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REHABILITATION ROBOT RRH1

The paper presents a prototype of a rehabilitation robot for lower extremities. It is created on the basis of cylindrical kinematic model, equipped with two rigid arms, special handles and fixtures. It has five active degrees of freedom and is designed to repeat the trajectories generated by physiotherapist during the learning phase. Presented prototype of rehabilitation robot has the ability to replay different types of trained exercises such as: hip and knee flexion/extension, leg abduction/adduction. The protection system (including overload detection) implemented in the robot ensures safe working with patients.

1. Development of rehabilitation robotic devices for lower extremities

The beginnings of lower extremities rehabilitation with motor-assisted devices is dated on seventies of XX century. At this time the concept of continuous passive motion rail has been tested. This kind of mechanical structure evaluated from the work of Robert B. Salter – an orthopedic surgeon – who noted that the cyclical flexion-extension of patient's joint reduces recovery time and increases their range of motion after orthopedic surgery. These devices are designed in two types, for upper limb and lower limb rehabilitation, as shown in Fig. 1.

Rapid technology revolution in the field of electronics and control systems increased the number of semi-automatic and automatic devices installed and used in rehabilitation clinics, mainly due to their new therapeutic properties [7]. Applying an electronic control system allows the user to adjust some basic parameters such as: the range and speed of motion. It also provides a compliance control which prevents from excessive force acting on rehabilitated joint. Moreover, with the progress of therapy the device performs an automatic increase in range of motion.

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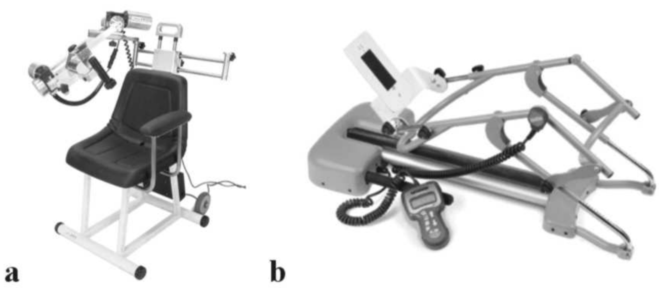


Fig. 1. CPM rails: a – for upper limb rehabilitation, b – for lower extremities rehabilitation, reproduced from [http://www.abledata.com]

Various designs allow the rehabilitation process being realized in standing, sitting, or lying position of the patient. However, the important limitation of these devices is fact that they are able to work in a single plane only. Therefore, changing the rehabilitation procedure very often requires moving patient to the different position or setting new orientation of the mechanical device. On the other hand, the main advantage of leg rehabilitation CPM rails is their low weight and relatively low cost.

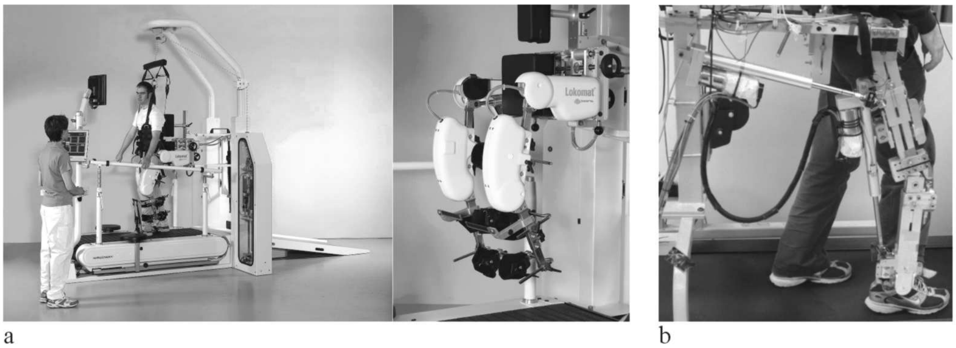


Fig. 2. Anthropomorphic Robotic orthosis for gait reeducation: a – LOKOMAT – Hocoma company, reproduced from [2], b – ALEX from University of Delaware, reproduced from [1]

Modern neurorehabilitation with robot-assisted devices is a relatively new field in rehabilitation. First attempts to develop this kind of devices appeared in the late 90s of the XX century. Experience on the field of rehabilitation and engineering knowledge allowed researchers from the University of ETH in Zurich to create a mechanical orthosis system Lokomat in the year 2000 [2, 5]. Lokomat (shown in Fig. 2) is designed for gait re-education process of patients with neurological disorders and spinal cord injuries.

Robotic orthosis Lokomat provides continuous progress in gait re-education. Body weight support system, an integrated part of the robot, is used for automated treadmill training and therapist assist. It may also be used for patients that required to be lifted out of the wheelchair. Regarding inertial forces that may affect patients during vertical movements, traditional counterweight systems could not be used during therapy. Lokomat is equipped with a computer driven unloading unit that imitates patient's movements during gait cycle and also provides regulation of contact forces during walking on treadmill.

During robot-assisted therapy the optimum number of repetitions of gait cycles is performed according to the programmed pattern. The specialized software provides adjustable range of motion for individual patients (regarding hip and knee joints), variable velocity of movements, and synchronization of the walking cycles with the treadmill speed. Universal mechanical modules and handles implemented in the construction of robotic legs allow for precise adaptation to the anatomy of different patients.

All over the world researchers are also working to develop similar devices. However, they did not go beyond the stage of prototypes and most of the constructions haven't been commercialized yet. The similar design to the Lokomat has been recently developed at the University of Delaware, Newark USA. Its name ALEX states for Active Leg Exoskeleton and it can be recognized by the larger number of degrees of freedom and the passive gravity compensation system, as shown in Figure 2b [1]. Mechanical orthosis leg has 3 active degrees of freedom corresponding to the bending move of the knee and the hip in sagittal plane. Additionally, orthosis has one degree of freedom responsible for adduction and abduction movements of the leg.

The whole mechanism is attached to the supporting structure with two passive degrees of freedom, which provide additional vertical and horizontal movements. Elastic elements used in construction of passive joints are used for compensation of the brace's weight, and perform the proper movements of the pelvis (lateral, vertical and rotation).

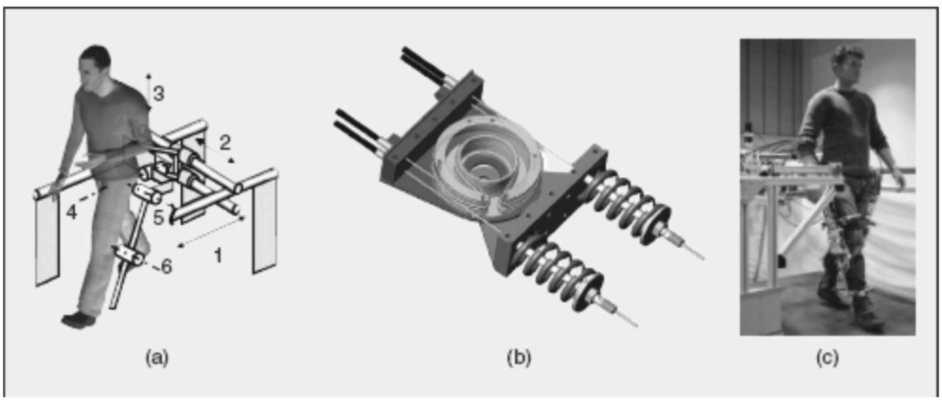
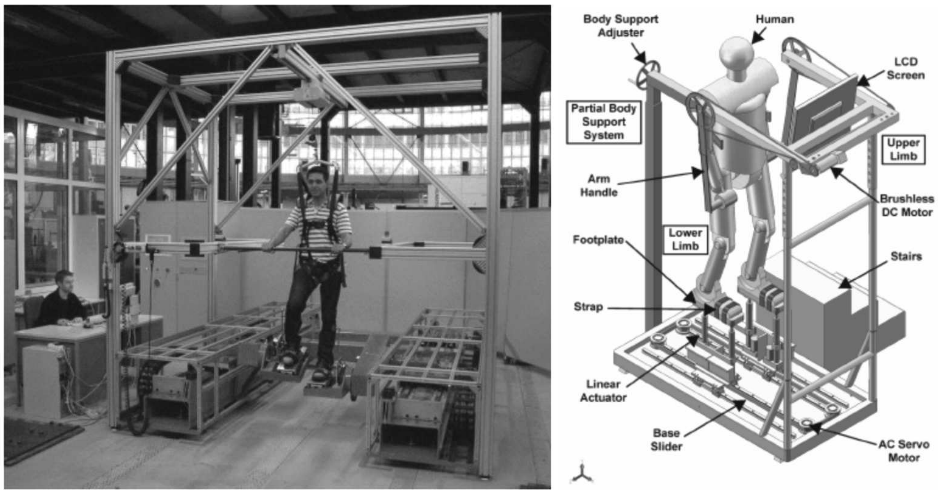


Fig. 3. LOPES robotic orthosis, reproduced from [3]

Structurally very similar to previous devices is LOPES – Lower-Extremity Powered Exoskeleton, shown in Fig. 3, which is designed for the gait rehabilitation purposes and uses treadmill in training procedure [3]. The main objectives of this project are: reducing the load of the physical therapist to improve the effectiveness of training in stroke patients and supporting selected elements of the locomotion apparatus in the process of gait re-education. Generating the movement of robotic orthosis is done according to the programmed trajectory. During training process the interaction between the patient and mechanical skeleton is taken into account. The compliant and adaptive control with adjustable serial elasticity in motor drives (shown in Fig. 3b) is applied for active joints of the exoskeleton [9, 10]. This solution allows patients to sense the minimal influence of mechanical orthosis to the rehabilitated limbs. Comparing to the commercial Lokomat, orthosis LOPES has larger number of active degrees of freedom. This provides free movements of the hip along three axes, indicated by 1, 2, and 3 in Fig. 3a. First and the second joint are active with servomotors while the vertical direction marked as 3 is a passive one (without drive).



a b

Fig. 4. Sytems for neurorehabilitation with motion generation by foot plates: a – HapticWalker (Germany) [8], b – device from the University of Gyeongsang (Korea) [6]

Completely different construction, which was recently clinically tested, is the HapticWalker device, created by German scientists from Technical University in Berlin and a group of engineers from Fraunhofer IPK [8]. The mechanism has the form of a cubic frame where the patient is suspended in special harness over the robotic arms, as shown in Fig. 4a. Effectors of the robot arms are made as the special platforms with the handles to attach patient's feet. The movements of the lower extremities are generated by pushing or pulling of patient's feet, as it is done in the CPM rails. In the HapticWalker device, the patient is supported by the dynamic weight compensation system. Generating leg's movements by acting on the patient's feet provides some extended possibilities to obtain more natural walking and stair climbing. This method of therapy involves not only the lower limbs but also the entire body. The first tests showed that therapy with HapticWalker increases the strength and efficiency of the body. Increasing these parameters is one of the fundamental aspects in convalescence and prepares people to return to the duties and activities of everyday life. However, acting only on the feet without additional constrains on knees and hips may lead to the situation where motion in one direction can result in pathological compensatory movements.

Another design of robotic system for lower extremities rehabilitation based on same approach of motion generation by foot plates is the robot shown in Fig. 4b, developed by a team from Gyeongsang University in Korea [6]. This robot can simulate walking of the flat surface, and therefore work as the most of the robots with treadmill, but its superior feature is generating gait patterns characteristic for walking over uneven terrain. For example, it can generate the trajectory corresponding to ascending or descending the stairs. Presented device has a lightweight, compact structure, which allows its use in therapy at home. Authors presented an innovative solution of supporting patient on the rehabilitation device. Usually in the systems with free pelvis, to prevent falling, patient is fastened at the waist to the frame of the robot using a passive suspension system. In the Korean design, an additional powered mechanical system is used to engage the upper limbs in the therapy process. Patient holds the arm handles during exercise. They are driven by DC motors, thus their movements can be controlled, according the programmed gait pattern.

In robot-assisted devices lack of limitations of attaching the lower extremities to an external skeleton (Lokomat, LOPES, ALEX) makes the process of rehabilitation much more efficient and allows to involve many muscle groups. The release of the pelvis causes the ability to perform its natural swing-type movements in three dimensions space. On one hand, it reflects the natural way of movement, but it can also produce unexpected, pathological compensatory movements.

In 2003, on the Conference of Advanced Intelligent Mechatronics, an advanced system for rehabilitation of the lower extremities was presented [4]. The concept of this wire driven manipulator is shown in Fig. 5. The patient lies in the specially prepared position. His legs are attached to the

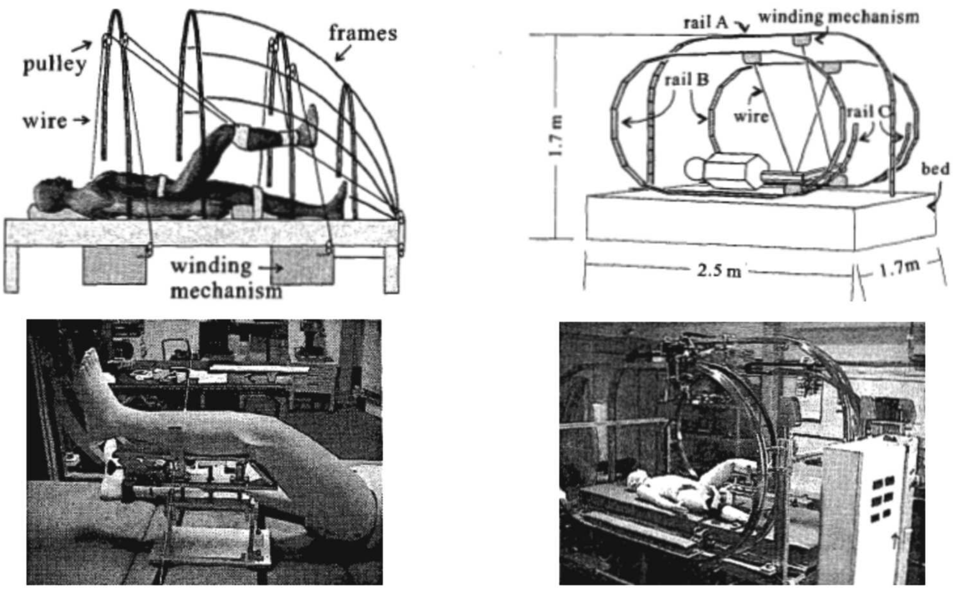


Fig. 5. Wire driven system for lower extremities rehabilitation: concept and the prototype, reproduced from [4]

adjustable harnesses, which are connected by the wires to electric motors mounted on an external frame. System of cables and blocks placed around the patient on the frame allows for easily manipulation of patient's leg within a designated workspace. Increasing the number of drives used in the system can produce more complex movements.

2. Construction of the RRH1 robot

Our own rehabilitation robot for lower extremities is presented in Fig. 6. Beside the photograph of the fully functional prototype, there is a schematic drawing showing major components, possible movements (with arrows) and the working space of the robot (dashed line presenting section of the cylinder).

Robot consists of an aluminum chassis and adjustable column located on the rectangular base. Lightweight construction (about 100 kg), together with two standard, and two castor wheels make whole mechanism easy to move from one hospital bed to another, even by one person. There is no need to relocate patients to special rehabilitation area; treatment can be started shortly after accident or can be applied even for unconscious person. Robot can be locked in place by brakes mounted on wheels (F1) while its height can be adjusted for specific bed and patient by the crank (E).

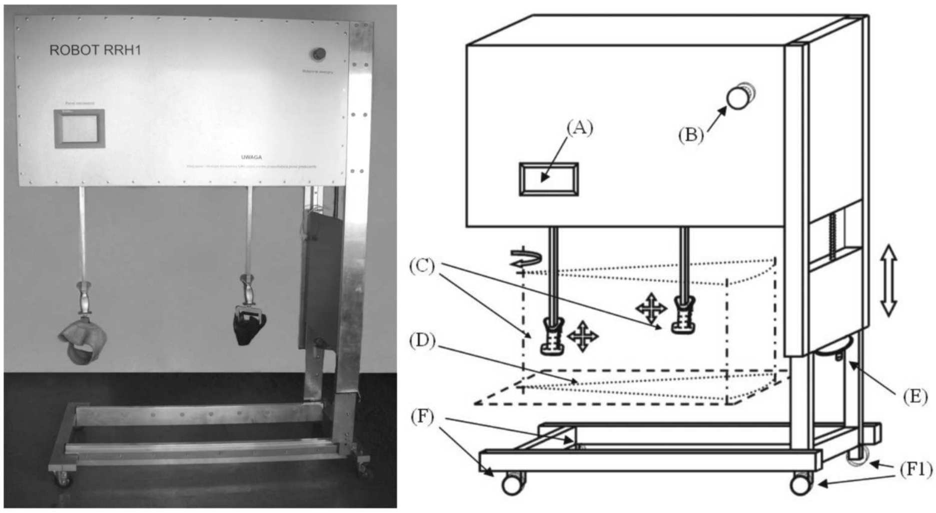


Fig. 6. Rehabilitation robot RRH1: A – Chassis with LCD display and touch panel, B – emergency stop, C – robot arms with handles, D – robot working space, E – adjustable column, base with standard (F) and castor wheels with brakes (F1)

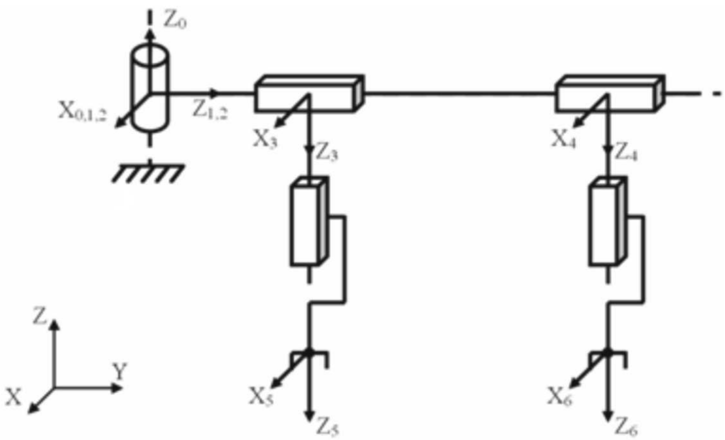


Fig. 7. Kinematic structure of rehabilitation robot RRH1 with coordinate frames according to D-H notation, note that it is double mechanism, and two handles for legs are located on the same linear guide

Kinematic structure of the robot is based on the cylindrical scheme shown in Fig. 7. Robot has 5 active degrees of freedom (DOF) numbered from 0 to 4 according to the Denavit-Hartenberg notation. Parameters of kinematic model are presented in Table 1. All joints of the robot have similar driving systems: DC motor with incremental encoder and reduction gear head, electromagnetic clutch and rotary potentiometer for absolute measurement of joint's position.

Inside the chassis (A) there is a special toothed guide with two carriages traveling on it, as show in Fig. 8. Each carriage contains two drives: one responsible for horizontal movement of the carriage and one motorizing vertical arm. These mutually perpendicular joints are numbered as pairs 1-3 and 2-4, and belong to the arms 1 and 2, respectively. Arm 1 is holding knee of the patient while arm 2 holds foot. Both arms work in vertical plane YZ and can generate exercises for flexion and extension of knee and hip, as shown if Fig. 9a. The ranges of movements for horizontal and vertical joints are 650mm and 470mm, respectively.

Table 1.

Denavit-Hartenberg parameters of kinematic model of the RRH1 robot

Arm	Joint	θ_i [rad]	d_i [m]	a_i [m]	α_i [rad]
1	0→1	$\theta_{0\to1}$*	0	0	$-\pi/2$
	1→3	0	$d_{1\to3}$*	0	$-\pi/2$
	3→5	0	$d_{3\to5}$*	0	0
2	0→2	$\theta_{0\to2}$*=$\theta_{0\to1}$*	0	0	$-\pi/2$
	2→4	0	$d_{2\to4}$*	0	$-\pi/2$
	4→6	0	$d_{4\to6}$*	0	0

where: θ – joint rotation angle; d – linear translation; a – length of the link; α – skew angle; according to the D-H notation

Additionally, the main toothed guide can rotate about the Z_0 axis. This movement is generated by the drive 0 located on the special guide shown on the right part of Fig. 8. This extra DOF expands functionality of rehabilitation robot by adding hip adduction and abduction exercises, shown in Fig. 9b. The range of rotation around Z_0 axis is ±15deg.

To optimally utilize working area of the robot height of the mechanism should be adjusted by crank (E).

3. Programing of the robot

The main idea of programming the rehabilitation robot is based on the teaching by showing method. After fixing the patient's leg to the arms of the robot, rehabilitant holds the handles mounted on the ends of the arms and moves the leg according to the exercise. Trajectories of positions and velocities of all joints are recorded by the controller and can be replayed in the cyclic manner.

Handles are equipped with buttons (shown in Fig. 10) to control the arms of the robot during preparation and teaching phases. After pressing

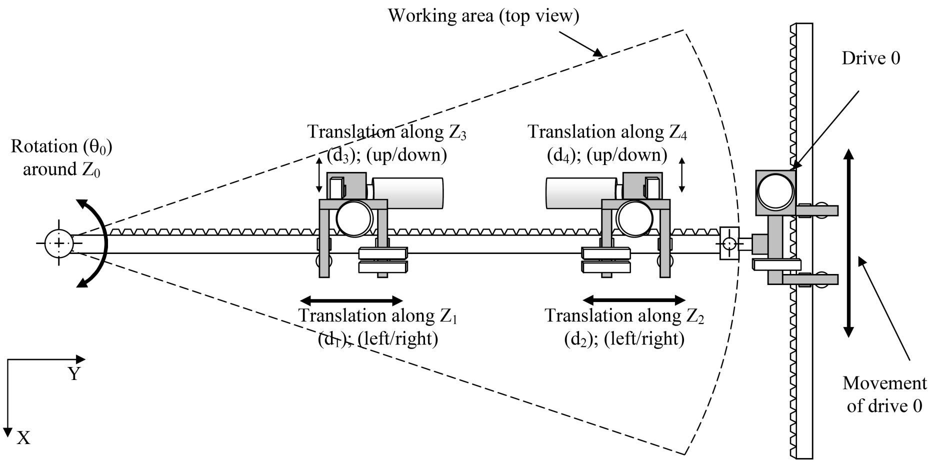


Fig. 8. Internal structure of driving mechanism of rehabilitation robot (top view)

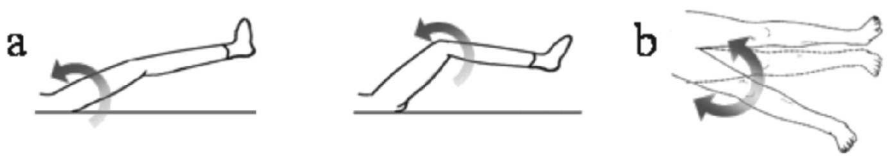


Fig. 9. Exercises generated by RRH1 robot: a – lifting up the leg, flexion and extension of knee and hip, b – abduction and adduction of hip joint

the button arm can be moved freely as the motors are disconnected from the joins and joints' positions are monitored by potentiometers. Additional functions are available through touch panel interface.

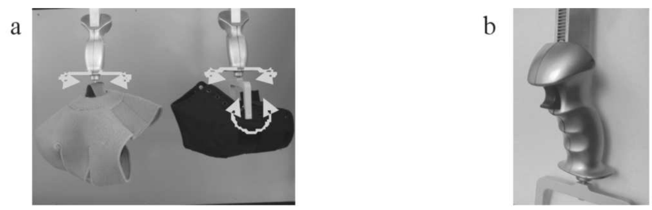


Fig. 10. Handles and fixtures on the robot's arm

Robot's arms are very light and the drag introduced by linkages and potentiometers is very low, therefore rehabilitant can feel weight of the leg and natural limits of movements. Exercises may also include some pushing against the limits. Teaching phase ends when both buttons on the handles are realized. The next phase is test run: robot executes the single cycle of movements; rehabilitant has to monitor correctness of trajectory, behavior of patient and system. This is also the time to adjust speed of the exercise.

In this phase, system records forces appearing in joints. In the next step, operator accepts trajectory and sets the number of cycles.

4. Safety systems

Working with people, in general, requires special safety measures. Rehabilitation robots have to be even more sensitive mechanisms as they work with disabled or even unconscious patients. Rehabilitation robot RRH1 was equipped with several safety systems:

- Immediately cease of the power for motors when the emergency stop button (B) is pressed,
- Software stop executed on the touch panel in any phase of the teach-execution algorithm,
- Continuous monitoring of the position, velocity, and force of each joint – immediate stop when any distortion appear,
- Immediate stop when malfunction of communication layer is detected.

5. Conclusion

We have presented the short review of rehabilitation devices for lower limbs. In general, there are three types of systems: exoskeleton based (Lokomat, LOPES, ALEX), generating motion by foot plates (HapticWalker, robot from Gyeongsang University), and generating motion by holding legs in knee and ankle joints. In the later case we have found only one example of the system using wires and external frame to lead leg in the working space of the robot.

We have designed and built original construction belonging to the same category of robots, however, using rigid links to hold and move leg along the learned path. Our prototype can be safely used both for conscious and unconscious patients in early stages of rehabilitation. It can be also used for daily exercises of legs for long term or intensive-care patients lying in beds. Proposed solution offers more compact construction and better mobility than wire driven robot. It has 5 DOF and allows for full spectrum of exercises including hip and knee flexion/extension, and leg abduction/adduction.

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Robot rehabilitacyjny RRH1

S t r e s z c z e n i e

Artykuł prezentuje prototyp robota do rehabilitacji kończyn dolnych. Robot zbudowany jest w oparciu o cylindryczny układ kinematyczny o dwóch sztywnych ramionach. Posiada 5 aktywnych stopni swobody i przeznaczony jest do odtwarzania zadanej przez fizykoterapeutę trajektorii ruchu. Robot posiada możliwość odtwarzania ćwiczeń zgięcia, wyprostu w stawie kolanowym i biodrowym oraz przywodzenia i odwodzenia nogi. Zastosowany w robocie system zabezpieczeń, zawierający detekcję nadmiernego oddziaływania kończyny dolnej na ramiona robota, pozwala na bezpieczną pracę z pacjentami.