Human-Robot Communication in Rehabilitation Devices

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Abstract:
Robotic systems assisting physical rehabilitation are developed for both commercial purposes and personal use. In the years to come, such devices will be used mainly by the elderly, the disabled, as well as children and adults after accidents and disorders limiting their physical capabilities. As the population is getting older, the issue becomes more and more critical. A growing number of people requiring rehabilitation generate significant costs, of which personal expenses are a major component. Providing the human personnel with appropriate mechatronic devices or replacing at least some rehabilitation medicine specialists with robots could reduce physical and mental workload of physicians. Broader application of such devices will also require lower prices and improved Human-Robot Communication (HRC) solutions. This article presents general requirements regarding the communication with rehabilitation robots, presents human-robot communication solutions developed by different manufacturers, describes the system applied in RENUS robots and indicates directions in which the HRCshould evolve.

Keywords: *rehabilitation robotics, Human-Robot Communication*

1. Introduction

At the initial stages of development of robotics, the efforts of research teams were focused mainly on industrial applications. The first practical implementations were also performed in industrial environments. The concepts involving the introduction of robots to our everyday environment started to gain real shape in the 1980s. Numerous research & development projects entered the application stage. The main objective of those works was creating intelligent appliances capable of taking over certain everyday tasks hitherto performed by people. At that time, the term of "service robots" was devised. The first synthetic works were elaborated: they were a bit visionary at first [1], but soon after they presented specific practical achievements [2]. As a result of the rapid development of service robots in terms of both their construction and possible fields of application, they have not been precisely systematised so far. The ISO standard [3] regarding the terms and definitions has not included any definition of a service robot until the 2012 issue, which stated: A robot that performs useful tasks for humans or equipment excluding industrial automation applications.

Service robots were divided into two groups:
- personal service robots or service robot for personal (private) use;
- professional service robots or service robot for commercial user.

The second category encompasses medical robots, including rehabilitation robots. According to the International Federation of Robotics IFR [4], the sales of medical robots exceeded 1,000 units per year in the years 2011–2012. The growth dynamics in this segment is relatively low (approx. 2%), as compared to personal service robots (approx. 20%). The growth in the second group in the years to come should be stimulated by growing demand for devices for older and physically disabled patients [18], [19], facilitating their care and assisting them in everyday tasks. They will also perform an important task of assisting them in maintaining or regaining physical capabilities. Subsequent development of personal rehabilitation or training robots might be expected. From the technical perspective, the contemporary state of development of material engineering, manufacturing devices, control systems and sensors is already sufficient for building such robots. The first barrier in their popularisation is pricing – such devices should be more affordable. Communication is yet another problem, particularly significant in the case of the elderly and the disabled. Offering rehabilitation robots with effective yet simple communication systems might determine the acceptance of such devices by their prospective users. It applies to commercial robots used in healthcare facilities, as well as to personal devices.

2. Arguments for the Application of Mechatronic Devices in Supporting Rehabilitation

2.1. Role of robotics in supporting the rehabilitation process

Rehabilitation of the disabled has been defined in the Polish legislation as a range of activities, including particularly, without limitation, organisational, medical, psychological, technical, training, educational and social activities, aimed at achieving the highest possible level of functioning, life quality and social integration of persons with disabilities with their active involvement (Act on vocational and social rehabilitation and employment of persons with disabilities). The classical rehabilitation model assumes the classification of rehabilitation types into:

- medical,
- psychological,
- vocational,
- social.

If possible, these modules are implemented simultaneously, but the process is based mostly on medical and psychological rehabilitation. Medical rehabilitation is expected to improve the quality of life and enable the patient to normally function in the society. For this goal to be achieved, the patient must be under care of an entire rehabilitation team led and managed by a rehabilitation physician. Other team members may include a physiotherapist, a nurse, a psychologist, a speech therapist, an occupational therapist, an orthotist, a social assistant or even a health care chaplain. Each member performs her or his own specific treatment practices and tasks, contributing to the final effect.

Improved capabilities and self-dependence of a patient are the milestones on the path to the higher quality of life. Improvement of capabilities requires the improvement in the range of joint motion, greater muscle strength and endurance, increased stamina resulting from improvements related to the cardiovascular and respiratory systems, improved neuromuscular coordination, improved balance recovery, better locomotion skills: walking or moving on a wheelchair, improved communication skills: speaking, speech comprehension, writing, reading, improved hand functions, better control over the anal and urethral sphincter. This emphasises the role of reducing and eliminating dysfunctions of locomotor system, i.e. physical training (called also physical/locomotor rehabilitation, motor/motoric/movement rehabilitation/training) in the entire rehabilitation process. Today, it is also the main field of rehabilitation, where automation and robotic technologies are being applied.

Simply speaking, the process of physical training involves specific and precisely defined exercises repeated with gradually increased parameters. Such parameters may include:

- resistance force,
- number of repetitions,,
- speed of movement,
- movement precision.

Many repetitions typically cause fatigue and – if there is no quick progress – a feeling of discouragement and a growing lack of faith in the ultimate success. This discouragement can be felt both by the patient and by the personnel, including particularly physiotherapists responsible for the exercises. Overcoming such negative feelings requires remarkable empathy. Therefore, efforts are made to make the exercises more attractive, improve their precision and boost the patient's commitment and motivation. Mechatronic and robotised rehabilitation devices respond to the aforementioned needs. Being a result of the collaboration of engineers, physicians and physiotherapists, they enable precise spatial motion repetition as long as it is required without changing any parameters, as well as documenting and recording therapeutic sessions and their results. Automatic documentation is important for evaluating the therapeutic value of the machine-assisted rehabilitation through comparative analysis; it also generates a collection of data for the patient, her or his family and the insurance company covering the costs of treatment.

2.2 Importance of the Problem

Rehabilitation is the field of medicine with the largest number of patients. Successes in the fields of cardiac surgery, neurosurgery, orthopaedics, neurology, cardiology, pulmonology, rheumatology, oncology, paediatrics or internal medicine cause a decrease in mortality and give patients a chance to return to normal life. Rehabilitation is a way to take this chance. Physical medicine and rehabilitation treat patients coming from all medical specialties. To visualise the broad need for rehabilitation, let us list the most typical disorders, injuries and conditions requiring physical rehabilitation:

- fractures;,
- muscle injuries,
- strokes,
- inflammatory and degenerative diseases of nervous tissue resulting in paresis or paralysis,
- post-amputation conditions,
- conditions after tumour surgeries,
- conditions after myocardial infarction,
- conditions after surgical heart valve replacement,
- conditions caused by asthma or chronic bronchitis,
- conditions caused by rheumatoid arthritis,
- conditions caused by degenerative joint and spine diseases,
- conditions caused by hypertension or diabetes,
- wasting syndromes or diseases caused by obesity.

The aforementioned conditions may cause diverse disabilities, among which the physical disabilities are the largest group. A growing number of new patients require rehabilitation, which is confirmed by medical statistics showing the numbers of cases in each category. For instance, in Poland, there are about 90,000 strokes every year and it is the most frequent cause of disability in patients over 40.

The second major cause of impaired physical capabilities is age. Increasing life expectancy all over the world is a great success of the modern civilisation in general, but its side effect is aging of the population. It, in turn, increases the demand for rehabilitation (mostly physical) among the elderly. The goal is to enable those people to remain fit and self-dependent as long as possible. According to the forecasts of the Polish Central Statistical Office [16], the population of Poland is bound to decrease in the next 35 years. However, the group of the elderly, i.e. citizens over 65, will grow in number. In 2030, the group will consist of 8 million people, while in 2050 – 11 million citizens, i.e. over 32% of the total population. Interestingly, the same forecasts assume that the number of people over 80 will exceed 3.5 million in 2050, constituting over 10% of the population of Poland (see: Table 1). Many of those people are expected to need assistance in the form of exercises or physical rehabilitation.

Table 1. Polish population forecasts by age groups

Year	2013	2015	2020	2030	2040	2050
Total [x1000]	38.496	38.419	38.138	37.185	35.668	33.951
65+ [x1000]	5.673	6.071	7.194	8.646	9.429	11.097
65+ [%]	14.7%	15.8%	18.9%	23.,3%	26.4%	32.7%
85+ [x1000]	1.483	1.560	1.684	2.206	3.373	3.538
85+ [%]	3.9%	4.1	4,4	5.,9	9.5	10.4

The situation of the disabled is addressed by numerous organisations and government institutions. The office of the Polish Government Plenipotentiary for People with Disabilities [29] publishes statistical data regarding the situation of this social group. According to the most recent information, the total number of people with disabilities in Poland as at the end of March 2011 amounted to 4.7 million, constituting 12.2% of the entire population. The most frequent causes of disability are cardiovascular, locomotor and neurological disorders, while the most frequent type of disability is impaired physical capability. It is currently estimated [17] that people with locomotor system disabilities constitute over 50% of the entire population of the disabled in Poland. It means that this group consists of about 2.5 million people, a large number of which need rehabilitation.

A growing number of people requiring rehabilitation generates significant costs, of which personal expenses are a major component. In the field of rehabilitation, such expenses generate 65% of the total costs. Providing the human personnel with appropriate mechatronic devices or replacing at least some rehabilitation medicine specialists with robots is a proper direction, which can boost the effectiveness and reduce physical and mental workload of physicians.

3. Robotised Technologies in Physical Rehabilitation

The positive impact of exercises on both physical and mental health was known even in the ancient times. Back in those days, exercises were meant to help improve and maintain general fitness, as well as regain such fitness by people who had been injured. Physical exercises were systematised according to their therapeutic effects on specific body parts by H. Ling [8], which laid the groundwork for the emergence of so-called medical gymnastics. In the 19th century, it was widely promoted and developed in many centres all over the world and often applied in the treatment of orthopaedic disorders. It would be combined with diverse other methods that were popular at the time, such as drinking healing waters, baths or massages. The first therapeutic facilities were opened in places with appropriate climate, where patients received comprehensive recuperation treatment. In such centres, where numerous patients would undergo medical gymnastic exercises (the term "rehabilitation" had not been introduced until the beginning of the 20th century) at the same time, exercise-facilitating devices were becoming more and more popular. Those included mainly mechanical devices, so the treatment techniques based on exercises employing such solutions became known as mechanotherapy.

Fig. 1. A room in the Salt Brewing and Health Resort Museum in Ciechocinek (Poland). Collection of medical gymnastics apparatuses designed by Wilhelm Zander

One of the most renowned creators of devices used in medical gymnastics (or 'apparatuses', as they were called at that time) was a Swedish doctor named Jonas Gustav Wilhelm Zander [8], who developed a method of treatment and regaining fitness through exercises performed on the apparatuses he designed. Since J. G. W. Zander was a highly talented designer, he created numerous devices, which today can be admired in many museums all over the world. The largest Polish collection of Zander apparatuses is displayed in the Salt Brewing and Health Resort Museum in Ciechocinek (Fig. 1), including several dozens of meticulously renovated devices for medical gymnastics designed by Zander. Many of them were used in local healthcare facilities (hospital, sanatoria, rehabilitation centres).

Devices assisting physical rehabilitation were developed through upgrading their construction and introducing new materials. The natural consequence of this development was emergence of a new field of study – rehabilitation robotics. The first R&D works on the application of robotised technologies in supporting physical rehabilitation were carried out in USA in the early 1960s. Rancho Los Amigos National Rehabilitation Center (Rancho) created an electrically-powered orthosis with seven degrees of freedom. This device called Rancho Golden Arm [9] was initially designed for patients with the post-polio syndrome. At the same time, scientists from the Case Institute of Technology (Cleveland, Ohio, currently: Case Western Reserve University) created a pneumatic orthosis with four degrees of freedom. In both cases, practical application of the inventions was difficult due to insufficiently effective control systems and the lack of sensors that would ensure feedback depending on the position, speed and force. Further development of advanced sensor and computer technologies and their subsequent application in the field of robotics encouraged works on rehabilitation robots. In the 1980s, those efforts took place mainly on American and Western European universities and their research and development centres. It coincided with a breakthrough in medical research over the organisation of brain functioning and the nervous tissue structure, which significantly expanded the knowledge about brain and its highly flexible internal construction. Scientists coined a term of neuroplasticity meaning the ability of nerve cells in the brain to regenerate and create new networks with other neurons. As a result, the healthy nervous tissue can take over those functions of the brain, which have been impaired as a result of a local irreversible damage, e.g. caused by a stroke. It means that, through effective physical training requiring regular and long-term exercises, patients can teach their brains again to perform certain activities (such as walking, grabbing, etc.). The results of the medical research encouraged further research and development works over new and advanced rehabilitation devices using the solutions hitherto applied in robotics.

One of the first mechatronic rehabilitation devices, which have been positively evaluated by the global medical community, is the Manus robot developed in MIT [10] to assist the rehabilitation of upper limbs (Fig. 2a). Its mechanical part is composed of a manipulator having the kinematic structure of the robot named SCARA. The control system integrates the sensors of force and location with the complex patient-robot communication interface. During the exercises, the patient observes the cursor reflecting the arm location and tries to relocate it as instructed or (at a later stage of the rehabilitation process) tries to reproduce the presented (displayed) cursor motion. The implemented software enables the evaluation of the patient's progress on the basis of analysis of the recorded arm movement in each and every exercise.

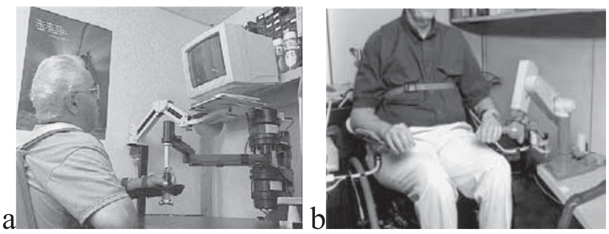

Fig. 2. Robots used in physical rehabilitation: a – Manus from MIT [10], b – MIME from Stanford [11]

The positive impact of the Manus robot application on the rehabilitation process was confirmed by research results [10]. The response of patients to the new device and exercise method was highly positive. An important factor in this respect is the graphical user interface enabling patient-robot communication. Carefully selected exercise, clear commands and ongoing assessment of the rehabilitation progress by the software and control system motivate the patients. However, kinematic properties of the Manus robot manipulator enable only a single-plane motion, which somewhat limits its application.

Another concept was implemented in the University of Stanford [11] – a major US centre of advanced rehabilitation robot development. The solution was based on a classic industrial robot called PUMA (Staubli Unimation Inc.), which, using a special mechanical interface, leads the patients arm along the programmed trajectory (Fig. 3b). This system named MIME (Mirror Image Movement Enabler) enables movement of the rehabilitated upper limbs along multi-plane trajectories [11].

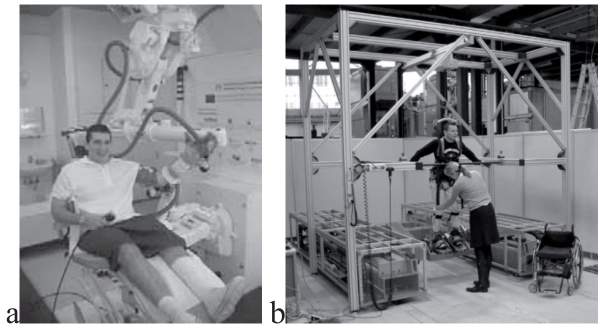

Fig. 3. European research projects in the field of application of robotised technologies in physical rehabilitation: a – demonstration of the Reharob project (BUTE Budapest), b – tests of the Haptic Walker – a robotised device for walking simulation (Fraunhofer IPK Berlin)

Similar approach was applied in one of the first European projects in the field of robot-assisted arm rehabilitation. Reharob project was created under the 5th EU Framework Program (IST-1999-13109) [38]. Its main objective was to develop an arm rehabilitation system using standard robots. The project was coordinated by the University of Budapest and the consortium included the ABB company which supplied two industrial robots. Owing to proper situation (one robot supports the arm near the elbow and another robot moves the patient's wrist) and control of those robots, the system enables the movement of the patient's arm on all anatomical planes of motion (Fig. 3a).

Research on devices assisting physical training has been performed for many years by the IPK institute in Berlin belonging to the Fraunhofer network [12]. One of their most interesting projects is Haptic Walker, developed in collaboration with the Technical University of Berlin. It is a device for learning or rather re-learning to walk. The patient's feet are supported by platforms, whose trajectories can be fully programmed. This principle is applied in many similar constructions, including those designed for the commercial market.

A modern medical robot used in rehabilitation must:
- accurately imitate the target movement of a body part as a passive movement,
- precisely adjust the resistance that the patient is supposed to overcome,
- communicate with the patient, signalling whether a given exercise is performed correctly or incorrectly (biofeedback),
- request the performance of specific tasks (including associating, memorising, observation),

- store a set of data enabling gradual increase of difficulty level and visualise the patient's work in an attractive way,
- "reward" satisfactory performance of exercises,
- record the course of exercises,
- quick diagnose the initial state and the final outcome of the rehabilitation process.

4. Communication of Human with Service Robot

Interaction between people and machines, including computers and robots, has been the subject of academic research for years, especially in the field of ergonomics, which attempts to adjust the machines to the requirements and specific needs of human physiology. In the case of computers and robots, including particularly service robots, the existing knowledge on ergonomics has proven insufficient for detailed and reliable analysis of complex interaction between people and computers/robots. Therefore, there have emerged new interdisciplinary areas of study named HCI (Human-Computer Interaction) and HRI (Human- Robot Interaction). The HRI researches refer to diverse fields of knowledge, such as computer technologies (including HCI), artificial intelligence, linguistics, medicine (including physiology), social sciences (including psychology and sociology), art (theory of aesthetics) and system technologies. Apart from theoretical, cognitive and systematising qualities, the results of the HRI research have also practical application, as they are expected to enable formulation of practical guidelines for human-robot interface designers. On the basis of such guidelines, a robot designer will be able to design more effective and user-friendly human-robot communication interfaces, whose absence is today a barrier in rapid popularisation of service robots [12].

The method of human-robot communication depends on the type of signal used to transmit the information (electrical, mechanical, acoustic, visual). Methods of generating and receiving such signals are also significant. People communicate using their senses. Interacting with other people or animals, we naturally use voice (acoustic signals), whose reception requires auditory perception. It must be mentioned that voice communication is not always based on natural language, but often involves other acoustic signals, whose meaning is understandable for both interacting parties. Such a set of acoustic signals is, for instance, developed by a dog and its human caregiver. Cities or housing estates use clearly defined signals to convey information, e.g. about danger. Communication with robots also uses specific acoustic signals [5].

Hearing is not the only sense used for communication. People receive also visual signals using visual perception, i.e. their sight. It is a frequent method of communication when hearing is impaired (sign language), when effective voice communication is not possible due to large distance between the interacting parties (maritime flag signalling systems) or in difficult conditions (communication between the airport ground crew and the aircrew during manoeuvres). This method of exchange of information can be called visual communication. In this case we also deal with a kind of visual communication alphabet, as well as with specific gestures or facial expressions, which often say more about the person's feelings or emotional state than a long speech.

People communicate also using mechanical signals received by touch. The complexity and informative content of such communication is typically reduced as compared to acoustic or visual messages. A poke, pat or caress typically convey assessment (acceptance, rejection) or feelings that a person intends to convey (praise, rebuke). However, the entire Braille language communication is based on touch perception. Particular signs (letters encoded in the form of specific dot patterns) are read through touching them with a finger. This method of exchange of information can be called tactile communication.

Those three types of communication (voice, visual and tactile) are used to exchange information between human operators and service robots. The first devices of that type employed mainly voice communication. The goal was to create robots capable of using the natural human language. The fields of speech synthesis and recognition have been extensively researched for a few dozen years by numerous centres all over the world. However, the results of the projects and programmes have not enabled any practical application and equipping robots with vocal and hearing apparatus. On the other hand, plenty of information regarding the application of visual and tactile communication has been presented on conferences devoted to human-robot communication [26], [27], on web portals [28] and in magazines. Such solutions are more frequently employed in the commercial service robots, including rehabilitation robots discussed in this paper.

5. Nature of Human-Robot Communication in Rehabilitation Devices

As regards the communication, rehabilitation robots should enable "multiple users – multiple robots" interaction [6]. A robot is operated both by a patient and a therapist, who can, in turn, operate several rehabilitation robots at a time. Human-robot communication in rehabilitation devices needs to take into account the tasks, requirements and limitations of both groups of potential users.

In the process of robot-assisted rehabilitation, a therapist has the following tasks:

- creating an exercise routine,
- teaching the exercises,
- initiation of and supervision over the exercises,
- evaluation of the exercises and adjusting the exercise routine.

Therefore, the communication system must enable the therapist to programme and save the robot movement trajectory during the exercises. The therapist must be able to programme many exercises, assign them to individual patients and select exercises out of all previously trained exercises, in accordance with the exercise routine. The therapist is typically a physically capable person and is expected to be generally familiar with modern technologies, including ICT (computer, Internet, etc.). Therefore, a personal computer with appropriate software is most frequently used as a human-robot communication interface in rehabilitation devices.

As far as patients are concerned, one should first of all take into account their limitations. Many patients suffer from poor hearing or sight. Some patients have also impaired limbs. A patient working with a rehabilitation robot performs specific tasks that can be divided into two groups:

1) Preparation of the exercise by the therapist: creating the trajectory of the manipulator's movement by leading the robot's arm on a given plane or within a given space and recording its subsequent positions.
2) Performing the exercise by the patient. Two modes of performing this task are possible:

– passive rehabilitation: reproducing the programmed trajectory by the robot's manipulator – the patient's limb is led along the desired trajectory,
– active rehabilitation: reproducing the desired trajectory by the patient – the patient moves the robot's manipulator along the desired trajectory.

Each of those tasks requires different communication system functionalities. Passive rehabilitation requires the patient to resist the movement of the manipulator. The communication system should enable the patient to monitor the performance of the exercise and its current evaluation. In the case of active rehabilitation, the manipulation system may assist or resist movement forced by the patient. During the exercises, the patient must be provided with clear information on the required movement trajectory. This information must be conveyed online, so that the patient is always aware of the next required position of the limb. The continuously updated information about the exercise performance quality must also be provided. In the case of both modes, the patient must also be able to call the therapist and stop the robot's operation due to fatigue or emergency, while the therapist must be able to adjust the course of the exercise, as well as its intensity (through the adjustment of specific robot parameters, such as speed or resistance). The work of the therapist would be significantly facilitated by a system enabling remote communication of comments and instructions regarding the exercises.

Rehabilitation robots are often based on solutions proven and tested in other medical devices, such as intelligent wheelchairs equipped with joysticks or small displays showing wheelchair status information. In the case of patients with impaired limbs, a small chin-controlled joystick can be used for human-robot communication. Other examples of human-robot communication systems found in commercial applications are solutions implemented in surgical robots, where the arm equipped with a camera is controlled by voice (a few short commands). There are also solutions based on eye movement or remote touch systems. Moreover, designers try to use popular ICT devices or at least make the rehabilitation robot solutions similar to such widely used appliances. Therefore, there are communication systems using touch screens similar to those found in smartphones or tablets. Some research works in the field of rehabilitation robotics have also involved virtual reality solutions [14], [15].

6. Solutions related to Human-Robot Communication in Rehabilitation Devices

Research and development works on modern rehabilitation systems are very expensive, time-consuming and requiring involvement of numerous teams representing diverse and complementary competences. Therefore, a vast majority of such works are performed with the support of public funds or private sponsors. Nevertheless, the main objective of research teams is commercial application of the results in the form of devices that can be actually put into use and compete in the demanding market of medical devices. Analysing different human-robot communication systems, one needs to take into account not only the solutions already applied in certain products available in the market, but also the results of the research and development works being conducted.

a

b

Fig. 4. Control panels of intelligent medical devices: a – Ottobock wheelchair (ORTHOPÄDIE + REHA-TECHNIK Fair, Leipzig, Germany 2006), b – Vertimo Hi-Lo Step tilt table with stepping functionality, manufactured by Meden-Inmed (Rehabiilitation 2014 Fair, Łódź, Poland)

Devices assisting physical rehabilitation, equipped with mechatronic or robotised components, are a relative new offer in the market of medical devices. Their designers are often inspired by other advanced appliances addressed to specific target groups, including particularly intelligent devices for the disabled, such as wheelchairs, available in different types, such as electrically powered models or devices with additional functionalities related to manipulation, communication or navigation. Such wheelchairs have their own computers controlling the entire equipment and responsible for communication with the operator/user. The device manufactured by Ottobock (Fig. 4) is controlled by a joystick, while all messages are displayed on a small screen. The operator's panel has also several large function keys. Tilt tables are yet another type of devices that can function as a model for rehabilitation robot designers. During the "Rehabilitation 2014" fair, the Meden-Inmed company presented the Vertimo Hi-Lo Step device with stepping functionality, based on the manipulation system that forces/assists the movement of the patient's legs (Fig. 4b). This device can, therefore, be classified as robotised medical equipment. It is operated (to some extent) both by the therapist/physician and by the patient. The former can use a touchscreen with appropriate software enabling, among other functionalities, setting the parameters of exercises and displaying messages related to the device operation. There is also a simple wired remote control (for the therapist or patient) enabling tilt angle adjustment and table height (up/down movement).

The commercial version of a Manus device was one of the first rehabilitation robots available in the market. In 1998, H. I. Krebs and N. Hogan, two scientists from the MIT team researching the field of robot-assisted rehabilitation, founded a company named Interactive Motion Technologies [31], which improved the prototype, obtained all required certificates and successfully marketed the device under the name of "InMotion Arm Robot". Today, the company offers a broad range of mechatronic systems assisting the rehabilitation of upper limbs (separate for the entire arm, wrist and palm). The company is also working on the devices for lower limb rehabilitation. The standard form of communication between the robot and the operator/patient in all devices is a personal computer and appropriate software (Fig. 5a) with advanced graphics and animated objects.

HOCOMA [30], a company from Switzerland, is the European leader in constructing advanced rehabilitation devices, collaborating with numerous major research centres in Europe and the USA. The company's offer encompasses a broad range of systems employing mechatronic and robotised solutions. The systems come in three main product families. Armeo manipulators are designed for upper limb rehabilitation. The Armeo-Spring (Fig. 5b) model has an adjustable system compensating the impact of gravity on the limb. The patient can move her or his arm in conditions similar to weightlessness. The system has a screen displaying the information about the device, instructions regarding the preparation of exercises or - during the performance of exercises – everyday scenes and images requiring an adequate response of the patient (raising a glass, grabbing or arranging apples, etc.). Versions for kids often have games with specific tasks (collecting items appearing on the screen, fighting monsters, etc.).

a

b

Fig. 5. Human-robot communication interfaces in devices for upper limb rehabilitation: a) InMotion Arm Robot (Gadgets Magazine, June 7, 2013, b) Armeo-Spring by Hocoma ("Rehabilitacja 2014" Fair, Łódź, Poland 2014)

This type of robot-human communication is gradually becoming a global standard. Patients and therapists can use input devices typical for computers and modern ICT appliances:
- keyboard;
- mouse;
- joystick;
- touchscreen.

Feedback is conveyed through the screen in the form of:
- text;
- graphic items - images rather than charts; more and more often: animation.

Such an approach is typical in the case of stationary rehabilitation robots, but there is also another relatively new type of robotised and mechatronic devices supporting the human movement – wearable robots. They are designed for applications in physical rehabilitation, but also to assist people in certain movement functions that might be impaired as a result of disability or difficult conditions [25]. The works on such devices are still on the research stage. Many of them are being designed in collaboration with military experts (combat support) and the information about them is not revealed. However, certain features of their user/operator communication systems can be indicated.

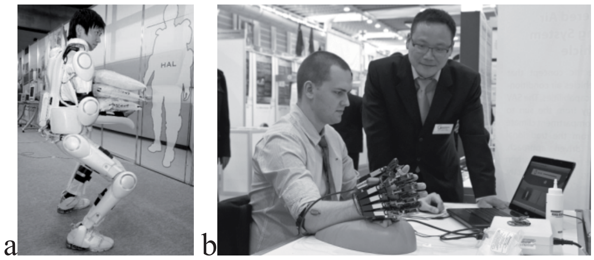

Fig. 6. Commercial offer from the Far East: a –HAL exoskeleton (Cyberdyne) for lifting heavy weights, b – presentation of the Hand of Hope robot (Rehab-Robotics Company Ltd. on the Geneva Inventions Fair 2012)

As regards communication, wearable robots typically have two phases of operation. During the operator-robot learning phase (fine-tuning of the device, training of the operator), the robot is connected to the computer with a user interface (typically GUI) displayed on the screen. The principles of communication are similar to other rehabilitation robots. During the operating phase, the robot is controlled by the control system that must also be worn by the human operator. Moreover, the user must wear batteries supplying both the control system and the movement-enabling actuators. Exoskeletons, which assist the movement of the entire body when standing up, walking, climbing stairs, etc., consume a lot of energy, so a battery unit can be as large as a big backpack. An example of such a solution is Robot Suit HAL [23] manufactured by CYBERDYNE [33] (Fig. 6a). In the case of smaller robots, such as the Hand of Hope [22] rehabilitation and training hand exoskeleton manufactured by Rehab-Robotics [37], whose construction resembles a glove with powered finger movement (Fig. 6b), the batteries are contained in a small box attached to the clothes. Wearable robot controllers are often equipped with wireless communication modules enabling the therapist supervising the patient's treatment to access the information about the patient and the device status. Operators of such robots control the actuators using EMG signals. Some works on a brain-computer communication interface are also being conducted, but they are still far from any commercial application [24].

7. Human-Robot Communication System in RENUS Rehabilitation Devices

In the years 2006–2009, in the Industrial Research Institute for Automation and Measurements (PIAP) have been designed and performed working models of two rehabilitation robots: RENUS-1 (for upper limb rehabilitation) and RENUS-2 (for lower limb rehabilitation).

7.1. Design and Operating Principle of RENUS Robots

Manipulators of both robots have three degrees of freedom each, which enables:
- RENUS-1 robot: to move the upper limb holder up/down, left/right, forward/backward;
- RENUS-2 robot: to move the patient's foot holder forward/backward, as well as it's twisting and inclining.

Each of the three manipulator axles is driven by a separate synchronous motor with permanent magnets controlled by an individual servo-drive integrated with the central unit. The motors are equipped with resolvers and electromagnetic releases. Each motor has specific and constant base position.

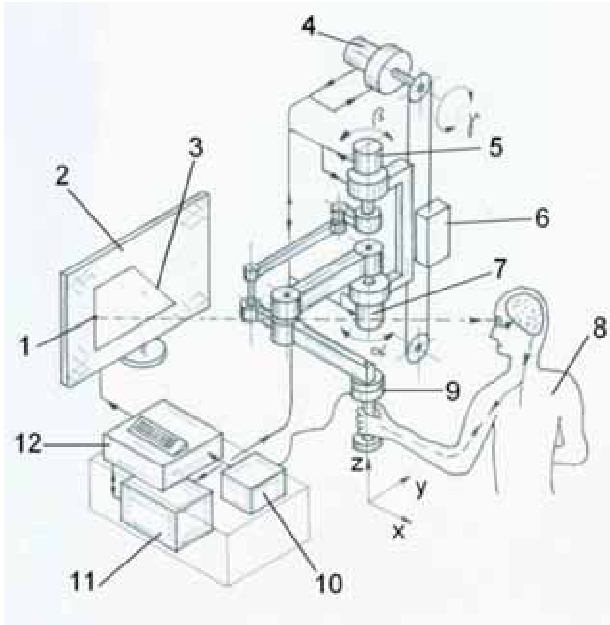

Fig. 7. RENUS-1 robot overview. 1- robot arm end location cursor, 2 – display, 3 – reference trajectory, 4 – Z-axis drive unit 3, 5 – drive unit 2 for the movement of the robot's arm on the X-Y plane, 6 – counterweight, 7 – drive unit 1 for the movement of the arm on the X-Y plane, 8 – patient performing the exercise, 9 – 6-axis strain gauge measuring forces and torques, 10 - signal processor cassette according to Item 9, 11 - servo-drive controller, 12 - personal computer

Using the servo-drive, the controller of a given axis can set the angular position to which the motor shaft needs to be moved or read the current angular position of the shaft as compared to the base position. The motor shaft is coupled with the manipulator's axis with reduction gears. Therefore, the spatial position of the limb is determined by the positions of shafts (i.e. their deviation from the base position) of each of the three motors. The movement trajectory is determined by angular position of the shafts [α_i, β_i, γ_i] (Fig. 7), where:

α_i – angle of rotation of the shaft of the motor 1 in point i,

β_i – angle of rotation of the shaft of the motor 2 in point i,

γ_i – angle of rotation of the shaft of the motor 3 in point i.

Definition of the movement trajectory involves manual movement of the limb holder attached to the robot's arm by the operator. During this process, the robot's controller regularly records the values of angular position of motor shafts from each servo-drive and saves the recorded values in its memory. The saved trajectory can be sent to the connected personal computer.

Reproduction of the movement trajectory is a reverse process, i.e. loading a predefined (reference) trajectory to the controller's memory and moving all three motors to the recorded positions.

7.2. Communication of the RENUS Robots with Human Operators

Control systems of both RENUS robots are made of components manufactured by Mitsubishi Electric. No RENUS robot has any additional control panel typical for industrial robots, as the function of such a panel can be performed by any personal computer with the Windows operating system, installed Mitsubishi communication software and a dedicated robot application, whose functionalities enable recording and saving the robot manipulator's movement trajectory and tracking its position online during the reproduction of the trajectory both by the manipulator (passive rehabilitation) and the patient (active rehabilitation).

The database containing the information about the trajectories is stored by the application on the hard drive of the computer. The coefficients of individual points of the trajectory are saved in separate text files which significantly facilitates the access to the database and verification of the information. All tasks related to creating and editing the movement trajectory, browsing the trajectory database and choosing the required trajectory are performed in a single Renus.exe application window (Fig. 8).

Active and passive rehabilitation can be performed in three trajectory reproduction modes:

1) Single reproduction of the selected trajectory: The process starts from the base position, from which the patient moves the manipulator (active rehabilitation) or the robot moves the patient's limb (passive rehabilitation) through the subsequent trajectory points until the last defined point is reached. When this point is reached, the manipulator automatically returns to the base position (in both active and passive rehabilitation).
2) Numerous reproduction of the selected trajectory with returning to the base position: The process starts from the base position, from which the patient moves the manipulator (active rehabilitation) or the robot moves the patient's limb (passive rehabilitation) through the subsequent trajectory points until the last defined point is reached. When this point is reached, the manipulator automatically returns to the base position (in both active and passive rehabilitation) and the entire cycle is repeated.
3) Numerous reproduction of the selected trajectory without returning to the base position: The process starts from the base position, from which the patient moves the manipulator (active rehabilitation) or the robot moves the patient's limb (passive rehabilitation) through the subsequent trajectory points until the last defined point is reached. When this point is reached, the manipulator does not return to the base position as in item 2, but allows further movement (active rehabilitation) or forces the movement of the patient's limb (passive rehabilitation) to the first point of the trajectory and the entire cycle is repeated.

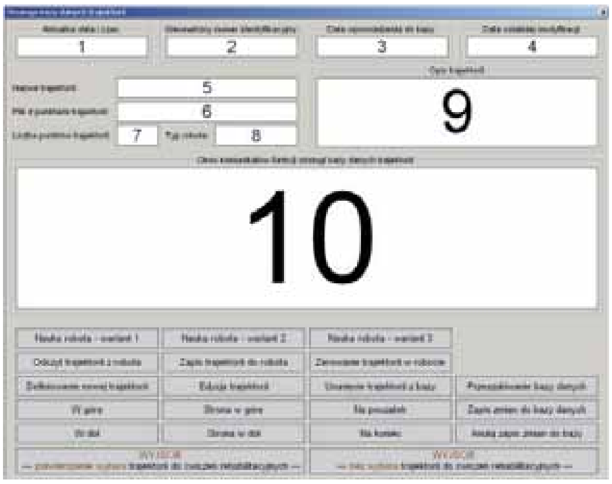

Fig. 8. Window of creating and editing the movement trajectory, browsing the trajectory database and choosing the required trajectory

During active rehabilitation, the patient's task is to "lead" the manipulator through subsequent trajectory points. Graphical information about the current position of the manipulator and the location of the next two points to which the manipulator should be led is displayed by the application on the computer screen.

During passive rehabilitation, the patient's limb is attached to the robot manipulator, which reproduces the programmed movement trajectory. The patient's task is to resist the manipulator's movement, whose speed and force applied on the patient's limb is individually adjustable. Diagrams showing the location of each of the manipulator's axis as a function of time and forces applied on the patient's limb are displayed by the application on the computer screen.

8. Summary

Development of rehabilitation robots should be considered in the context of the development of the entire service robot range, including both commercial and personal devices [20]. It might be assumed that their design will employ solutions already tested in other types of appliances, particularly medical devices. However, due to the specific nature of their application, certain features or functionalities will be developed individually. Rehabilitation robots must meet two kinds of (often contradictory) requirements. On one hand, they must be universal to meet the expectations of a possibly broad target group, whereas on the other hand, they must be adjustable to individual needs of their users, including, in particular, the rehabilitated patients. It also applies to communication interface systems of those robots. The experience in working with RENUS robots and the current trends clearly indicate that the functional requirements regarding human-robot communication interfaces are different from the perspective of therapists and patients. Therefore, two levels of users should be distinguished:

1st-level users – direct users, patients.

2nd-level users – physiotherapists, as well as other people having remote access to robots used at home (family members, nurses, social workers, domestic service, guards).

Furthermore, a human-robot communication system in rehabilitation devices used in medical facilities or in home environment needs to offer specific properties and functionalities appropriate for the elderly and/or the disabled. Such users tend to be less physically capable and may have limited cognitive abilities.

Another specific target group for rehabilitation robots are kids. In their case, it is particularly important to make interaction with a robot less boring. Therefore, the communication system should contain elements of games and plays encouraging young patients to perform the required exercises.

The publications reflecting the point of view of medical personnel often mention the problem of acceptance of rehabilitation robots by patients. Such devices must have attractive design and evoke positive emotions. A rehabilitation robot may not be scary. This issue to a great extent depends on the human-robot communication system. New technical devices are more likely to be accepted, particularly by older users, if they are similar to other well-known solutions. Therefore, it is recommended that such proven and familiar solutions are used in the design of interfaces enabling the communication between patients and rehabilitation robots.

Rehabilitation supported by mechatronic devices is often performed within the following triangle: patient - therapist - robot. The communication interface should also meet the requirements of the therapist, so that her or his work is easier and more effective. Important factors in this respect include remote access to the robot's control system, monitoring of the course of exercises, assessment of the patient's condition, providing information or adjusting the exercise routine.

To sum up, the development works in the field of human-robot communication in rehabilitation devices in the nearest future should be focused on the following issues:

– multimedia system, addressing at least two and preferably all three basic models of human communication: visual (sight), acoustic (audio), tactile (touch);
– user-friendliness and evoking positive emotions;
– integration of the rehabilitation robot with the local computer network (in the medical facility or home environment) and with the global Internet network;
– enabling users to work with several robots simultaneously;
– making robots accessible to numerous users at a time, possibly with different user priorities, including remote access;
– application of popular mobile ICT devices with which people are familiar through their use in other circumstances.

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