bioness Inc., USA	medical device using low-level electrical stimulation to activate the various muscle groups in the hand and forearm, allowing the user to open and close the hand
Enobio system [25]	Starlab, Spain	wearable modular and wireless electro-physiology sensor system for recording EEGs, ECGs and EOGs
Biosemi Active Two	Starlab, Spain	advanced EEG data acquisition system, using active electrode technology and open architecture
g.BCIsys (family of devices)	Guger Technologies, g-tec Medical Engineering, Austria	commercial system for data acquisition, analysis, classification and neurofeedback
g.EEGsys (family of devices)	Guger Technologies, g-tec Medical Engineering, Austria	commercial EEG research system
g.USBamp	Guger Technologies, g-tec Medical Engineering, Austria	commercial high accuracy biosignal data acquisition and processing system (brain, heart and muscleactivity; eye movements; respiration; galvanic skin response; other physiological and physical parameters)
BETTER Project	consortium of research centers, Project in the ICT area under the European Community's 7th Framework Programme (FP7)	brain-neural computer interaction for evaluation and testing of physical therapies in stroke rehabilitation of gait disorders
BrainAble Project	consortium of research centers, EU FP 7 financed project	multimodal interface via brain/neuronal computer interaction (BNCI) and affective computing for motor-disabled people to get training, interact with their living environments and join social networks
DECODER Project	consortium of research centers	brain-computer interfaces for the detection of consciousness in non-responsive patients
FUTURE BICI Project	consortium of research centers	encourages interaction among various BCI research groups with different backgrounds
RENACHIP Project	EC project	rehabilitation of a discrete motor learning function by a prosthetic chip
Rehabilitation Gaming System	consortium of research centers	novel approach for motor function relearning following stroke or brain injury
SM4ALL Project	consortium of research centers	improves the use of BCIs to control smart homes
TOBI Project	consortium of research centers, Coordinator: Ecole Polytechnique Fédérale de Lausanne, Switzerland	tools for brain-computer interaction, improving the quality of life of disabled people and the effectiveness of rehabilitation

Table 1. Selected BCI and neuroprosthetic solutions currently being developed or easily adaptable for neuroprosthetic use – cont.

Tabela 1. Wybrane rozwijane obecnie rozwiązania interfejsów mózg-komputer i neuroprotez lub mające możliwość łatwej adaptacji do tych zastosowań – cd.

Name (Nazwa)	Researcher/Producer (Producent)	Short description (Krótki opis)
BrainVision	Brain Products GmBH, Germany	family of BCI hardware, related software and accessories
Speech Restoration Project	Neural Signals Inc., USA	invasive and non-invasive BCIs to restore speech
MindSet	NeuroSky	commercial BCI hardware and software, e.g. for game control or device control (Mac OS, iPhone, iPad)
Minball Game	Interactive Productline	game controlled by the players' mental processes and degree of relaxation

Research in the area of neuroprostheses and BCIs is interdisciplinary, involving the participation of medical staff (neurologists, physiologists, physical therapists, occupational therapists), engineers, philosophers, psychologists and specialists in cognitive science.

Since 2001 institutions in Germany and the US have organized BCI Competitions to assess and compare research being carried out in these areas, The most recent competitions were in 2008, but the 2005 edition was the largest to date, receiving 99 submissions.–

Clinical Applications

It is possible to use BCIs and the types of neuroprostheses described above in the therapy of traumatic brain injury or severe movement deficits of varying etiology (congenital, MS, etc.). The implantation of the interface is the beginning of the therapeutic process. Learning how to use the neuroprosthesis can be included among the rehabilitation procedures in the therapy schedule, in one or more of rehabilitation sessions per day. The learning process is based on work with a simulator, similar to biofeedback technology. During the training the patient learns how to intentionally use the signals produced in his or her brain to achieve desired effects. The number of erroneous trials decreases during the training until the patient is able to deliver commands precisely when he/she intended to. This learning process can be long and arduous because of the required precision of control (e.g., accuracy of motions), but basic functional outcomes can be achieved after several sessions. The main goal during the learning process is to control neural plasticity in way that achieves desired behavior within the brain-machine system.

BCI training is perceived by some researchers as a form of therapy that can possibly be performed at the patient's home [26], for example with an EEG-based Wadsworth BCI system. Several visits are required to complete the patient's and carers' preparation, and after succesful completion of the process of choosing the BCI and training in its use, control visits are needed every 1–2 months. At present the number of possible patients who can receive BCI training at home is limited to those located near Wadsworth Center (in Albany, New York, USA) and/or Helen Hayes Hospital (in West Haverstraw, New York, USA), which provide this service.

The whole process of BCI training calls for extensive knowledge, experience and cognizance among the members of a multidisciplinary team, especially physical therapists and occupational therapists. Ensuring that medical, paramedical and IT personnel are prepared to provide BCI training will no doubt require changes in teaching programs.

The most important thing in the implementation of neuroprostheses is user approval and joint goal-setting [2], which can help the patient and staff cooperate in the most efficient way during therapy in order to achieve the therapeutic goals. Other problems to solve in the implementation of neuroprostheses include:

– ethical implications of BCIs: procedures for the informed consent of the patient, personal and shared responsibility within the team, issues of alteration of patients' personality, the social consequences of "brain upgrading" (e.g. K. Warwick's human enhancement [27]), finding a balance between complete control by the user and autonomy of the BCI and neuroprostheses (e.g. in emergency situations);

– establishing widely approved standards in the area [28];

– identifying and treating potential complications and side effects;

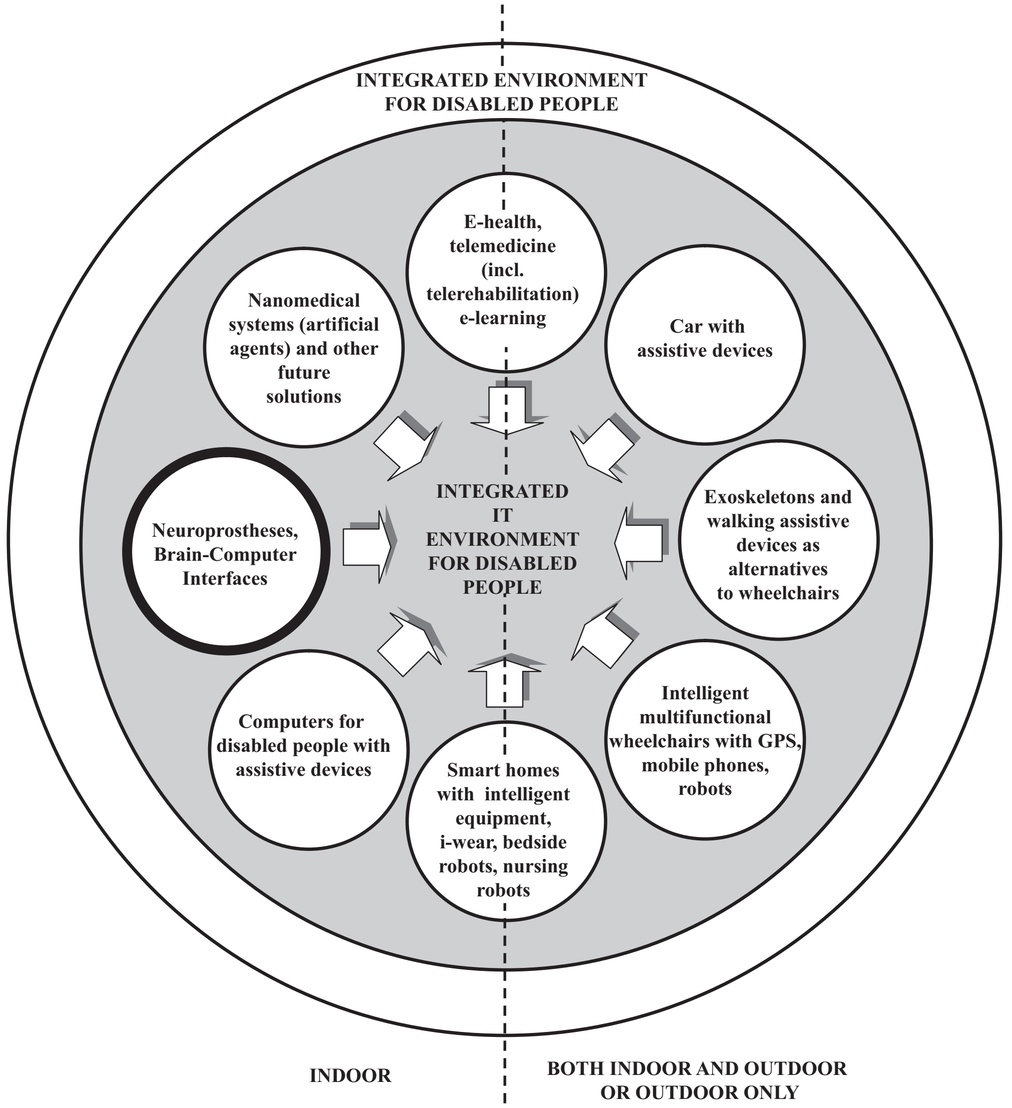

Fig. 4. Neuroprostheses within the concept of disabled people’s integrated IT environment [30–32]

Ryc. 4. Miejsce neuroprotez w ramach koncepcji zintegrowanego środowiska osoby niepełnosprawnej [30–32]

– establishing clinical guidelines regarding indications (severe disability, inability to use conventional assistive communication devices, stable physical and social conditions, ability to understand and apply instructions, ability to use selected BCI instructions, imaging and biofeedback) and contraindications (hypertension, tachycardia, tics);

– ensuring the bio-compatibility of implants (electrode arrays);

– developing correct and repetitive implantation procedures, both surgical and non-surgical,

– developing guidelines and recommendations for pre- and post-operative therapy and rehabilitation, patient learning and re-learning, and co-operation within the multidisciplinary team,

– improving the size, shape and appearance of neuroprosthetic elements;

– reducing power consumption;

– improving data transmission, processing and analysis and data resistance to interference;

– improving security (called neurosecurity);

– improving the convenience of neuroprosthetic use in everyday activities, including the co-ordination of natural and artificially-controlled movements, the smoothness and accuracy of movements, which affects the user's quality of life;

– developing a service and troubleshooting infrastructure for users and carers;

– increasing mobility and co-operation with other systems, such as Ambient Intelligence or a disabled person's integrated IT environment [21, 26, 27]. An integrated solution that is currently widely discussed involves the use of carbon nanotubes (CNT) in BCIs and similar applications [29].

A very important factor in clinical practice can be resistance on the part of patients, especially older ones, to a new technology, and patients' concerns over the ethical issues of direct implantation to the nervous system. It may be necessary to provide additional time for familiarizing these patients and their families/carers with the concepts and issues. In some cases it can be useful to offer more than one option, e.g. with and without implanted electrodes.

Clinical trials confirm the effectiveness of the clinical application of neuroprostheses [28, 30–34], but there is a need for further research in the area. One of the possible directions for the further development of BCIs is the simulation of processes in brain during brain-computer interaction to optimize it in all brain states. This research can contribute to the development of a common frame for several kinds of BCI, easy adjustable to particular patient needs [35]. Other directions for further studies include:

– the development of useful, simplier and user-friendly applications similar to natural interaction (e.g. integrated analysis EEG/ENG [28], wireless technologies [36]);

– research on the long-term effects [22];

– the development of a family of simple, universal, accessible interfaces between BCIs and commonly-used devices: remote controls, mp3/mp4 players, cell phones (see the MindSet family of products Table 1);

– technical development with easy technical support and troubleshooting;

– educating both biomedical (rehabilitative) engineers and medical staff to assistance with therapy using BCIs;

– integration with other solutions.

The European DECODER project (see Table 1) developing brain-computer interfaces for the detection of consciousness in non-responsive patients (in a vegetative state, minimally conscious state, locked-in syndrome, etc.) may be very important for clinical practice. The variability of consciousness disorders and a lack of precise definitions make proper diagnosis difficult. Assistive technology based on BCIs can help with the exact diagnosis of these disorders and support the patients' interaction with the environment. Then the most appropriate rehabilitation strategy and the most effective supportive technology can be defined. There is great hope among both medical personnel and biomedical engineers that the ok DECODER project will lead to significant improvements in the quality of life of patients and their families/carers. The most important issues in the project are:

– overcoming the diagnostic gap, providing easy to use diagnostic tools;

– further developing and adapting existing BCI systems and applications for single-switch BCI (ssBCI) control purposes, because some patients with consciousness disorders cannot use multi-switch devices or hybrid BCIs, even after lengthy rehabilitation.

In the research area, the DECODER project is related to the TOBI and FutureBCI projects (see Table 1). Another development contributing to progress in BCIs may be simultaneous EEG-fMRI, combining the high spatial resolution of the fMRI with the high time resolution of the EEG. Such developments can contribute in a non-invasive way to the understanding of brain dysfunction.

Conclusions

The technology of neuroprostheses for mobility and control is still in the early stages, but.BCIs and neuroprostheses are promising technologies that can significantly help restore the commmunication abilities, mobility and independence of disabled people, especially those with the biggest limitations and deficits [30, 37–48]. These technologies can break down another barrier between humans and computers, replacing some of the current adaptive devices for disabled people. Technical development in this area calls for close co-operation between scientists and medical staff in order to provide more clinical trials and experience with BCIs and neuroprostheses. Further BCI and neuroprosthetic applications require clear and safe clinical procedures. All of this can significantly increase the effectiveness of contemporary and future rehabilitation.

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Address for correspondence:

Emilia Mikołajewska
Rehabilitation Clinic
Military Clinical Hospital No. 10 and Polyclinic
Powstańców Warszawy 5
85-681 Bydgoszcz
Poland
e-mail: e.mikolajewska@wp.pl

Conflict of interest: None declared

Received: 19.05.2011
Revised: 31.01.2011
Accepted: 29.03.2012