REVIEWS

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Exoskeletons in Neurological Diseases – Current and Potential Future Applications

Egzoszkielety w terapii schorzeń neurologicznych – zastosowania obecne i przyszłe

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Abstract

An exoskeleton is a distinctive kind of robot to be worn as an overall, effectively supporting or, in some cases substituting for, the user's own movements. The development of exoskeletons can lead to important changes in the rehabilitation of disabled people by introducing an alternative to wheelchairs. Exoskeletons can be an efficient tool in gait re-education and in the restoration of upper limb functions, and they can support therapists and caregivers in tasks that require major physical effort. The functionality of exoskeleton can easily be extended by a "disabled person integrated IT environment", described by authors. Exoskeletons can also be easily adapted to the needs of severely ill or aged people (**Adv Clin Exp Med 2011, 20, 2, 227–233**).

Key words: neurological diseases, rehabilitation, robotics, exoskeleton, hospital care, home care.

Streszczenie

Egzoszkielet to szczególny rodzaj robota zakładanego na użytkownika w formie kombinezonu skutecznie wspomagającego lub, w wybranych przypadkach, zastępującego jego ruch. Rozwój egzoszkieletów może doprowadzić do zmian w rehabilitacji osób niepełnosprawnych dzięki wprowadzeniu alternatywy dla wózków dla osób niepełnosprawnych, wykorzystanie egzoszkieletów jako skutecznych narzędzi do reedukacji chodu i czynności kończyn górnych oraz jako wsparcie terapeutów i opiekunów osób niepełnosprawnych, ciężko chorych i w podeszłym wieku przy wykonywaniu czynności związanych ze znacznym wysiłkiem fizycznym. Funkcjonalność egzoszkieletu może zostać zwiększona dzięki włączeniu go w przedstawione przez autorów „zintegrowane środowisko teleinformatyczne osoby niepełnosprawnej". Prezentowane rozwiązania mogą w łatwy sposób być przystosowane do potrzeb osób ciężko chorych lub w podeszłym wieku (**Adv Clin Exp Med 2011, 20, 2, 227–233**).

Słowa kluczowe: choroby neurologiczne, rehabilitacja, robotyka, egzoszkielet, opieka szpitalna, opieka domowa.

An exoskeleton is a distinctive kind of robot to be worn as an overall or frame, effectively supporting, or in some cases substituting for, the user's own movements [1–4]. The aim of this article is to discuss the possible use of exoskeletons in the treatment of neurological diseases, including neurorehabilitation. The authors have reviewed publications in the *PubMed* database (Figure 1); the keyword "exoskeleton" does not occur in the MeSH database.

Exoskeletons are still at the early stages of their development. They need detailed technical and clinical research not only in the area of safety, but also in terms of their influence on the human body, biomechanics and mind. It seems that in the future exoskeletons may become a form of therapy in neurological diseases and neurorehabiltiation.

Exoskeletons can be divided into two categories: those for all four extremities (arms/legs) and those for the lower extremities only.

Exoskeletons are controlled by the user's movements and do not need any external control terminal (with the exception of a service terminal). The main parts are: the frame; the power system, including engines, actuators and batteries; and the control system with sensors.

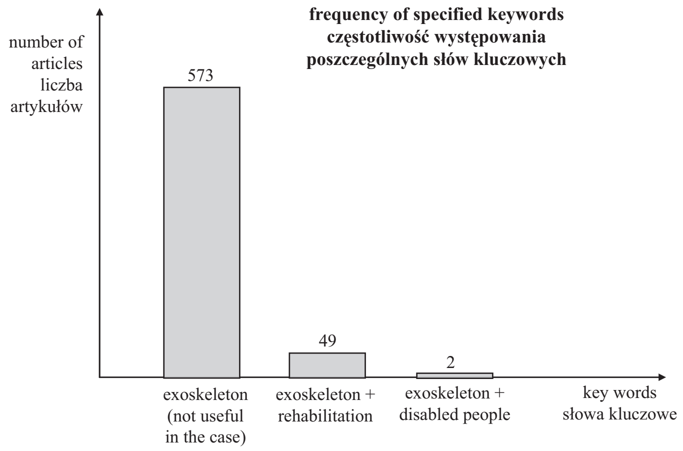

Fig. 1. Results of investigation of the *PubMed* database (U.S. National Library of Medicine) [5]

Ryc. 1. Wyniki przeszukiwania bazy danych *PubMed* (U.S. National Library of Medicine) [5]

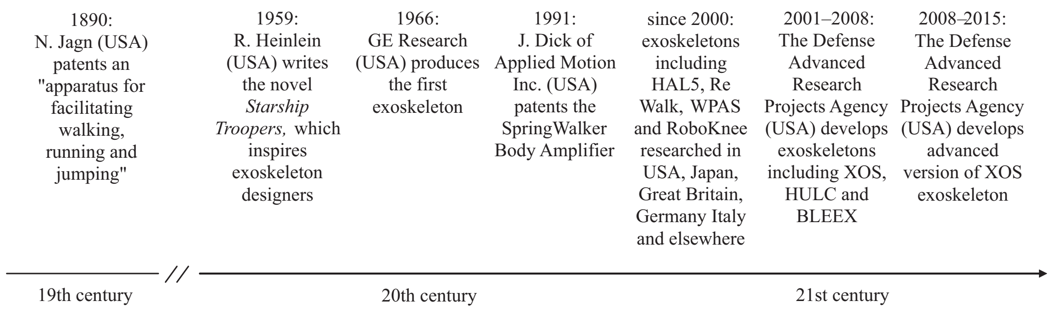

Fig. 2. Milestones in the history of exoskeletons

Ryc. 2. Kamienie milowe w historii egzoszkieletów

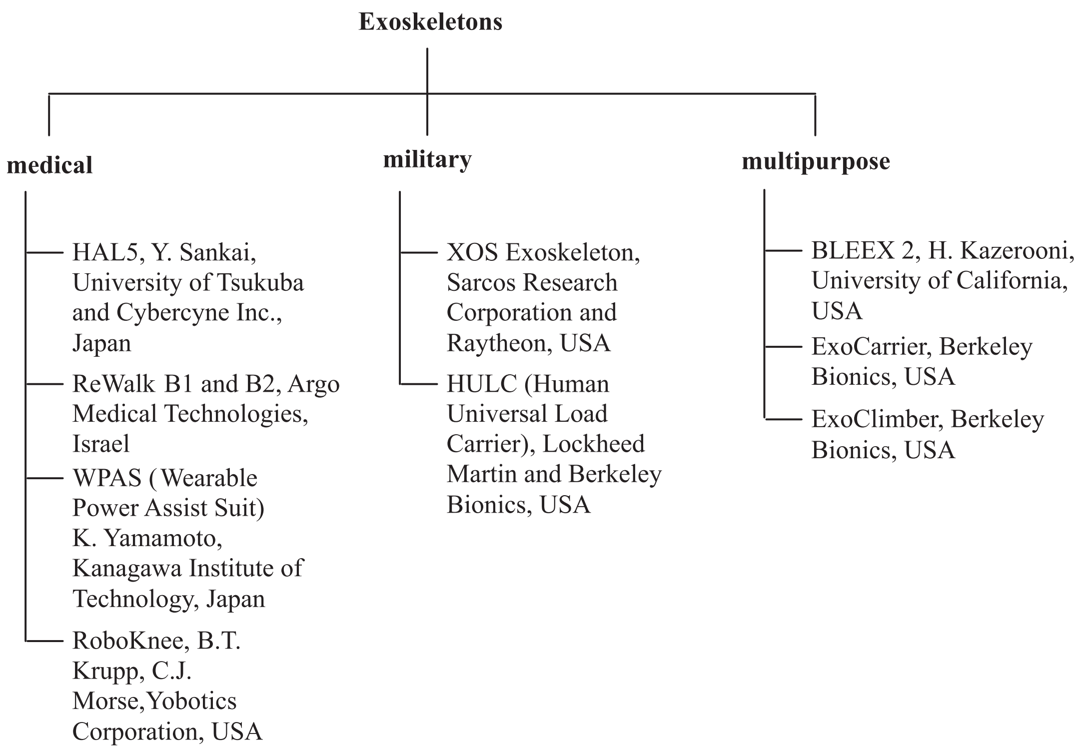

Fig. 3. The main current exoskeletons

Ryc. 3. Najważniejsze współczesne egzoszkielety

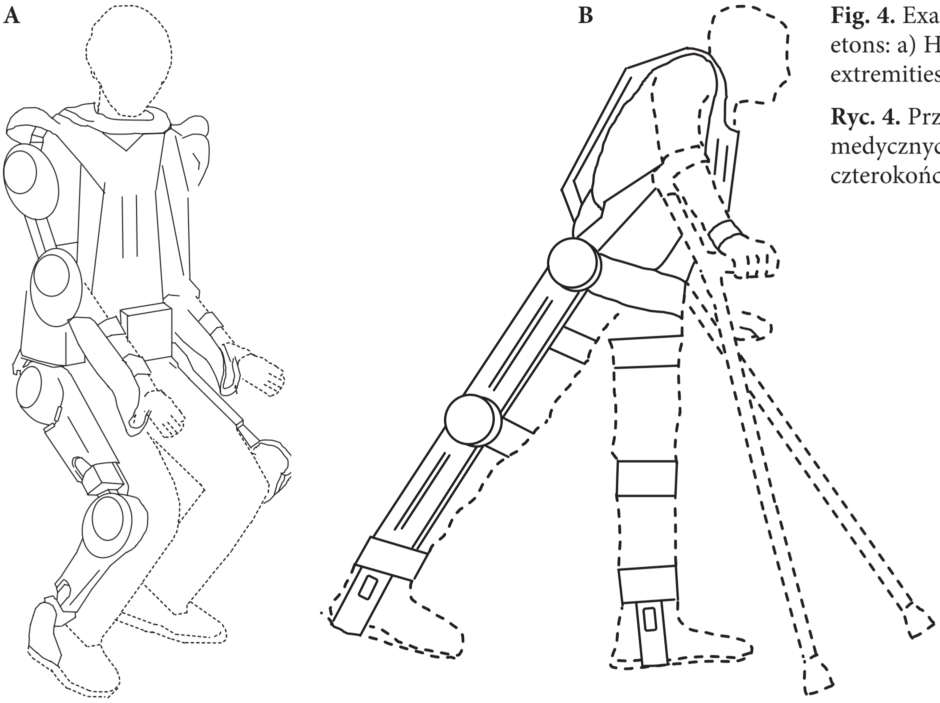

Fig. 4. Examples of medical exoskeletons: a) HAL5 – version for four extremities [1], b) ReWalk

Ryc. 4. Przykłady egzoszkieletów medycznych: a) HAL5 – wersja czterokończynowa [1], b) ReWalk

Generally, the main features that are important for exoskeleton users are: the means and level of support; the ways the device is controlled and how the user conveys intentions: EEG, electromyography (EMG), angle sensors, pressure sensors, etc.; the weight; limitations due to the user's height and length of limbs; the time and effort needed for fitting and pre-setting the exoskeleton before its first use; convenience and comfort in all-day use; the time needed to recharge batteries; in some cases, the possibility of folding and transporting ready-to-use (programmed) exoskeleton; the exoskeleton's self-diagnostic capabilities; compatibility with local intelligent systems (smart home, i-wear, Ambient Intelligence, etc.) at home, at work, in the hospital, etc.; trends in the development of exoskeletons, including their integration into disabled people's wider environments, including the need for sufficient levels of home care and therapy, telerehabilitation and distant supervision (distant measurement of parameters, alerts, etc.).

Further technical developments are needed to solve current limitations and problems with exoskeletons: longer-lasting power batteries; lighter and stronger materials for the frame; more powerful actuators; more sophisticated control systems, such as EEG instead of EMG, advanced neuroprostheses and Brain-Computer Interfaces (BCIs), more efficient processes of fitting and customizing.

Support for User Intent in Exoskeletons

Information for the exoskeleton control system can usually be provided by several sets of sensors: EMG sensors or sensors of other bioelectric activity attached to skin; angle sensors, pressure sensors, gyroscopes, accelerometers, etc., attached to the frame of the exoskeleton: in the future, EEG sensors, pulse rate sensors, etc., attached to the skin or implanted. Additionally, the power system provides information about the working load in each part of the exoskeleton and about the power reserve. Generally, the procedure of assisting the user with an intended movement is as follows: 1) analysis of the current situation: posture, limb positions, etc., based on signals collected from EMG or other sensors (muscle contraction, etc.); 2) when the user attempts to move: the exoskeleton control system analyzes the sensor signals and determines the user's intended movement; 3) the control system selects a pre-programmed movement pattern, adjusts it to the user's current position and supports the movement with actuators using the appropriate force; 4) after completing the movement, the control system analyzes the new situation – posture, limb positions, etc. – assessing and preparing for the user's next possible movements [7–9].

This algorithm also includes balance control (necessary for fall protection) [10] and co-ordination of several movements at the same time. An exoskeleton can have two or more control systems working together, e.g. the HAL5 exoskeleton with

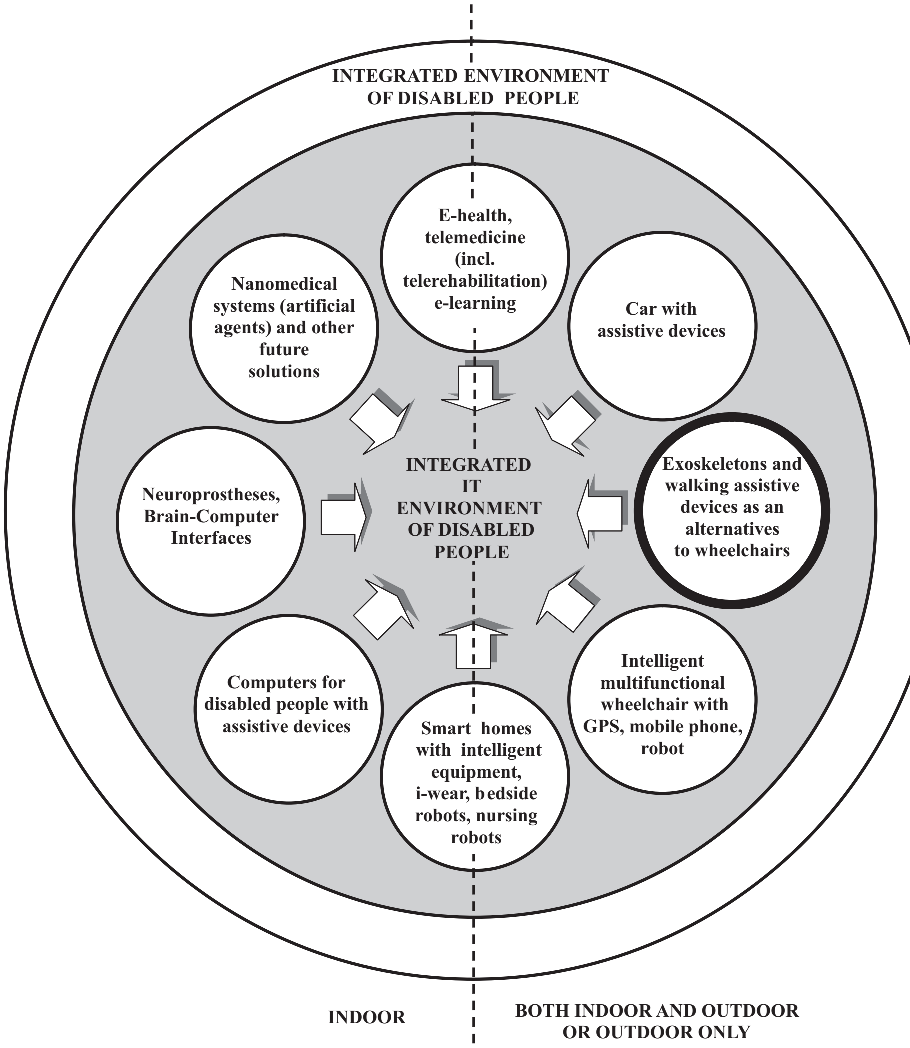

Fig. 5. Exoskeletons within the concept of disabled people's integrated IT environment [6]

Ryc. 5. Miejsce egzoszkieletu w ramach koncepcji zintegrowanego środowiska osoby niepełnosprawnej [6]

two control systems: Cybernic Voluntary Control, based on bio-electric signals observed on the surface of the skin, and the Robotic Autonomous Control System, based on a database of elementary movements, allowing for exoskeleton movements despite poor bio-electric signals from the user.

For patients with hemiparesis, it is important to provide more support for the affected side. For safety reasons it is necessary for the exoskeleton to work properly even in emergency situations, e.g. when the sensors unexpected malfunction. Also, an exoskeleton being worn by user must not collapse even if the battery is low. An easy-to-operate emergency switch-off systems for disable people (e.g. a puff/sip switch) is also necessary.

Medical Uses of Exoskeletons

Generally an exoskeleton is a technical tool that expands and improves selected abilities of the user. From a medical point of view, it can serve as a multi-purpose medical device: as an alternative to wheelchairs (both powered and manual), providing mobility and increasing patients' possibilities, especially in climbing stairs. Using an exoskeleton is closer to natural human mobility than using a wheelchair; as an efficient supplementary tool in gait re-education and as an option in restoring upper-limb functions. Exoskeletons are perceived as probably more effective than the traditional assistance and support of therapists and rehabilitative devices (e.g. rehabilitative robots) [13–15]; to support therapists and caregivers in tasks requiring major physical effort, e.g. patient transfer; as a tool for gaining a better understanding of human body posture and movement.

Because of this wide range of possibilities it is important to develop medical exoskeletons, designed for use in the therapy of patients with CNS diseases, stroke or spinal cord injury (SCI). In this kind of therapy exoskeletons can provide: all-day supported mobility, with a full range of motions and proper movement patterns; the possibility of training in (or re-learning of) all functional activities: lying, sitting, standing, walking, transfer, stair climbing, ascending/descending slopes and activities of daily living (ADLs) in a way similar to normal life (some exoskeletons even permit the users to drive cars); efficient support for weak patients, improving their muscle strength, bone density, cardiovascular system and endurance, to prepare them for normal functioning; the possibility of nearly-natural all-day functioning, with posture and movements that are better for the digestive, respiratory and urinary systems; a reduction in the energy expenditure required for exercises [16–18].

Because exoskeletons are multi-purpose robots their wide implementation could decrease the number of rehabilitation tools needed, and the total cost of rehablitation. Generally, the use of exoskeletons can: increase the possibilities and effectiveness of rehabilitation, especially neurorehabilitation, through intensive all-day functional therapy during normal life activities; increase the accessibility of rehabilitation, including home rehabilitation and home care; increase the user's safety (fall protection); save money and time, decreasing the average hospital stay and the number of therapists needed per patient (especially in gait re-education); stimulate developments in other branches, e.g. geriatric therapy and care.

These developments require additional clinical research following the Evidence-Based Medicine paradigm, to provide standards and guidelines for prescribing, selecting and fitting the exoskeleton and conducting the therapy; for effectivity assessment, safety and troubleshooting; for the training of medical staff, especially physiotherapists; and for the training of users and carers. Clinical research on the medical exoskeleton HAL5 (Hybrid Assistive Limb 5) is being conducted at Danderyds Hospital in Sweden and Odense Universitetshospital in Denmark; and on the exoskeleton ReWalk at the Chaim Sheba Medical Center Neurological Rehabilitation Department (Israel), and at the MassRehab Massachusetts Rehabilitation Commission (USA).

The Prospects for Clinical Use

The clinical use of exoskeletons requires the co-operation of a whole multidisciplinary team, including biomedical engineers. It calls for careful preparation, and could consist of the stages described below.

1) Patient preparation:

– explaining the procedures to the patient;

– assessment of the patient's health status (including secondary health problems, indications and contraindications);

– functional diagnosis: what the patient can do, hidden potentials, deficits and limitations;

– anthropometric measurements;

– clinical gait analysis;

– other movement analysis: upper limbs and spine evaluation;

– assessment of the patient's way of life and ADLs;

– discussion of the preferences, goals and motivation of the patient and caregivers (e.g. in the area of home rehabilitation);

– assessment of the patient's possibilities for controlling the exoskeleton (cognitive and functional deficits, limitations and weaknesses);

– choice of exoskeleton type and features (dimensions, ranges of adjustment, modes of support and control, etc).

It is important to emphasize the fact that an exoskelton works with the user, so the user must be able to control the exoskeleton properly. Using the exoskeleton should help the patient to achieve therapeutic goals, functional independence and an improved quality of life more efficiently than traditional therapy.

2) Exoskeleton fitting and set-up:

– matching the exoskeleton features to the patient's current health status and anthropometric measurements;

– implementing patterns of the patient's posture (lying, sitting, standing, etc.), transfer (sitting to standing, etc.), gait and other activities such as stair climbing, ascending/descending a slope and ADLs;

– adjusting the level of exoskeletal support and the exoskeleton control modes;

– trials with the patient and fine-tuning adjustments.

Exoskeletons need to be comfortable, convenient and functional for all-day use, and allow the user to move in the most natural way possible.

3) Clinical trials with the patient:

– training with the patient and caregivers, including emergency situations;

– assessment of the effectiveness of the therapy, including the influence of other rehabilitation methods used at the same time;

– assessment of functioning, comfort and convenience, and of the patient's adaptation to human-robot interaction;

– analysis and implementation of conclusions in both the exoskeleton technology and the way the therapy is conducted.

At present, stages 1–3 can last up to several months. There is a clear need to reduce this time span by introducing standards and clinical guidelines.

4) Normal clinical use:

– therapy with the patient (including the family and caregivers if necessary);

– assessment of the goals and results of the therapy, including the patient's preferences;

– implementation of the conclusions;

– if necessary, establishing a program of normal home use.

The use of an exoskeleton during acute rehabilitation and hospitalization is a only a supplement to other forms of therapy, such as physiotherapy, kinesitherapy and pharmacotherapy, However, if a patient needs only exoskeleton therapy (e.g. in gait re-education), this can be provided on an outpatient basis or at home. Additional studies are needed to establish standards and guidelines for the safe and effective use of exoskeletons in home rehabilitation programs under the regular oversight of a therapist.

5) Normal home use and rehabilitation (optional):

– normal all-day home use of the exoskeleton, including therapy (from simple exercises to telerehabilitation),

– ongoing assessment of the patient's health status and functional abilities, including secondary changes such as pressure ulcers;

– continued assessment of the goals and results of the therapy;

– ongoing assessment of the technical condition of the exoskeleton;

– analysis and implementation of conclusions.

It is important to emphasize that in a significant percentage of patients it may be possible to abandon the exoskeleton after therapy and to live normally without it, and the therapy should be conducted in a manner that takes this into account.

All of the procedures proposed above call for more clinical research and detailed guidelines.

Conclusions

Exoskeletons can significantly change the model of therapy in neurological diseases and the lives of disabled people, improving their quality of life and their chances for independence, education, work and entertainment. The further development of control systems, especially neuroprostheses and brain-computer interfaces, can significantly improve access to this form of therapy for people with severe deficits. Broadening the medical uses of exoskeletons can stimulate development of other branches such as geriatric therapy and care.

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