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ANALYZIS OF REHABILITATION SYSTEMS IN REGARDS TO REQUIREMENTS TOWARDS REMOTE HOME REHABILITATION DEVICES

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Abstract:
The contemporary international pandemic proved that a flexible approach towards work, trade and healthcare is not only favorable but a must. Hence, the devices enabling home-rehabilitation became one of the urgent needs of the medical market. The following overview is a part of an R&D project aimed at designing an exoskeleton and developing methods enabling effective home rehabilitation. It contains a comparison of current devices in terms of their kinematics, applications, weights, sizes, and integration with selected ICT technologies. The data is analyzed regarding conclusions from qualitative research, based on in-depth interviews with physiotherapists and questionnaires organized beforehand. The investigation assesses whether commercial and developed devices enable feedback from a patient by all possible means; hence, if they could allow effective telerehabilitation. Moreover, their capabilities of increasing engagement and accelerating improvements by supervising techniques and measuring biomechanical parameters are evaluated. These outcomes are a base to set the constraints and requirements before designing an exoskeleton dedicated to home treatment.

Keywords: *Home rehabilitation, Exoskeleton, ICT technologies, Market overview, Rehabilitation robotics, Remote rehabilitation, UX analyzis.*

1. Introduction

The modern world transforms continuously. Thus, new approaches towards common activities are developed. The pandemic in 2020 caused an urgent need to transfer processes, such as working [73], learning [46], treating or training [49], into the online environment. The situation got so bad in some of the countries, Poland, among others, that patients were not permitted to leave their houses even for necessary physiotherapy sessions. What is worse, a scenario of repeating such an emergency is relatively possible. As a result, not only do post-COVID patients require rehabilitation, but also the ones suffering from motor diseases, whose therapy was restricted [30]. To avoid these situations in future, treatment shall be easily transferable to the patients' houses and possible to continue even without the physical presence of a physiotherapist. As proven to be effective for kinesiotherapy, rehabilitation robots may be used for this purpose [76].

Even though there are a lot of robot–aided rehabilitation devices, an effective home rehabilitation without a great effort of a physiotherapist is not possible yet. However, a fusion of medicine and engineering should enable such a remote treatment in an efficient way [67]. What is more, almost 30% of examined physiotherapists stated that the remote–home–therapy should be the main direction of physiotherapy development. Moreover, new trends in healthcare ICT technologies [25], advanced control methods for complex goal functions [37, 38, 62, 66], and the miniaturized, lightweight design of the rehabilitation robots [35, 36, 58] brought new needs for such devices. Therefore, as a revival of the *RENUS* project [52], the *ExoReha* system is being designed by the *Łukasiewicz Research Network – Industrial Institute for Automation and Measurements PIAP*.

The initial phase described within this paper is an in–depth overview and comparison of possible competition – the current or significant by different means robot–aided rehabilitation devices for human extremities, both the upper and the lower. They are assessed in terms of their kinematics, applications, weights, sizes, and integration with selected ICT technologies. To gather relevant practical insights, the results of the literature research are taken into consideration regarding the outcomes of the initial interviews with therapists. The details on the analyzed devices are compared according to the same criteria. These are selected to enable the evaluation of possible implementation into home rehabilitation.

2. Requirements Towards Systems for Home Rehabilitation

The requirements presented within the following section are based on in–depth interviews with the young Polish physiotherapists [39, 40]. Hence, they shall be interpreted only to analyze needs in robot–aided motor therapy practices in the countries of central Europe. Nevertheless, most of the conclusions on technical requirements for the devices apply to home rehabilitation international practices.

The qualitative research defined the following needs and problems. They should shape the direction of development for the rehabilitation devices.

1) The younger physiotherapists are eager to use additional weight support for their patients. However, robot–aided rehabilitation devices are

relatively expensive and hardly accessible in the local markets. Therefore, to increase their popularity, the designs should be relatively portable and inexpensive to build. Moreover, the devices have to be created to help the rehabilitators, not take over their duties fully.

2) One of the main difficulties in providing effective treatment is keeping the patient's constant engagement. It may be challenging while the rehabilitation sessions are long and consist of monotonous movements. The physiotherapists claim to involve multimedia and ICT technologies in the therapy willingly. However, according to their observations, such means of technology can only motivate a patient for a short time. Thus, the rehabilitation devices should be designed to enable connection with different interactive systems. By this approach, patients could stay entertained while training without exchanging the device so often. Moreover, an entertaining aspect of VR may stay in synergy with high precision in motion assessment provided by other technologies [57].
3) Over 58% of the respondents declared that goal–oriented functional therapy is a future of rehabilitation. Thus, the robots for such treatment shall enable the mobilization of multiple degrees of freedom (DOFs) simultaneously. With this approach, the patient may focus on the motion required for daily–life activities and follow the most genuine patterns within rehabilitation sessions.
4) All of the physiotherapists agree that motor therapy without visual and audio feedback is not possible. Therefore, the systems dedicated for home rehabilitation should be either remotely monitored by a professional (e.g. presentation of the current configuration and applied moments of forces, and direct contact with a patient via camera), or need to gather information on patient's condition with additional sensors, and process data with more advanced algorithms.

For these reasons, rehabilitation devices are mainly presented in terms of their portability, automation level, virtual or augmented reality application, and involvement of different ICT technologies. However, they shall be compared according to their purpose of application. The analyzed devices were chosen based on their high accessibility in Europe or potential applicability for remote home treatment in terms of technology advancement. They were sought with *Google Scholar*, *ResearchGate* and *IEEE Xplore Digital Library* using the following phrases: rehabilitation robot, home robot–aided rehabilitation, robot–aided motor therapy, and rehabilitation exoskeleton.

3. Commercial and Developing Devices for Robot–aided Rehabilitation of Upper Extremity

3.1. *Physio* by *Gridbots*

Physio is an Indian commercial device for the rehabilitation of an upper extremity (see Fig. 1a).

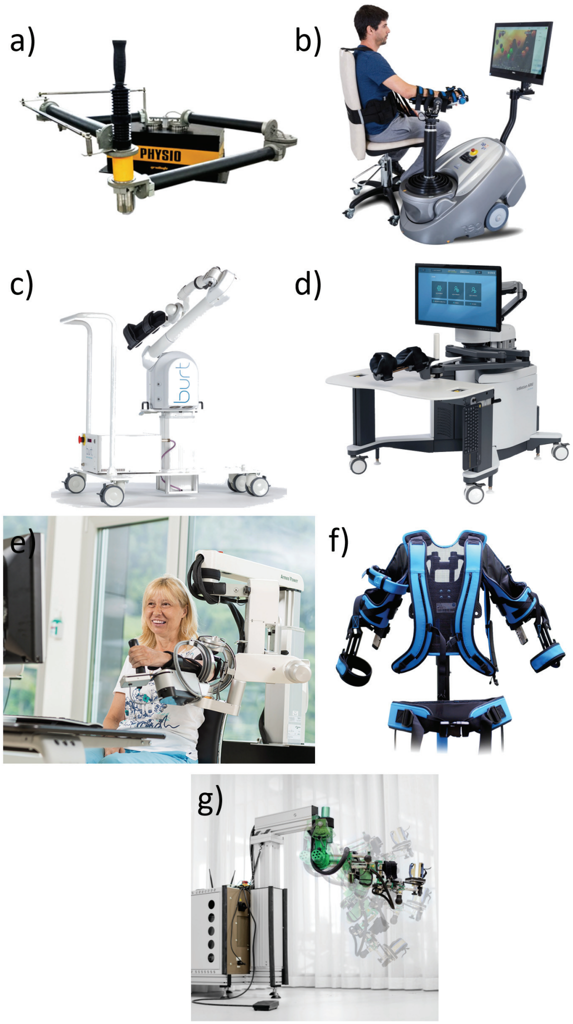

Figure 1. Contemporary rehabilitation robotic systems for upper extremities – a) *Physio* [11], b) *ReoGo* [17], c) *Burt* [3], d) *InMotionARM* [8], e) *Armeo Power* [1], f) *EksoUE* [6], g) *ARMin* [2]

A patient may use it to perform their training by grabbing a grip at the robot's end–effector and leading the programmed trails. *Physio's* parallel kinematic structure enables the 2D plain motion of the hand (2 DOFs, Degrees of Freedom), but it does not activate any particular joint directly.

The device is supported with intelligent algorithms based on machine learning techniques. These enable the online learning performance of a patient and adjust the therapy towards their needs.

The robot may reach within a rectangular envelope of 1000x1200 mm, and work under a load of up to 50 N. Its mass is 15 kg, and it can be transported within the package dimensions of 300x400x800 mm. However, it also requires a dedicated controller and an HMI (Human–Machine Interface) display. The device is cobot compliant [11].

3.2. *ReoGo* by *Motorika*

ReoGo is a commercial robotic system for an upper limb therapy (see Fig. 1b). It is dedicated mostly for post–stroke patients and the ones suffering from neurological diseases [41, 77].

To train with the device, a user has to sit and attach their forearm to the end–effector of the machine (or a hand, while the other handle is assembled). The kinematic structure of the *ReoGo* enables the 2D or 3D motion of the extremity (2–3 DOFs). However, none of the particular joints is activated directly.

The device may track and assess a patient's performance. The system offers workouts based on a library of exercises and games. Nevertheless, while using *ReoGo*, the physiotherapist plays a key role, as they are responsible for designing and personalizing treatments.

The *ReoGo* is relatively mobile due to its mass of 79 kg and integrated wheels. Its overall dimensions stay within 1010x580x900 mm [17].

3.3. *Burt* by *Barret Medical*

Burt is an easy–setup commercial robotic system for an upper extremity rehabilitation (see Fig. 1c). It is dedicated to recovering post–stroke patients. To train with the device, a sitting user has to attach their forearm to the end–effector of the *Burt's* manipulator and leads along the programmed trail. The device enables the 3D motion of the limb (3 DOFs), but none of the joints is activated directly. The manipulator may operate within the human–sized work volume (with a reach of 1050 mm).

Burt may track and gather data on patients' improvements over time. However, a physiotherapist is still required to program the whole treatment. Not only does the system provide manual therapy, but it also works on the attention, memory and visual neglect of a patient. The methods applied for the therapy include a game environment.

The *Burt* may operate with the maximum velocity of 1.5 m/s and under the load of up to 45 N. It is relatively mobile due to its mass of 80 kg and the integrated wheels [3, 19].

3.4. *InMotionARM* by *Bionik*

InMotionARM is a commercial system for rehabilitation of an upper extremity (see Fig. 1d). It is dedicated to neurological patients, post–stroke among others [50] [45]. To train with the device, a user must place their forearm in a brace on the robot's end–effector. The system is designed to support the leading motion of a patient's hand on a plane (2 DOFs), but it does not necessarily need to be active (the device may also be used in the treatment of totally immobile people) [59]. Even though, none of the user's joints are activated directly.

The device may track users' performance and send reports wirelessly. However, it does not create nor modify workouts automatically. A physiotherapist's assistance is still needed then.

The *InMotionARM* consists of a manipulator, a control cabinet, an HMI display, and a desk. It may also be enriched with the hand rehabilitation module. The total mass of all the devices is 271 kg, but as the system is placed on a set of wheels, it may be transferred [8].

3.5. *ArmeoPower* by *Hocoma*

ArmeoPower is an exoskeleton–type commercial robotic system for an upper extremity rehabilitation (see Fig. 1e), clinically tested for post–stroke patients [47]. The training with the device is possible after attaching an arm and a forearm to the braces and grabbing a handle on the end–effector. The system supports or resists motion along the programmed trails. Moreover, it may support the weight of a limb. The *ArmeoPower* activates up to 6 DOFs directly within a range of a human's reach [26]. It is also equipped with a 400 mm long electric lifting column to adjust the comfortable training height.

The system tracks a patient's progress and assesses the support needed at further stages. A physiotherapist's role is limited to creating an initial training set and then adjusting the machine according to the reports. To increase the motivation of a user, the *ArmeoPower* offers a library of game–like exercises.

The system consists of a robot, a control system, and a flat–screen HMI display. It may also be enriched by a hand–rehabilitation module. The *ArmeoPower* may be transported as it is mounted on the mobile platform, and its overall dimensions are held within 2050x780x1660 mm. The total mass of the device is approximately 205 kg. A room to perform the training should not be smaller than 2.70x3.50x2.00 m. The *ArmeoPower* may be used for rehabilitation of patients up to 135 kg of weight [1].

3.6. *EksoUE* by *Ekso Bionics*

EksoUE is a non–actuated upper–extremity commercial rehabilitation exoskeleton; thus it is not a robot in a strict sense (see Fig. 1f). However, it is used as a device applied for the treatment of people affected by strokes and neurological or orthopedic diseases to increase their joint reach. The construction supports 5 DOFs per limb and directly activates the shoulder and elbow joints. Its principle of work is based on spring forces, so it can only assist the motion of a patient. The device may provide lift assistance of even 6.8 kg per side.

As the construction is drive–less, implementing it into treatment requires constant monitoring by a physiotherapist or even performing parallel manual therapy. The exoskeleton is easy to put on, making it a plug–and–play type device.

The mass of the exoskeleton is approximately 5.5 kg. Due to its weight, size, and light design, the *EksoUE* is a truly portable solution [6].

3.7. *ARMin*

ARMin is a rehabilitation system for upper extremity developed at *ETH Zurich* university (see Fig. 1g). It is dedicated to the neurorehabilitative training of patients and, above all, to the research on motor learning, and therapy [2]. Working out with the device is possible after attaching an arm and a forearm to the segments of an exoskeleton and grabbing a handle on the end–effector by a patient. The *ARMin* enables 6 DOFs motion and activates joints of a limb directly within their anatomical range [63].

The device tracks the changes during the treatment process and assesses a patient's needs. The *ARMin* system was also prepared and tested to be used for game therapy with biosignals involved. However, as the device is still in progress with clinical testing, it is not available for wide use [68].

The system consists of an exoskeleton on a vertical column and a control cabinet. It can also be attached to an HMI display (e.g. computer screen). Due to its relatively big size and no wheels assembled, the *ARMin* requires additional equipment to be transported to another place [2].

4. Commercial and Developing Devices for Robot–aided Rehabilitation of Lower Extremity

4.1. *Lokomat* by *Hocoma*

Lokomat is a commercial, treadmill–based, stationary rehabilitation system for lower extremities, applicable for post–stroke and neurological therapy [51, 56] (see Fig. 2a). It offers the natural patterns of gait [28] and the bodyweight support of a patient (up to 85 kg). To train with the device, a patient needs to get fastened in the lift and have their lower limbs attached to the exoskeleton (however, conventional training without exoskeleton on is also possible) [33]. The therapy is based on walking on the treadmill, which may be speeded up to the velocity of 3.2 km/h (up to 10 km/h without gate orthosis). The device activates hip and knee joints directly (2 DOFs per limb) but does not lock other natural DOFs. Therefore, it is possible to be used for function–oriented rehabilitation [74].

The system tracks a user's performance and presents this to the physiotherapist and the patient. A therapist is required to set up the first workout plan and then adjust it based on the reports from the device. However, they may organize more than one session at the same time. Also, the *Lokomat* offers a wide range of game–like exercises, which are designed to increase the motivation of patients.

The system consists of an exoskeleton mounted on the pelvic support moving along the vertical column, a bodyweight support lift, a treadmill, and a display for augmented performance feedback. Its mass is approximately 1000 kg, and its overall dimensions vary up to 3500x2140x2460 mm. Moreover, the system requires a minimum room of 5x4x2.6 m. Thus, it is not a transferable solution and may be used only in specialist clinics. The *Lokomat* is suitable for patients up to 135 kg of weight [10].

4.2. *ReoAmbulator* by *Motorika*

ReoAmbulator is a commercial stationary, treadmill–based system for lower extremity rehabilitation (see Fig. 2b) [33]. It is dedicated to gait training, with possible bodyweight support. A patient has to attach their thighs and calves to the mechanical legs to begin a workout on the treadmill. However, conventional gait training without any additional robotized support is also possible.

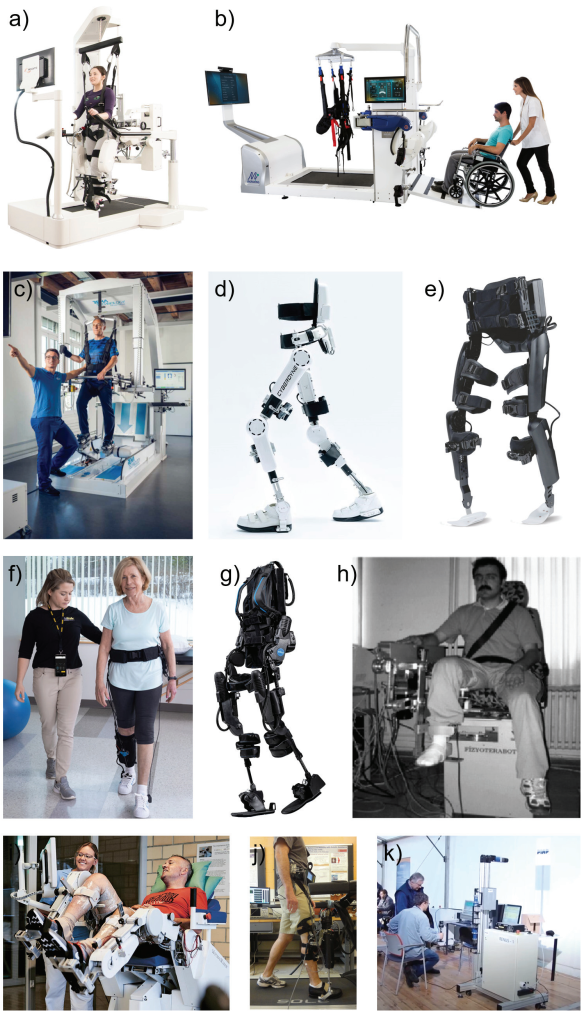

Figure 2. Contemporary rehabilitation robotic systems for lower extremities – a) *Lokomat* [10], b) *ReoAmbulator* [15], c) *G–EO* [16], d) *HAL* [7], e) *ReWalk Personal 6.0* [18], f) *ReStore* [18], g) *EksoNR* [5], h) *MotionMaker* [9] , i) *Anklebot* [20] , j) *PHYSIOTHERABOT* [42], k) *RENUS–1* [14]

The integrated treadmill may move with a velocity of up to 3.5 km/h (up to 10 km/h without mechanical legs applied). Every mechanical leg activates 2 DOFs (1 DOF at heap and knee joints each) directly and supports the vertical motion of the pelvis. What is more, the construction of these results in a complex motion of extremities mimicking natural gait patterns.

The *ReoAmbulator* tracks and analyzes the performance of a user and provides a physiotherapist with this information, so they are responsible only for setting up a training and then modifying it according to the received reports. Also, a machine gives real–time visual and audio feedback, which may be helpful for immediate improvement of technique. The system also involves virtual reality and game–like exercises to maximize users' engagement in treatment.

The system consists of two exoskeletons (mechanical legs) mounted on the modules moving along the vertical column, a bodyweight support lift, a treadmill, and two displays, one for the patient and one for the physiotherapist.

The treadmill ramp is designed to allow accessing it with a wheelchair. The mass of a whole system equals approximately 960 kg while its overall dimensions reach up to 4050x1310x2750 mm, dependent on the chosen modules. Even though the device is equipped with wheels, it is typically used stationary in specialist clinics. To obtain flexibility of use, the producer of the device declares the time of adjusting it to the features of the user to be no longer than 10 minutes. The *RoboAmbulator* can be used for the treatment of patients up to 150 kg of weight and 90–200 cm tall [15].

4.3. *G–EO* by *Reha Technology*

G–EO is a commercial stationary system dedicated to gait training (see Fig. 2c). It enables a diversity of motion patterns such as walking, climbing stairs or slopes, and backward trajectories; all these with the optional dynamic bodyweight support [64]. To train with the device, a patient has to attach their feet to the holders at the end effectors. The system can perform gait–like movements up to 2.3 km/h while activating 3 DOFs per limb. However, none of the extremities' joints is mobilized directly. To receive the most natural effect of treatment, the *G–EO* mimics genuine patterns of human motion [23].

Even though the system gathers and processes diverse data on treatment, it requires a physiotherapist to operate it. Nevertheless, limiting persons responsible for rehabilitation based on climbing–like exercises is more advantageous than conventional therapy. The *G–EO* may be additionally equipped with an FES (Functional Electrical Stimulation) module muscles or a heartbeat and blood oxygen tracking system. Also, the device uses virtual scenarios to make the rehabilitation process more entertaining.

The system consists of two manipulators attachable to the patient's feet and equipped with tactile sensors, a bodyweight support harness, a construction rack, a computer of the physiotherapist, acting as an HMI, and the control system with the patient's display for the virtual reality. The mass of a whole setup is approximately 900 kg, while its overall dimensions are held within the 4060x1240x2800 mm space. The *G–EO* is generally used stationary in specialist clinics, as it is relatively heavy and requires constant monitoring by a therapist. It is suitable for patients up to 150 kg of weight and 90–200 cm tall [16, 65].

4.4. *HAL* by *Cyberdyne*

HAL is a commercial cyborg–type device. The producer does not exactly designate its application; however, it may be used for medical purposes (see Fig. 2d). Besides the overall wearable robot, the *HAL* is also available in a few different versions. One of them is an exoskeleton (one–legged or two–legged) for rehabilitating lower extremities for patients with musculoskeletal ambulation disabilities. The device activates 2 DOFs per limb directly (one in a hip joint and one in a knee joint) [27, 72].

The exoskeleton's motion depends on the bioelectrical signal (BES) control scheme, so the device tries to follow the intentions of the move triggered by the user. Thus, the robot teaches a patient how to activate the areas of the neurological system responsible for specific movements [29, 61]. As the *HAL* is not strictly a rehabilitation device, it does not require the operation of the physiotherapist. However, it may be beneficial, as the system enables manipulating operations of the exoskeleton with a detachable controller. Hence, this method may be used for robot–aided motor therapy. Also, the device allows monitoring the status of a user graphically.

The system consists of a complete exoskeleton with a freely detachable controller. It is a truly portable solution, as the mass of a whole system is approximately 9 kg while its overall dimensions are 430x470x1230 mm. The *HAL* is suitable for patients of 150–200 cm height, and a mass of 40–100 kg, wearing shoes 23–30 cm long [72]. The exoskeleton could be used for home rehabilitation; however, it is relatively expensive, and its battery enables only one–hour of operation [7].

4.5. *ReWalk Personal 6.0* by *ReWalk*

ReWalk Personal 6.0 is a commercial exoskeleton–type robot dedicated to gait–support (see Fig. 2e) [33]. However, thanks to its ability to mimic natural walking patterns, the device may also be used for post–stroke therapy. The device is controlled by sensing subtle changes in the patient's centre of gravity. It may activate 2 DOFs per limb (one–legged and two–legged versions are available) directly and assist everyday motion at home or in the community, as well as be used for motor treatment. The maximum speed of gait achievable with the assistance of the system is 2.6 m/s [54].

The exoskeleton is designed for people with spinal injuries, as the *ReWalk* company also offers wearable devices *ReStore*, dedicated explicitly to rehabilitation purposes. However, compared to them, *ReWalk Personal 6.0* is applicable for the cases of immobile patients [78]. As the device is applicable for everyday activities support, it does not require the assistance of a physiotherapist. It may be treated as a rehabilitation device as it stimulates the brain to recall the motion stimuli and connect them with the particular gait swings.

The whole system is packed in the exoskeleton. As its construction is based on a lightweight exoskeleton, the *ReWalk Personal 6.0* could be applied in home rehabilitation; however, it is relatively expensive and available only in some countries (mainly in Germany, Italy and the United Kingdom in Europe). The wearable device is suitable for patients 160–190 cm tall, and up to 100 kg of weight [18, 55].

4.6. *ReStore* by *ReWalk*

ReStore is a commercial soft exoskeleton–type device for post–stroke rehabilitation (see Fig. 2f). It is only applicable to the therapy of patients able to walk with the support of any additional device. The soft exoskeleton is placed like a calf orthosis and activates directly 1 DOF of the ankle joint [48].

The *ReStore* is designed to support gait by improving its symmetric technique and increasing the speed. As the solution is relatively simple and safe, no assistance of physiotherapy is required [24]. It is driven based on the data from the motion sensors to synchronise the limp extremity's swing with the one non–injured.

The system consists of a soft exoskeleton, and its control system is placed on the belt connected with the wiring. However, the device is also remotely accessible with a mobile application. It is the most portable rehabilitation robot, designed only for one segment of a limb. However, it does not give a possibility of holistic and more advanced therapy, and it is still mainly used locally in the specialist European and American clinics [18, 24].

4.7. *EksoNR* by *Ekso Bionics*

EksoNR is a lower–body commercial rehabilitation exoskeleton for gait training; thus, in contrast to the *EksoUE* it is a typical rehabilitation robot (see Fig. 2g). It may be applied for motor therapy and posture support for people suffering from various diseases. Its construction enables activation of 2 DOFs per side when mobilizing directly, one at the hip and one at the knee joint. The maximum speed of gait achievable with the assistance of the system is 1.6 m/s [54].

The exoskeleton gathers data on speed, distance, and gait training time. Afterwards, this may be processed and used to improve treatment and correct the common technique mistakes. Also, the intelligent software adapts to the users' needs and optimizes the workouts to increase their effectiveness. As the device is designed to be operated by a physiotherapist, the system allows adjusting swing support and other parameters of strides.

The system consists of an exoskeleton and a control panel with a display to present data on performance to the patient and the therapist. The *EksoNR* is relatively compact and has a mass of 25 kg itself; however, it is still only used in specialist clinics. The exoskeleton is suitable for patients of 150–195 cm tall and up to 100 kg of weight [5, 72].

4.8. *MotionMaker* by *Swortec*

MotionMaker is a stationary system for rehabilitation of lower extremities, dedicated for disabled people (see Fig. 2i) [33]. Originally, it was developed at the *Swiss Federal Institute of Technology Lausanne*, and then the concept has transformed into a start–up. The device is designed to train both limbs while sitting by performing programmed routines with parallel Functional Electrical Stimulation (FES) [9]. To begin the session, a patient has to attach their extremities into two exoskeletons – by their feet, calves and thighs. The system activates 3 DOFs per extremity when mobilizing directly, one at the hip, knee and ankle joints respectively [71].

The device must be operated by the physiotherapist. Due to its university background, besides clinical application, it has also been used as a research device. The design of the *MotionMaker* has been developed, and in 2011 the company presented a new rehabilitation robot, *WalkTrainer*, dedicated to gait training [9].

The original system consists of the main device with two exoskeletons and a control system with an HMI display. Even though they all are attached to the mobile platform, the *MotionMaker* is rather a stationary solution due to its size and mass of 210 kg. However, it is placed on wheels, making the device possible to relocate. Its overall dimensions are equal to 1520x750x1580 mm; however, it requires 2x4x2.2 m free room to operate. The exoskeletons fit people 140–195 cm tall, and of weight up to 135 kg [4].

4.9. *Anklebot*

Anklebot is a lower extremity rehabilitation exoskeleton–type robot constructed at the *Massachusetts Institute of Technology* (see Fig. 2j). It is dedicated to people suffering after strokes. To use it, a patient has to attach their calf to the brace and place a foot in the dedicated shoe holder. Afterwards, the device moves the foot along its natural trajectories within the ergonomic range of an ankle. The robot activates directly 2 DOFs of this joint [75].

The device was widely used for research purposes. Among others, it contributed to determining the stiffness of ankles for people with paralyse. However, due to its early stage of market–readiness, the *Anklebot* requires operating by a therapist [69, 70].

The system consists of an exoskeleton with its control system. The mechanism itself is relatively low–weight and could be used nearly anywhere [75]. Due to its construction, it may be applied for training in sitting, lying or standing positions. Moreover, it could be used for gait training with a treadmill. Nevertheless, it is still in the test phase. The company *Bionik* is trying to develop the product as *InMotion Ankle* and wants release it to sell. So far, the device has completed pre–clinical tests [20].

4.10. *PHYSIOTHERABOT*

PHYSIOTHERABOT is a Turkish system designed at the *Yildiz Technical University* (see Fig. 2h). It consists of two devices – *PHYSIOTHERABOT*, an exoskeleton for motor rehabilitation of both extremities, and *PHYSIOTHERABOT/W1*, an exoskeleton for the physiotherapy of a wrist and elbow. The universal robot requires attachment of either a forearm or a thigh and a calf to the braces to begin treatment. The wrist–and–elbow–rehabilitation device must be attached to the forearm and grabbed by the handle. Both the machines may activate 3 DOFs of a limb directly and be used for either active or passive rehabilitation [21].

The rehabilitation process takes place in a sitting position. Operating the system is possible even with a professional staff involved only remotely via the HMI system. Both the devices gather the data and use them in a feedback loop to self–adjust [22].

The *PHYSIOTHERABOT* consists of an exoskeleton attached to the seat, its control system and an HMI based on a PC. The *PHYSIOTHERABOT/W1* set is the same apart from the seat and the different construction of an exoskeleton. Both parts of the system may be used separately. The mass and sizes of the devices make them capable of transport to the patients' houses. However, they are not approved for commercial use yet. Thus, they are still treated as research equipment to develop advanced control technologies for medical devices, also involving AI–based algorithms and EMG tracking [12, 13, 22, 31].

4.11. *RENUS*

RENUS is a Polish post–stroke rehabilitation system designed at the *Industrial Institute for Automation and Measurements PIAP* (see Fig. 2k). It consists of two devices – a manipulator, *RENUS–1*, dedicated for the upper extremity and a manipulator, *RENUS–2*, dedicated for the lower extremity [53]. They both may be used for active or passive treatment. To do so, a patient has to either grab a handle or place a foot in the shoe–holder; respectively, for the device. Each of the machines is capable of activating 3 DOFs of a limb indirectly [34].

Rehabilitation of an upper limb may be realized in either sitting or standing position, while the training of a lower limb requires remain seated. Using the *RENUS* system may be done only under constant supervision of a professional therapist [52].

The devices are relatively big and heavy. Moreover, they have never completed the clinical trial tests. Due to these, they were treated only as research equipment to assess the capabilities of robot–aided treatment. Hence, they cannot be used as the system for home rehabilitation.

5. Comparison of the Systems

The presented devices are compared in terms of their potential for home rehabilitation. As intended by the questioned physiotherapist, the systems should be capable of multi–joint mobilization to recall natural movement patterns. Also, they are expected to enable remote control over the physiotherapy process and constant monitoring of the patient. Moreover, they should be usable in the limited space of flats. The main factors enabling these are their kinematics structure, size, weight, transport difficulty, commercial availability, minimum room size needed, ICT technologies implemented, and requirements for patients and physiotherapists. These are presented in the Tables 1–5.

Table 1. Comparison of the rehabilitation systems in terms of their kinematics structure (abbr.: physio...–physiotherabot)

Device	Extremity	DOFs	Activation of Joints
Physio	Upper	3	Indirect
ReoGo	Upper	2–3	Indirect
Burt	Upper	3	Indirect
InMotionARM	Upper	2	Indirect
Armeo Power	Upper	6	S, E, W (1)
EksoUE	Upper	5 (10)	S, E
ARMin	Upper	6	S, E, W (1)
PHYSIO.../W1	Upper	3	E (1), W
RENUS–1	Upper	3	Indirect
Lokomat	Lower	2 (4)	H (1), K
ReoAmbulator	Lower	2 (4)	H (1), K
G–EO	Lower	3 (6)	Indirect
HAL	Lower	2 (4)	H(1), K
ReWalk	Lower	2 (4)	H(1), K
ReStore	Lower	1	A (1)
EksoNR	Lower	2 (4)	H (1), K
MotionMaker	Lower	3 (6)	H (1), K, A (1)
Anklebot	Lower	2	A (1)
RENUS–2	Lower	3	Indirect
PHYSIO...	Upper/Lower	3	S (1), E (1), W (1) H (1), K, A (1)

Table 2. Comparison of the rehabilitation systems in terms of their availability and offered rehabilitation schemes (abbr.: physio...–physiotherabot)

Device	Motion	Position	Availability
Physio	Plane	Any	Commercial
ReoGo	Plane	Sitting	Commercial
Burt	Any	Any	Commercial
InMotionARM	Plane	Sitting	Commercial
Armeo Power	Any	Any	Commercial
EksoUE	Any	Any	Commercial
ARMin	Any	Any	Commercial
PHYSIO.../W1	Dłoni	Any	R&D
RENUS–1	Any	Any	R&D
Lokomat	Gait	Standing	Commercial
ReoAmbulator	Gait	Standing	Commercial
G–EO	Different types of gait	Standing	Commercial
HAL	Gait (learning by practicing)	Standing	Commercial
ReWalk	Gait (learning by practicing)	Standing	Commercial
ReStore	Ankle joint (gait)	Standing	Commercial
EksoNR	Gait (learning by practicing)	Standing	Commercial
MotionMaker	Any	Sitting	Commercial
Anklebot	Ankle joint	Sitting	Commercialised
RENUS–2	Any	Sitting	R&D
PHYSIO...	Any	Sitting	R&D

Even though there are multiple commercial systems available, there were no standardized trials conducted to systematically compare their efficacy in recalling life functions to the patients. This means assessment of their applicability for remote home applications can be based only on their functions and investigated needs of the physiotherapists [39].

The colors of cells in the tables depend on an impact of a certain parameter on the device's applicability for home rehabilitation.

- Green cells contain favorable parameters;
- Yellow cells contain parameters, which may hinder home–rehabilitation with the device;
- Red cells contain parameters which hinder and may even prevent the devices from being applied for home rehabilitation.;
- Grey cells contain parameters with no data available.

As presented, the contemporary devices dedicated to robot–aided rehabilitation do not necessarily meet all the desired parameters to be applied for home rehabilitation. The most significant one is the lack of remote connection to the control systems (see Table 4). This is no surprise, as the machines are designed to be used in the clinics. There, physiotherapists may adjust the therapy parameters

Table 3. Comparison of the rehabilitation systems in terms of their physical properties and requirements (abbr.: physio...–physiotherabot, n/a no–data, v. difficult–very difficult)

Device	Mass [kg]	Size [cm]	Transport	Room [m]
Physio	15	30x40x80	Possible	N/A
ReoGo	79	101x58x90	Possible	N/A
Burt	80	N/A	Possible	N/A
InMotionARM	271	N/A	Possible	N/A
Armeo Power	205	205x78x166	Possible	2.7x3.5x2.0
EksoUE	5.5	N/A	Possible	–
ARMin	N/A	N/A	Difficult	N/A
PHYSIO.../W1	N/A	N/A	Difficult	N/A
RENUS–1	N/A	N/A	Difficult	N/A
Lokomat	1000	350x214x246	V. difficult	5.0x4.0x2.6
ReoAmbulator	960	405x131x275	V. difficult	N/A
G–EO	900	406x124x280	V. difficult	N/A
HAL	9	43x47x123	Possible	–
ReWalk	N/A	N/A	Possible	–
ReStore	N/A	N/A	Possible	–
EksoNR	25	N/A	Possible	–
MotionMaker	210	152x75x158	Possible	2.0x4.0x2.2
Anklebot	3	N/A	Possible	–
RENUS–2	N/A	N/A	Difficult	N/A
PHYSIO...	N/A	N/A	Difficult	N/A

Table 4. Comparison of the rehabilitation systems in terms of involved ICT technologies (abbr.: physio...–physiotherabot, n/a–no data)

Device	Performance feedback	VR/game	Biosignals	Remote connection
Physio	Yes	Yes	No	N/A
ReoGo	Yes	Yes	No	N/A
Burt	Yes	Yes	No	N/A
InMotionARM	Yes	Yes	No	Yes
Armeo Power	Yes	Yes	No	N/A
EksoUE	No	No	No	No
ARMin	Yes	Yes	Tested	N/A
PHYS.../W1	Yes	Yes	Tested	Yes
RENUS–1	No	No	No	No
Lokomat	Yes	Yes	No	No
ReoAmbulator	Yes	Yes	No	N/A
G–EO	Yes	Yes	Yes	N/A
HAL	Yes	Yes	Yes	N/A
ReWalk	Yes	Yes	Yes	N/A
ReStore	No	No	No	Yes
EksoNR	Yes	Yes	No	No
MotionMaker	N/A	Yes	Yes	N/A
Anklebot	N/A	Yes	No	N/A
RENUS–2	No	Yes	No	No
PHYS...	Yes	Yes	Tested	Yes

according to their observations. As to providing a possibility of telerehabilitation, the safe remote connection technology needs to be implemented to the devices designed for that aim [67]. Another finding regarding the current rehabilitation–devices market is a tendency to implement virtual reality (VR) technologies (see Table 4), even though these do not yet guarantee a constant level of entertainment. Thus, they are not solving the need to increase a patient's engagement within the whole therapy. However, as the market tends to apply VR and people are more familiar with this, it may be good to keep this trend and enhance the quality of user experience.

Based on the questionnaire research results, the devices for home remote motor therapy of extremities should be designed to:

- Provide stable remote connection to adjust the workout parameters and monitor the patient's measurable progress (e.g., by analyzis of tracked biosignals or information on sensed forces). So far, only four of the analyzed devices has such functionality. In the future, the rapid development of the digital twin and VR technologies may contribute to creating the methodology of remote manual robot–aided therapy. It could be based on dragging a virtual copy of the rehabilitated extremity and causing corresponding motion of the exoskeleton used by the patient;

Table 5. Comparison of the rehabilitation systems in terms of requirements towards patients and physiotherapists (abbr.: physio...–physiotherabot, n/a–no data)

Device	Paralysed patients	Physiotherapist's duties
Physio	After modification	Initial workout, supervision
ReoGo	Yes	Workout, supervision
Burt	Yes	Workout, supervision
InMotionARM	Yes	Workout, supervision
Armeo Power	Yes	Workout, supervision
EksoUE	With assistance	None, or additional manual therapy
ARMin	Yes	Workout, supervision
PHYS.../W1	Yes	Initial workout, remote supervision
RENUS–1	After modification	N/A
Lokomat	Yes	Workout, supervision
ReoAmbulator	Yes	Workout, supervision
G–EO	Yes	Workout, supervision
HAL	Yes	Training in operation and parameters adjustment
ReWalk	With assistance	Training in operation and parameters adjustment
ReStore	With assistance	None
EksoNR	With assistance	Setting the parameters
MotionMaker	Yes	Workout, supervision
Anklebot	Yes	N/A
RENUS–2	Yes	Workout, supervision
PHYS...	Yes	Initial workout, remote supervision

- Enable motion along with the natural patterns. Therefore, they should not constrain degrees of freedom in particular joints, but not necessarily by supporting every degree of freedom with drives. Only seven analyzed devices were not over–constraining natural DOFs of the extremity;
- Offer comprehensive treatment capabilities thanks to the implemented ICT technologies rather than powerful mechanical components. So far, only four of the analyzed devices have biosignals tracking implemented, while all but two use VR or another game environment. The mechanical design should enable transporting the device to the patients' flats and using them onsite. Therefore, they should fit the standard housing doors and not exceed the load capacity of the floors by weight. Hence, devices with treadmills or additional lift bars are not recommended.

It is worth noticing that the devices for rehabilitation of lower extremities are more likely to be used for home therapy. This may be, because most of them are dedicated to gait training, which needs to be performed daily, if it is to be effective. Therefore, their technological advancement is usually also superior to the devices for upper limbs. For this reason, the market shall be more open to new rehabilitation systems for upper extremities, especially portable ones, involving innovative ICT technologies.

Additionally, the devices for upper extremities, which are the most complex in terms of implemented technologies, are also the most complex in their construction. Hence, the ICT sophistication and portability are not likely to characterize one system. It is significant, as these parameters are required to enable effective telerehabilitation – so far, rather presented as advanced conceptual studies [40] or research [32], but without real–life implementation .

6. Conclusion

The overview of technologically advanced or widely available in Europe rehabilitation robots of extremities was presented to assess their applicability for remote home kinesiotherapy. The main requirements for them were based on prior in–depth interviews and questionnaire research. Considered parameters of the robots were gathered in tables and analyzed in terms of corresponding to the defined needs. According to the observations, there is no commercial and widespread device enabling full remote home rehabilitation of upper extremities. The systems offered for the clinics typically suffer from a lack of remote connection and technologies allowing telerehabilitation. As the role of a local operator is significant, a physiotherapist may not fully use the advantage of intelligent algorithms adjusting workouts to maximize their effectiveness. Therefore, the presented technological gaps must be completed with the highest priority. Nevertheless, the policy of constant development of ICT technologies shall be continued, as their effectiveness is confirmed with multiple studies; also for post–stroke and home therapy in particular [44,60,80]. The presented insights on the market of rehabilitation robots shape the direction of its development. As the concept of telerehabilitation becomes a reality, the devices shall enable the effective transfer of multiple and various sensory stimuli to the operator. Thanks to this, the physiotherapists will get sufficient information to monitor and lead a workout. Moreover, the devices need to be both portable and affordable. Only with these the rehabilitation systems may be leased to the patients. Thus, the production costs need to be decreased. It may be realized by replacing redundant sensors and non–required activated DOFs with intelligent algorithms. Also, with the technology advancement, the commonly used devices, such as smartphones, computers or smartwatches, could enrich the rehabilitation system with everyday collected data. Even with this, the devices would remain significantly more expensive than single therapy sessions. Thus, they will be still dedicated to the people who need long–term or intensive therapy, post–stroke among others [43]. Based on the conducted research, the main trends for the future include robotization of the task–oriented motor treatment and providing teleoperation. The technology likely to be used for such application is a digital twin, possibly combined with advanced sensors and VR/AR [40]. With arising interest on *Metaverse*, also this platform can contribute to the development of telehealth. Moreover, the appropriate safety means have to be developed. The technologies expected to be involved for this purpose are EMG tracking, simple wearable devices (related with mHealth), and AI analyzes of the treatment [79]. The neural networks can be used both in diagnoses and supporting control over treatment [38]. To provide truly available solutions, the devices offered for the different local markets should differ one from another. It is a consequence of the differences in economic situation among world regions, and even more critical – differing technology awareness of their societies. Moreover, some of the diseases restrain the variety of exercises allowed. These aspects may be considered by designing the system holistically but as a set of freely attachable modules. With this approach, the system's applicability is not limited to particular cases, which contributes to the popularization of robot–aided treatment.

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References

[1] "Armeo power website [online]". https://www.hocoma.com/solutions/armeo-power/. Accessed: 2020-10-21.

[2] "Armin website [online]". https://sms.hest.ethz.ch/research/current-research-projects/armin-robot. Accessed: 2020-10-23.

[3] "Barrett technology website [online]". https://medical.barrett.com/. Accessed: 2020-10-22.

[4] "The datasheet of motion maker by swortec [online]". http://www.swortec.ch/index.php/products/motionmaker. Accessed: 2020-11-02.

[5] "Eksonr by ekso bionics website [online]". https://eksobionics.com/eksonr/. Accessed: 2021-01-15.

[6] "Eksoue by ekso bionics website [online]". https://eksobionics.com/eksoue/, Accessed: 2020-10-23.

[7] "Hal by cyberdene website [online]". https://www.cyberdyne.jp/. Accessed: 2021-01-15.

[8] "Inmotionarm by bionik labs website [online]". https://www.bioniklabs.com/products/inmotion-arm. Accessed: 2020-10-23.

[9] "An interview with hans peter gmünder. pwc [online]". https://magazine.pwc.ch/en/item-detail-view/partake-in-life. Accessed: 2021-01-15.

[10] "Lokomat by hocoma website [online]". https://www.hocoma.com/solutions/lokomat/. Accessed: 2021-01-15.

[11] "Physio by gridbots website [online]". https://www.gridbots.com/physio. Accessed: 2020-10-10.

[12] "Physiotherabot project website [online]". http://ytubiomechatronics.com/portfolio-item/lower-limb/, note = Accessed: 2021-11-05.

[13] "Physiotherabot/w1 website [online]". http://ytubiomechatronics.com/portfolio-item/physiotherabot-w1/. Accessed: 2021-11-05.

[14] "Presentation of prototypes of rehabilitation robots by piap (in polish) [online]". https://www.youtube.com/watch?v=FSBf5kPEz3k. Accessed: 2021-01-15.

[15] "Reoambulator by motorika website [online]". http://motorika.com/reoambulator/. Accessed: 2021-01-15.

[16] "Reoambulator by motorika website [online]". https://www.rehatechnology.com/en/. Accessed: 2021-01-15.

[17] "Reogo by motorika website [online]". http://motorika.com/reogo/. Accessed: 2020-10-22.

[18] "Rewalk website [online]". https://rewalk.com/. Accessed: 2021-01-15.

[19] C. Adans-Dester, A. O'Brien, R. Black-Schaffer, and P. Bonato. "Upper extremity rehabilitation with the burt robotic arm", *Archives of Physical Medicine and Rehabilitation*, vol. 100, no. 12, 2019, e208–e209.

[20] J. Ahn, and N. Hogan. "Walking is not like reaching: evidence from periodic mechanical perturbations", *PloS one*, vol. 7, no. 3, 2012, e31767.

[21] E. Akdoğan, and M. A. Adli. "The design and control of a therapeutic exercise robot for lower limb rehabilitation: Physiotherabot", *Mechatronics*, vol. 21, no. 3, 2011, 509–522.

[22] E. Akdogan, and M. E. Aktan. "Impedance control applications in therapeutic exercise robots". In: *Control Systems Design of Bio-Robotics and Biomechatronics with Advanced Applications*, 395–443. Elsevier, 2020.

[23] E. Andrenelli, M. Capecci, L. Di Biagio, L. Pepa, L. Lucarelli, C. Spagnuolo, P. Guidoni, P. Serafini, F. Morgante, and M. Ceravolo. "Improving gait function and sensorimotor brain plasticity through robotic gait training with g-eo system in parkinson's disease", *Annals of Physical and Rehabilitation Medicine*, vol. 61, 2018, e79–e80.

[24] L. N. Awad, A. Esquenazi, G. E. Francisco, K. J. Nolan, and A. Jayaraman. "The rewalk restore™ soft robotic exosuit: a multi-site clinical trial of the safety, reliability, and feasibility of exosuit-augmented post-stroke gait rehabilitation", *Journal of neuroengineering and rehabilitation*, vol. 17, no. 1, 2020, 1–11.

[25] P. Bontje, R. Kruijne, M. Pol, K. Inoue, R. Kobayashi, Y. Ito, and M. Van Hartingsveldt. "Developing an international research of health-care ict applied for rehabilitation and daily living support between japan and the netherlands", *Assistive Technology*, vol. 34, no. 2, 2022, 140–147.

[26] R. S. Calabrò, M. Russo, A. Naro, D. Milardi, T. Balletta, A. Leo, S. Filoni, and P. Bramanti. "Who may benefit from armeo power treatment? a neurophysiological approach to predict neurorehabilitation outcomes", *PM&R*, vol. 8, no. 10, 2016, 971–978.

[27] B. Chen, H. Ma, L.-Y. Qin, F. Gao, K.-M. Chan, S.-W. Law, L. Qin, and W.-H. Liao. "Recent developments and challenges of lower extremity exoskeletons", *Journal of Orthopaedic Translation*, vol. 5, 2016, 26–37.

[28] Y. Cherni, M. Hajizadeh, F. Dal Maso, and N. A. Turpin. "Effects of body weight support and guidance force settings on muscle synergy during lokomat walking", *European Journal of Applied Physiology*, vol. 121, no. 11, 2021, 2967–2980.

[29] O. Cruciger, T. A. Schildhauer, R. C. Meindl, M. Tegenthoff, P. Schwenkreis, M. Citak, and M. Aach. "Impact of locomotion training with a neurologic controlled hybrid assistive limb (hal) exoskeleton on neuropathic pain and health related quality of life (hrqol) in chronic sci: a case study", *Disability and Rehabilitation: Assistive Technology*, vol. 11, no. 6, 2016, 529–534.

[30] S. De Biase, L. Cook, D. A. Skelton, M. Witham, and R. Ten Hove. "The covid-19 rehabilitation pandemic", *Age and ageing*, vol. 49, no. 5, 2020, 696–700.

[31] U. Demir, S. Kocaoğlu, and E. Akdoğan. "Human impedance parameter estimation using artificial neural network for modelling physiotherapist motion", *Biocybernetics and Biomedical Engineering*, vol. 36, no. 2, 2016, 318–326.

[32] I. Díaz, J. M. Catalan, F. J. Badesa, X. Justo, L. D. Lledo, A. Ugartemendia, J. J. Gil, J. Díez, and N. García-Aracil. "Development of a robotic device for post-stroke home tele-rehabilitation", *Advances in Mechanical Engineering*, vol. 10, no. 1, 2018, 1687814017752302.

[33] I. Díaz, J. J. Gil, and E. Sánchez. "Lower-limb robotic rehabilitation: literature review and challenges", *Journal of Robotics*, vol. 2011, 2011.

[34] J. Dunaj, W. J. Klimasara, and Z. Pilat. "Human-robot interaction in the rehabilitation robot renus-1". In: *International Conference on Systems, Control and Information Technologies 2016*, 2016, 358–367.

[35] D. Eguren, M. Cestari, T. P. Luu, A. Kilicarslan, A. Steele, and J. L. Contreras-Vidal. "Design of a customizable, modular pediatric exoskeleton for rehabilitation and mobility". In: *2019 IEEE international conference on systems, man and cybernetics (SMC)*, 2019, 2411–2416.

[36] P. Falkowski. "Light exoskeleton design with topology optimisation and fem simulations for fff technology", *Journal of Automation, Mobile Robotics and Intelligent Systems*, 2021, 14–19.

[37] P. Falkowski. "An optimisation problem for exoskeleton-aided functional rehabilitation of an upper extremity". In: *IOP Conference Series: Materials Science and Engineering*, vol. 1239, no. 1, 2022, 012012.

[38] P. Falkowski. "Predicting dynamics of a rehabilitation exoskeleton with free degrees of freedom". In: *Conference on Automation*, 2022, 223–232.

[39] P. Falkowski, T. Osiak, and A. Pastor. "Analysis of needs and requirements of kinesiotherapy in poland for robot design purposes", *Prace Naukowe - Politechnika Warszawska. Elektronika z. 197, Postępy robotyki. T. 2*, 2022.

[40] P. Falkowski, T. Osiak, J. Wilk, N. Prokopiuk, B. Leczkowski, Z. Pilat, and C. Rzymkowski. "Study on the applicability of digital twins for home remote motor rehabilitation", *Sensors*, vol. 23, no. 2, 2023, 10.3390/s23020911.

[41] S. Faran, O. Einav, D. Yoeli, M. Kerzhner, D. Geva, G. Magnazi, S. van Kaick, and K.-H. Mauritz. "Reo assessment to guide the reogo therapy: Reliability and validity of novel robotic scores". In: *2009 Virtual Rehabilitation International Conference*, 2009, 209–209.

[42] P. A. Gómez, M. D. Rodríguez, and V. Amela. "Design of a robotic system for diagnosis and rehabilitation of lower limbs", *arXiv preprint arXiv:1710.08126*, 2017.

[43] T. Gueye, M. Dedkova, V. Rogalewicz, M. Grunerova-Lippertova, and Y. Angerova. "Early post-stroke rehabilitation for upper limb motor function using virtual reality and exoskeleton: equally efficient in older patients", *Neurologia i Neurochirurgia Polska*, vol. 55, no. 1, 2021, 91–96.

[44] M. Gustavsson, C. Ytterberg, and S. Guidetti. "Exploring future possibilities of using information and communication technology in multidisciplinary rehabilitation after stroke–a grounded theory study", *Scandinavian journal of occupational therapy*, vol. 27, no. 3, 2020, 223–230.

[45] Y.-w. Hsieh, K.-c. Lin, C.-y. Wu, T.-y. Shih, M.-w. Li, and C.-l. Chen. "Comparison of proximal versus distal upper-limb robotic rehabilitation on motor performance after stroke: a cluster controlled trial", *Scientific reports*, vol. 8, no. 1, 2018, 1–11.

[46] N. Iivari, S. Sharma, and L. Ventä-Olkkonen. "Digital transformation of everyday life–how covid-19 pandemic transformed the basic education of the young generation and why information management research should care?", *International Journal of Information Management*, vol. 55, 2020, 102183.

[47] M. Iosa, A. Martino Cinnera, F. Capone, A. Cruciani, M. Paolucci, V. Di Lazzaro, S. Paolucci, and G. Morone. "Clinical interpretation of working volume and weight support in upper limb robotic neurorehabilitation after stroke", *Applied Sciences*, vol. 11, no. 24, 2021, 12123.

[48] L. J. Jasinski. "Structural exoskeletons and soft fabric exosuits for assistive walking". In: *Wearable Robotics*, 311–333. Elsevier, 2020.

[49] B. A. Jnr. "Use of telemedicine and virtual care for remote treatment in response to covid-19 pandemic", *Journal of medical systems*, vol. 44, no. 7, 2020, 1–9.

[50] G. J. Kim, J. Hinojosa, A. K. Rao, M. Batavia, and M. W. O'Dell. "Randomized trial on the effects of attentional focus on motor training of the upper extremity using robotics with individuals after chronic stroke", *Archives of physical medicine and rehabilitation*, vol. 98, no. 10, 2017, 1924–1931.

[51] J. H. Kim. "Effects of robot-assisted therapy on lower limb in patients with subacute stroke", *Journal of the Korea Academia-Industrial cooperation Society*, vol. 17, no. 7, 2016, 459–466.

[52] W. Klimasara, J. Dunaj, P. Stempniak, and Z. Pilat. "Renus-1 and renus-2, the assisted robots system for after stroke mobility rehabilitation", *Prace Naukowe Politechniki Warszawskiej. Elektronika*, no. 175, t. 1, 2010, 55–62.

[53] W. J. Klimasara, A. Bratek, M. Pachuta, and Z. Pilat. "Systemy mechatroniczne w rehabilitacji ruchowej", *Pomiary Automatyka Robotyka*, vol. 13, no. 2, 2009, 577–586.

[54] K. Kong, J. Choi, K.-W. Park, J. Park, D.-H. Lee, E. Song, B. Na, S. Jeon, T. Kim, H. Choi, et al. "The history and future of the walkon suit: A powered exoskeleton for people with disabilities", *IEEE Industrial Electronics Magazine*, 2021.

[55] D. Kuhn and B. Freyberg-Hanl. "Exoskelett: Therapiesystem oder hilfsmittel zum behinderungsausgleich", *Trauma und Berufskrankheit*, vol. 20, no. 4, 2018, 254–259.

[56] H. Y. Lee, J. H. Park, and T.-W. Kim. "Comparisons between locomat and walkbot robotic gait training regarding balance and lower extremity function among non-ambulatory chronic acquired brain injury survivors", *Medicine*, vol. 100, no. 18, 2021.

[57] M. F. Levin. "What is the potential of virtual reality for post-stroke sensorimotor rehabilitation?", *Expert review of neurotherapeutics*, vol. 20, no. 3, 2020, 195–197.

[58] Y. Liu, X. Li, A. Zhu, Z. Zheng, and H. Zhu. "Design and evaluation of a surface electromyography-controlled lightweight upper arm exoskeleton rehabilitation robot", *International Journal of Advanced Robotic Systems*, vol. 18, no. 3, 2021, 17298814211003461.

[59] S. Macovei, and I. Doroftei. "A short overview of upper limb rehabilitation devices". In: *IOP Conference Series: Materials Science and Engineering*, vol. 145, no. 5, 2016, 052014.

[60] M. N. Marwaa, H. K. Kristensen, S. Guidetti, and C. Ytterberg. "Physiotherapists' and occupational therapists' perspectives on information and communication technology in stroke rehabilitation", *Plos one*, vol. 15, no. 8, 2020, e0236831.

[61] K. Miura, M. Koda, K. Tamaki, M. Ishida, A. Marushima, T. Funayama, H. Takahashi, H. Noguchi, K. Mataki, Y. Yasunaga, et al. "Exercise training using hybrid assistive limb (hal) lumbar type for locomotive syndrome: a pilot study", *BMC Musculoskeletal Disorders*, vol. 22, no. 1, 2021, 1–8.

[62] M. Mohammadi, H. Knoche, M. Thøgersen, S. H. Bengtson, M. A. Gull, B. Bentsen, M. Gaihede, K. E. Severinsen, and L. N. Andreasen Struijk. "Eyes-free tongue gesture and tongue joystick control of a five dof upper-limb exoskeleton for severely disabled individuals", *Frontiers in Neuroscience*, vol. 15, 2021, 739279.

[63] T. Nef, M. Guidali, V. Klamroth-Marganska, and R. Riener. "Armin-exoskeleton robot for stroke rehabilitation". In: *World Congress on Medical Physics and Biomedical Engineering, September 7-12, 2009, Munich, Germany*, 2009, 127–130.

[64] I.-A. Niţică, and E. Nechifor. "Antrenamentul mersului cu ajutorul sistemului robotic g-eo evolution", *Journal of Physical Rehabilitation and Sports Medicine*, no. 2, 2020, 20–29.

[65] I.-A. Niţică, and E. Nechifor. "Antrenamentul mersului cu ajutorul sistemului robotic g-eo evolution", *Journal of Physical Rehabilitation and Sports Medicine*, no. 2, 2020, 20–29.

[66] N. Pavón-Pulido, J. A. López-Riquelme, and J. J. Feliú-Batlle. "Iot architecture for smart control of an exoskeleton robot in rehabilitation by using a natural user interface based on gestures", *Journal of Medical Systems*, vol. 44, no. 9, 2020, 1–10.

[67] J. Prvu Bettger, and L. J. Resnik. "Telerehabilitation in the age of covid-19: an opportunity for learning health system research", *Physical Therapy*, vol. 100, no. 11, 2020, 1913–1916.

[68] N. Rehmat, J. Zuo, W. Meng, Q. Liu, S. Q. Xie, and H. Liang. "Upper limb rehabilitation using robotic exoskeleton systems: A systematic review", *International Journal of Intelligent Robotics and Applications*, vol. 2, no. 3, 2018, 283–295.

[69] A. Roy, H. I. Krebs, J. E. Barton, R. F. Macko, and L. W. Forrester. "Anklebot-assisted locomotor training after stroke: A novel deficit-adjusted control approach". In: *2013 IEEE International Conference on Robotics and Automation*, 2013, 2175–2182.

[70] A. Roy, H. I. Krebs, S. L. Patterson, T. N. Judkins, I. Khanna, L. W. Forrester, R. M. Macko, and N. Hogan. "Measurement of human ankle stiffness using the anklebot". In: *2007 IEEE 10th International Conference on Rehabilitation Robotics*, 2007, 356–363.

[71] C. Schmitt, and P. Métrailler. "The motion maker™: a rehabilitation system combining an orthosis with closed-loop electrical muscle stimulation". In: *8th Vienna international workshop on functional electrical stimulation*, no. CONF, 2004, 117–120.

[72] R. A. Søraa, and E. Fosch-Villaronga. "Exoskeletons for all: The interplay between exoskeletons, inclusion, gender, and intersectionality", *Paladyn, Journal of Behavioral Robotics*, vol. 11, no. 1, 2020, 217–227.

[73] P. Soto-Acosta. "Covid-19 pandemic: Shifting digital transformation to a high-speed gear", *Information Systems Management*, vol. 37, no. 4, 2020, 260–266.

[74] S. Straudi, G. Severini, M. Da Roit, L. D. M. Pizzongolo, C. Martinuzzi, and N. Basaglia. "The dose of robot-assisted gait therapy may influence functional recovery in a multidisciplinary rehabilitation program: an exploratory retrospective study", *International Journal of Rehabilitation Research*, vol. 43, no. 2, 2020, 175–182.

[75] K. Swaminathan, and H. I. Krebs. "Analysis of the anklebot training as a method for reducing lower-limb paretic impairment a case study in electromyography". In: *2015 IEEE International Conference on Rehabilitation Robotics (ICORR)*, 2015, 555–558.

[76] K. Takahashi, T. Takebayashi, S. Amano, Y. Uchiyama, K. Domen, and K. Hachisuka. "Constrained-induced movement therapy transfer the function gained by upper arm robotic therapy into daily activities". In: *STROKE*, vol. 51, 2020.

[77] T. Takebayashi, K. Takahashi, S. Amano, Y. Uchiyama, M. Gosho, K. Domen, and K. Hachisuka. "Assessment of the efficacy of reogo-j robotic training against other rehabilitation therapies for upper-limb hemiplegia after stroke: Protocol for a randomized controlled trial", *Frontiers in neurology*, vol. 9, 2018, 730.

[78] R. B. van Dijsseldonk, I. J. van Nes, A. C. Geurts, and N. L. Keijsers. "Exoskeleton home and community use in people with complete spinal cord injury", *Scientific reports*, vol. 10, no. 1, 2020, 1–8.

[79] J. Wilk, and P. Falkowski. "A concept of detecting patient hazards during exoskeleton-aided

remote home motor rehabilitation", *Prace Naukowe - Politechnika Warszawska. Elektronika z. 197, Postępy robotyki. T. 2*, 2022.

[80] H. Zheng, R. Davies, T. Stone, S. Wilson, J. Hammerton, S. J. Mawson, P. Ware, N. D. Black, N. D. Harris, C. Eccleston, et al. "Smart rehabilitation: Implementation of ict platform to support home-based stroke rehabilitation". In: *International Conference on Universal Access in Human-Computer Interaction*, 2007, 831–840.