Lower Limb Rehabilitation Exoskeleton with a Back Support – Mechanical Design

Bartosz Stańczyk, Olga Jarzyna, Wojciech Kunikowski, Dariusz Grzelczyk, Jerzy Mrozowski, and Jan Awrejcewicz

Abstract Mobility impairment is a serious medical and social problem with an increasing prevalence. Therefore, it is important to develop devices that would help both the patients and the therapists. In this paper, a literature overview of available constructions of lower limb exoskeletons was presented. Degrees of freedom (DOFs), kinematics and drive systems of regarded devices were studied. The outcomes of the investigation of the literature regarding active and passive DOFs and torque requirements were used as guidelines for the development of the conceptual design and a prototype of the exoskeleton. The proposed device is intended to be used for gait rehabilitation for patients suffering from different types of gait abnormality. It has 11 DOFs that can be actuated, or not, depending on the needs of the wearer. These DOFs are accompanied by two complex movements, which are flexion/extension of the patient's upper body as well as flexion/extension of toes.

Keywords Human gait · Exoskeleton · Lower limb · Gait · Rehabilitation · Powered orthosis · Paraplegia

1 Introduction

According to the World Report on Disability, published by the World Health Organization (WHO), more than 1 billion people (which is about 15% of the world population at the time of publication of the Report) live with some form of disability, with about 200 million having considerable difficulties in functioning (see [1]). The same report says that not only health outcomes of the disabled but also their educational achievements and financial status are lower than of people without

B. Stańczyk (✉) · O. Jarzyna · W. Kunikowski · D. Grzelczyk · J. Mrozowski · J. Awrejcewicz
Department of Automation, Biomechanics and Mechatronics, Lodz University of Technology, Lodz, Poland
e-mail: bartosz.stanczyk@p.lodz.pl

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disabilities. According to the National Center for Health Statistics (see [2]), 7.1% of the U.S. adults cannot of find it very difficult to walk a quarter of a mile. In Poland, 15% of population declare some sort of disability, 59% of which is motor disability [3]. Also 13% of Polish population declare that walking a distance of 500 m without assistance (walkers, canes) is very difficult or impossible.

The number of people suffering from different forms of disability, including mobility impairments resulting from past injuries and various diseases, is constantly growing mainly due to the increase in the average life expectancy followed by age-related diseases, which are accompanied by the increase in the number of traffic accidents or sports injuries [4, 5]. Other reasons of motor disability are various diseases such as stroke, cerebral palsy, multiple sclerosis, partial or complete spinal cord injury, to mention a few [6–9].

In spite of the causes, dysfunctions of the locomotor and neural system yield negative consequences, both medical and social, by limiting the mobility and social activity of the disabled. Mobility impairment is a serious health, social, psychological, and economic problem, which can be improved by removing the barriers in accessing various aspects of life, for instance by gait rehabilitation.

Nowadays, the most frequently used and effective form of rehabilitation of patients with the mobility impairment is physiotherapy [10]. Handling of patients, however, is labour-intensive and often requires sustained demanding postures or lifting and transferring patients, which results in occupational conditions such as lower back problems [11–13]. Therefore, it is of great significance to use scientific and technological advances to develop devices that can be used to restore motor and cognitive functions of the disabled patients, increase capabilities of physiotherapists and other specialists, and improve the available therapeutic methods and techniques [14].

According to numerous studies, motor functions of patients can be successfully facilitated by external stimulation with the use of lower limb exoskeletons (LLEs) [15–20]. Hence, these robotic devices have become the subject of numerous studies in the last decades.

The term “exoskeleton” or “active orthosis” is usually used to describe a device intended to increase the mobility of a person suffering from lower limb dysfunction. Namely, an exoskeleton is a machine that increases power in one or more joints, which results in an increase in the operator’s efficiency. In contrast to passive orthoses, active exoskeletons can not only provide simple mechanical reinforcement but also actively control movement in the joints of the device. Despite many active orthoses, including LLEs, have been developed, this area still has great potential for research [21–25].

In this paper, the state-of-the-art of the strategies used in rehabilitation LLEs is presented, after which the conceptual design of the developed exoskeleton (further referred to as a “K11 exoskeleton”) is given. The name “K11” originates from authors’ affiliation – it is the symbol of the Department of Automation, Biomechanics and Mechatronics at the Lodz University of Technology. The main focus has been put on the mechanical design of the exoskeleton, including feet elements and a novel element for back support, which is aimed at improving patient's posture.

2 Available Solutions (State-of-the-Art)

We focus on a review of available exoskeleton kinematic solutions. The information was sought on the number of DOFs, the number of driven DOFs, and the types of actuators used. Although many commercial devices have become available recently, this overview focuses mainly on academic studies. Detailed information about commercial products are usually regarded as trade secrets and are not available to the public. A summary of the information collected is provided in Table 1 at the end of the section.

The first of the considered constructions was the Vanderbilt exoskeleton [9, 26]. It was created in order to facilitate the movement of people suffering from paraplegia and also as a support for the rehabilitation therapy. The Vanderbilt exoskeleton allows for the movement in an upright position with the support of a pair of crutches and performing sit-down and sit-up manoeuvres. This LLE provides support in the sagittal plane in both the hip and knee joints. Lithium-polymer battery is used for

Table 1 Summary of the reviewed exoskeletons

Exoskeleton	Total number of DOFs	Number of actuated DOFs	Actuators
Vanderbilt [9, 26]	4	4	BLDC motors with reduction gears
BLEEX [27, 28]	14	6	Hydraulic servomechanisms and actuators
HAL3 [29, 30]	6	4	DC servomechanisms with wave gears
LOPES [31]	10	8	AC servomotors with reduction gears; linear servomechanisms
HEXAR [32]	15	4	BLDC servomotors with wave gears
MINDWALKER [33, 34]	12	6	BLDC motors with screw nut gear
IHMC [35]	10	6	BLDC servomotors with wave gears

powering DC motors that drive the joints through reduction gears. Each actuator is able to produce a continuous torque of 20 N·m and a maximum torque of 80 N·m. Knee joints are additionally equipped with normally clamped brakes in order to avoid knee hyperextension in the event of a power failure.

The Berkeley Lower Extremity Exoskeleton (commonly known as BLEEX) is a much more advanced construction. It is a system created to provide the user with the ability to carry considerable loads on the back with minimal effort relative to any type of terrain [27, 28]. BLEEX has seven independent DOFs per leg: 3 DOFs in the hip, 1 DOF in the knee (pure rotation in the sagittal plane), and 3 DOFs in the ankle. The construction of the exoskeleton allows the user to freely modify the length of individual modules. For safety reasons, mobility in all joints has been reduced to the normal human range. The actuated degrees of freedom are: ankle, knee, and hip, all in the sagittal plane. Hydraulic servomechanisms were used to drive the device. On the basis of the BLEEX exoskeleton, many similar constructions were created in the Berkeley Robotics & Human Engineering Laboratory: The Human Universal Load Carrier (HULC), ExoHiker, ExoClimber, eLEGS.

The best known medical exoskeleton is the HAL-3 system [29, 30]. The first prototype was completed in 1997, and since 2008, the manufacturer, Cyberdyne, started to rent it on the territory of Japan. The exoskeleton supports walking in an upright position, climbing stairs, and the movement of getting up and sitting down. HAL-3 has three degrees of freedom for each leg, suitable for hips, knees, and ankles. All these joints work in the sagittal plane. To protect the user in the event of power failure, the mobility in each joint was mechanically limited. To drive hip and knee joints, DC servomechanisms with wave gears were used.

A different approach is presented in LOPES [31]. LOPES consists of two main parts: the exoskeleton itself and a static frame connected to the pelvic segment of the exoskeleton. The system uses a treadmill for gait recreation. This solution allows to apply supporting forces to the pelvic segment, thus relieving the leg segment. The exoskeleton itself has two actuated DOFs in the pelvis (frontal and sagittal rotation) and one actuated DOF in the knee (knee rotation in the sagittal plane). The ankle element consists of a frame that allows one to mount an external ankle foot orthosis. The place of connection of the pelvis to the frame has two driven DOFs (linear actuators) in the transverse plane and one non-actuated DOF in the frontal plane. The engines are mounted outside the exoskeleton, and the drive is transmitted through a set of flexible bowden cables.

Another example of the human strength augmenting construction is the Hanyang Exoskeleton Assistive Robot (HEXAR) [32]. In principle, the exoskeleton was supposed to be able to carry, in addition to its (21 kg) and user's mass, an additional mass of 35 kg. HEXAR has 15 DOFs: three DOFs in the hip segment, rotation in the knee, and three DOFs in the ankle. An additional DOF is the rotation in the frontal plane at the level of the spine in the lower back section. Turning back is possible because the hip segment frame is not a rigid structure but a serial connection of four torsion elements. Such a chain combines a joint that allows for rotation in the lower back with a joint that realizes the hip abduction and adduction. In the foot segment, the structure allows one to perform movements in three DOFs: flexion/extension, internal/external rotation as well as inversion and eversion. Actuators that drive flexion in the hip and knee are brushless DC motors with 100:1 reduction gearboxes.

One of the most kinematically advanced rehabilitation constructions is the MINDWALKER exoskeleton [33, 34]. The equipment was created for patients after severe spinal injuries in order to allow moving in an upright position and the sitting down and up manoeuvres. The exoskeleton has ten DOFs, six of which are driven. DOFs with own actuators are: knee flexion, hip flexion and hip abduction and adduction. The remaining non-driven DOFs (hip rotation, ankle flexion) are equipped with spring elements whose deformation is zero in the neutral position. The exception is the inversion and eversion of the foot, the mobility of which results from the elastic construction of the exoskeleton. The actuators that drive each of the aforementioned DOFs consist of: BLDC (brushless direct-current motor), screw-nut system, torsion spring with high rigidity, and encoder. The motor drives the linear movement of the screw which deflects the torsion spring. Thanks to the measurements from the encoder, it is possible to calculate the torque generated in a given joint. Thus, the actuator becomes a controllable source of torque.

A similar construction to the MINDWALKER is the IHMC exoskeleton [35]. The total number of DOFs and the number of those that are driven is almost the same as in the MINDWALKER (the IHMC design does not allow for the inversion and eversion of the foot). Like the MINDWALKER, IHMC uses actuators equipped with spring elements and encoders to measure torques in the joints. The difference is in the construction of elastic elements. The IHMC drives the joint directly via the BLDC motor with the wave gear and a steel rope wrapped around the driven axis, the ends of which are attached symmetrically to two linear springs. Based on the data from the encoder and the spring stiffness constants, the torque is determined.

In recent years, commercial exoskeletons have become increasingly popular rehabilitation equipment. Their great advantage is the possibility of extending the time of the patient's rehabilitation session and relieving the physiotherapist carrying out the procedure.

The LLE HANK, produced by the Spanish GOGOA Mobility Robots, is used to rehabilitate people with gait disorders and in cases of complete paralysis. It has six driven DOFs, responsible for the rotation in the hip, knee, and ankle, all in the sagittal plane [36].

Another popular example is the ReWalk Rehabilitation System produced by ReWalk Robotics [37]. It has four driven DOF – rotation of the hip and the knee in the sagittal plane. The gait is initiated by tilting the trunk forward. Then, ReWalk generates a series of movements that reproduce the movement during a normal walk.

One of the most advanced rehabilitation exoskeletons is HAL MEDICAL, produced by Cyberdyne [38]. It is an exoskeleton with actuated DOFs in the sagittal plane of the knees and hips. An advanced control system detects the intentions of the user and allows for free gait as well as the sit-to-stand and stand-to-sit movements. The device is the next generation of exoskeletons HAL-3 and HAL-5.

Another commercialized university construction is the INDEGO exoskeleton, previously developed under the name Vanderbilt [39]. This version does not significantly differ from the previously mentioned exoskeleton in terms of construction.

EksoGT is a rehabilitation equipment supporting the movement of the lower limb in the sagittal plane [40]. Similarly to the previous example, the only actuated DOFs are flexion/extension in the hip and knee. The exoskeleton supports the walking motion, but the patient is forced to use a pair of crutches or a walking frame. Some parameters of motion generated by the machine can be adjusted in real time during a rehabilitation session.

Based on the literature review above, one can observe that the essential joints for enabling walking in the upright position, which require driving, are the hip and the knee. Driving the rotation in the ankle can be omitted in order to reduce the mass and demand for power (as can be seen in commercial devices). It was observed that the BLDC motors equipped with wave or reduction gears are the most common types of actuators due to their power to weight ratio.

The outcomes of the above overview were used as guidelines for construction of the K11 exoskeleton, described in the next section of the paper.

3 Conceptual Design of the Developed LLE

In what follows, we describe the design and construction of the developed exoskeleton. Wherever it is possible, we include a justification for the choice of particular solutions. We give additional arguments concerning price, ability to block certain DOFs (depending on the therapy), or modularity. The exoskeleton is intended to be used for gait rehabilitation of patients suffering from paraplegia resulting, for instance, from a spinal cord injury. To fulfil its purpose, it is planned to be mounted to a mobile frame so as to assure the safety of the patient.

One of the most important features of an exoskeleton is the number of DOFs and the number of those DOFs that can be powered. It determines to what extent the natural pattern of the human gait can be recreated. The prototype of the K11 LLE has a total number of 11 DOFs accompanied by the capability of performing the motion in other segments, i.e. the back and feet. The exoskeleton allows for fundamental movements of the lower limb such as foot dorsi- and plantarflexion, foot inversion/eversion, knee flexion/extension, hip extension/flexion, abduction and adduction (which make a total of 6 DOFs per side). These movements have been supplemented by the capability of rotating the upper body and performing flexion/extension of the upper body as well as performing flexion/extension of toes. Hence, gait rehabilitation is possible. Actuation of particular movements (DOFs) can be modified, i.e. abled/disabled (allowed/blocked), based on the decision of the physiotherapist, depending on the specific treatment strategy for the patient.

By design, mobility in particular joints has been mechanically limited to the range presented in Table 2 so as to allow for normal changes in angles expected during gait as well as the sit-to-stand (and stand-to-sit) movement. The main purpose of limitation of the range of motion is to avoid knee hyperextension in the event of a power failure. The maximum angles have been retrieved from the source literature

Table 2 Range of motion of the most important movements of the developed exoskeleton

Segment/Motion	Flexion – extension	Abduction – adduction
Hip	90° – 20°	10° – 10°
Knee	90° – 0°	–
Ankle	15° (DF) – 25° (PF)	5° (INV) – 5° (EV)
Back (upper body)	45° – 0°	–

DF dorsiflexion, *PF* plantarflexion, *INV* inversion, *EV* eversion

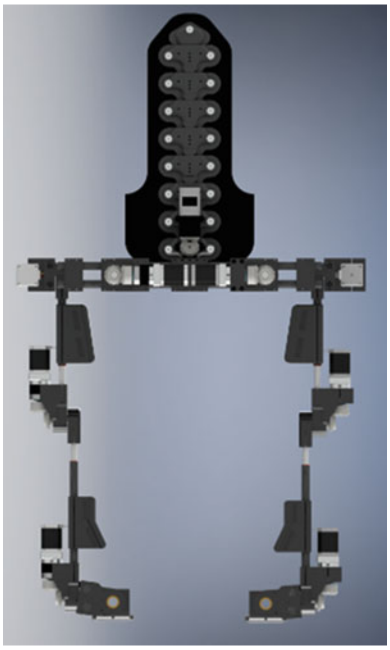

Fig. 1 3D model of the developed exoskeleton – rear view

[41–43]. However, as many patients may have the range of motion reduced, the mobility of the K11 exoskeleton can be also modified by the control system.

Rapid prototyping was used for the development of the model. For this purpose, Autodesk Inventor software was used for 3D computer-aided design, and then the parts were fabricated by 3D printing by the Zortrax M300 device. The CAD model of the exoskeleton in presented in Figs. 1 and 2. The lengths of the modules (hip width, thighs, shanks, feet) can be easily adjusted by virtue of the employment of telescopic elements.

The main purpose of facilitation of extension of the upper body is to increase the stability of the patient during the rehabilitation process by means of correcting the inclination of the pelvis. Facilitation of upright posture is also beneficial for the hip extension range and loading [43]. In the literature, one can find a few studies aimed at assisting spine flexion/extension [44, 45]. However, the motivation of the authors of the present study was to implement a simple and inexpensive solution. Thus, the back support element (see Fig. 3) was inspired by a back protector for snowboarders.

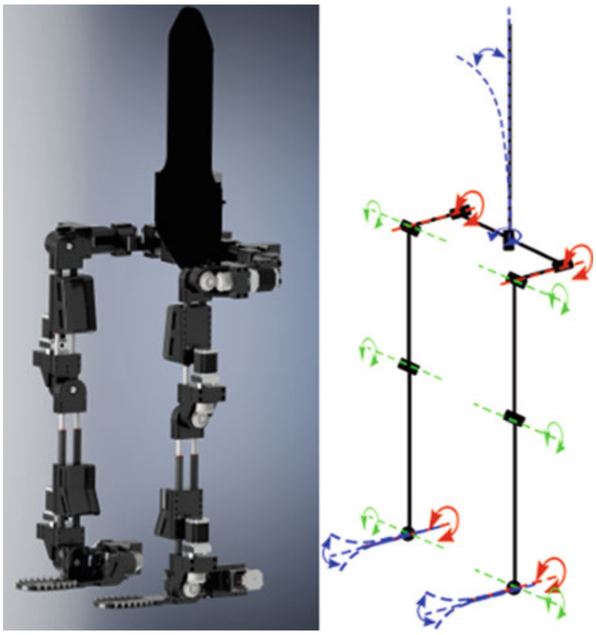

Fig. 2 3D model of the developed exoskeleton (left) and DOFs (right)

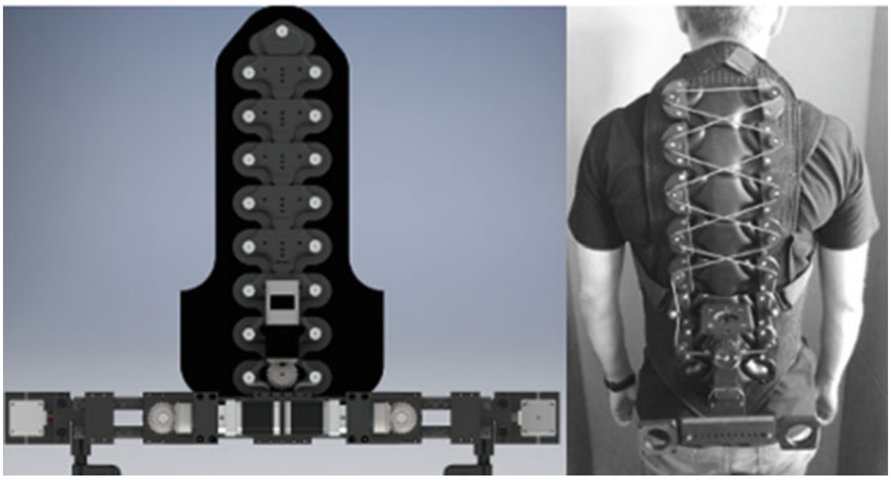

Fig. 3 3D model (left) and a real-photo (right) of the back support segment

Fig. 4 3D model of the knee segment

It is supplemented by rollers attached to each segment of the element and connected via a cable to an additional electric motor, the role of which is to manage tension so as to keep the patient's upper body properly extended. The extension of the upper body changes the position of the centre of mass (centre of gravity) of the human body and shifts it towards the spine, which results in the improvement in balance. As the developed exoskeleton is intended to be used only for rehabilitation, and not for force augmentation purposes, such a simple construction is believed to be satisfactory.

To assist motion in the hip joints, four electric motors (two per side) are used. Two motors at the back are used for hip adduction and abduction while flexion and extension are driven by two motors placed on the sides of the pelvis (in parallel to hip joints).

Flexion and extension of the knee joint consist of sliding and rolling, which results in the fact that the axis of rotation is variable. Thus, we assumed that the structure of the exoskeleton should not be a simple kinematic node. In the developed device, the axis of the knee rotation can change by means of air dampers (telescopic elements), see Fig. 4. Namely, the lengths of shanks and thighs change so as to make the axis of rotation of the knee joint of the exoskeleton follow the natural axis of the knee rotation.

As far as the design of a foot segment is concerned, in the distal part, the foot plate has been supplemented by modules enabling the patient to extend and flex their toes during walking (see Fig. 5). The modules are passive and their main purpose is to increase the comfort of the patient and allow for movement as close as possible

Fig. 5 3D model of the foot segment

Table 3 Literature overview of normalized joint torques during human gait

Flexion [N·m/kg]	Zelik and Kuo [50]	Kirtley [49]	Winter [48]	Linskell [49]	Sloot and van der Krogt [51]
Hip	0.4	0.8	0.55	0.8	0.7
Knee	0.3	0.8	0.65	0.4	0.5
Ankle	1.3	1.45	1.6	1.45	1.4

to the natural one. To adjust the length of the foot segment, some of the above-mentioned modules can be removed. The foot segment is mounted to the patient's shoe by means of Velcro fasteners.

In order to select the appropriate drive for the exoskeleton, the dynamic gait parameters [46, 47] were investigated and compared with the known normal gait patterns given by Winter [48], Kirtley and Linskell [49], and others [50, 51]. As a preliminary condition, it was assumed that the exoskeleton should generate sufficient driving torques to propel the movement of a man weighing at least 85 kg. The reconstruction of correct angular velocities of motion was considered less important in purely rehabilitation applications. Table 3 presents a list of peak values of normalized driving torques for the most loaded joints (rotation in the sagittal plane of the hips, knees, and ankles).

Assuming the maximum values from the sources presented above, it follows that the motors used should generate the minimum holding moments for: hip – 65 N·m; knee – 65 N·m; ankle – 130 N·m.

In order to meet the assumptions mentioned above, it is suggested to use SM 57/76-3008B stepper motors with a holding moment of 1.9 N·m, together with 40:1 planetary gears. The advantage of this solution is the moderate weight of the drive system, and simple control of stepper motors. Bevel gears have been introduced to increase ergonomics of use by means of placing the motors along the main profiles of the device. The main profiles of the K11 exoskeleton are intended to be eventually made of carbon fibre round tubes. Such a solution will ensure more than satisfactory

Fig. 6 Passive prototype of the developed exoskeleton. Front view (on the left), side view (centre), rear view (right)

mechanical properties due to high resistance to compression that is likely to occur in the device. In the prototype, PVC (polyvinyl chloride) tubes have been successfully used. The mechanical design of the lower limb exoskeleton developed in the present study is shown in Fig. 6.

4 Discussion

In the present paper, a literature overview concerning active lower limb orthoses (exoskeletons) has been presented. Many academic and commercial constructions have been studied and described with the emphasis put on the number of passive and active DOFs, kinematics, and drive. Also an analysis of torque requirements for selected joints has been conducted. Based on the findings, some guidelines regarding the construction of a lower limb exoskeletons have been presented. They have been used to design a lower limb and spine exoskeleton. The developed exoskeleton has been made for gait rehabilitation of patients suffering from different mobility impairments (paraplegia). The device can be scaled for a specific patient and actuation of particular movements can be adjusted (allowed/blocked), depending on the therapy needed. These features make the use of the exoskeleton possible and affordable for many patients as the personalization is easy and one device can be used for more than one person. The only segment, the length of which cannot be adjusted, is the back module, and thus the future work will cover redesign of this element so as to solve this problem.

Concurrently, the control system is being developed [52], based on the previous studies of the authors [53, 54]. However, further tests and research have to be performed in order to test the operation of the whole exoskeleton and analyse real effects of the introduced concepts. Recently, experimental studies on the influence of the exoskeleton, both passive and active, on the gait of a healthy individual have been conducted with the use of a force plate, electromyography and a motion capture system which has also been used in other studies of authors' department [55, 56]. Furthermore, stability, kinematic and dynamic biocompatibility with a natural limb, as well as material strength should be investigated.

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