Robotica (2018) volume 36, pp. 1743–1756. © Cambridge University Press 2018
doi:10.1017/S0263574718000693

Empowering lower limbs exoskeletons: state-of-the-art

Slavka Viteckova†*, Patrik Kutilek†,
Gérard de Boisboissel‡, Radim Krupicka†,
Alena Galajdova§, Jan Kauler†, Lenka Lhotska† and
Zoltan Szabo†

†Faculty of Biomedical Engineering, Czech Technical University in Prague, Prague, Czechia
‡Saint-Cyr Military Academy Research Center, Guyer, France
§Faculty of Mechanical Engineering, The Technical University of Košice, Košice, Slovakia

(Accepted July 11, 2018. First published online: August 15, 2018)

SUMMARY

Given the advanced breakthroughs in the field of supportive robotic technologies, interest in the integration of the human body and a robot into a single system has rapidly increased. The aim of this work is to provide an overview of empowering lower limbs exoskeletons. Along with lower exoskeleton limbs, their unique design concepts, operator–exoskeleton interactions and control strategies are described. Although many problems have been solved in recent development, many challenges remain. Especially in the context of infantry soldiers, fire fighters and rescuers, the challenges of empowering exoskeletons are discussed, and improvements are outlined and described. This study is not only a summary of the current state, but also points to weaknesses of empowering lower limbs exoskeletons and outlines possible improvements.

KEYWORDS: Augmentation; Empowering; Exoskeleton; Lower limbs; Wearable robot.

1. Introduction

Given the advanced breakthroughs in the field of supportive robotic technologies, an interest in the integration of the human body and a robot into a single system has rapidly increased. Systems in which people contribute to the form of intelligence and benefit from a robotic systems performance are called user-oriented robots. Here, we limit the scope of a broad spectrum of user-oriented robots to those that run parallel to the human body, which implies robotic exoskeletons. Although the first attempts to develop exoskeletons are dated to almost 50 years ago, development expansion started about 10 years ago due to the rapid development of new electronics and computer technology.

Depending on its purpose, exoskeletons can be divided into either rehabilitative, assistive or augmentative systems. The aim of rehabilitation exoskeletons is to provide guided movement to restore the function of limbs (e.g. after a stroke), or repetitive training, and facilitating labour-intensiveness by decreasing the action load on the operator (wearer). Rehabilitation exoskeletons can be further divided into three subclasses: stationary devices, full lower limb mobile (wheeled) devices and partially mobile (wearable) devices.[1] Most often stationary devices, such as treadmills, consist of a supportive framework and a robotic orthosis that exercises the patient in the required movements. Assistive exoskeletons are intended to be worn by people with a movement disorder (e.g. elderly, physically weak) to provide physical support to Activities of Daily Living such as walking, walking up and down stairs, sitting and standing up. Examples of known assistive exoskeletons are ReWalk,[2] IHMC,[3] Rex,[4] some others which were recently published,[5–7] and many others which are

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* Corresponding author. E-mail: slavka.viteckova@fbmi.cvut.cz

still in the developmental stage or commercially available.[1] Rehabilitation exoskeletons are reported in many papers.[1,8] Therefore, our focus will be on empowering exoskeletons.

The later, empowering exoskeletons, include devices that are designed to help operators do strenuous work. These exoskeletons provide soldiers, disaster relief workers, fire fighters, industry workers, etc., the ability to carry heavy loads with minimal effort, and to increase accuracy, power, velocity and endurance.[9–11] Empowering devices are intended to be worn by healthy operators.

Based on supporting the human body, exoskeletons can be classified as upper limb exoskeletons, lower limb exoskeletons, back exoskeletons, full-body exoskeletons or specific joint exoskeletons. The aim of this paper is to provide an overview of lower limbs exoskeletons, namely empowering exoskeletons, including both those still in research stages and those already in commercial development. Along with exoskeletons, their mechanical design, including its structure, sensors and actuators, and the operator interaction system are outlined.

This paper is organised as follows. Section 2 aims at establishing a list of the advantages of empowering exoskeletons. Related works are mentioned in Section 3. The mechanical structure of exoskeletons is introduced in Section 4. Next, the interaction between the exoskeleton and the operator is presented in Section 5. Section 6 encompasses empowering exoskeletons for lower limbs. Challenges for future exoskeletons development are stated in Section 7. Finally, a summary and concluding remarks are given in Section 8.

2. The Need for Exoskeletons

Throughout the ages, a workers (e.g. infantry soldiers) manoeuvrability has been reduced by the load s/he must carry during the performance of work tasks and operations.[12] For example, in the case of military applications, missions for forces deployed on operations are always lengthy and challenging, with a mix of long marches and movements in hostile environments. The use of exoskeletons could lessen the effects of heavy loads carried, notably the rucksack, by shifting some of the weight to the ground during marches and lessening the rucksacks weight during pauses. So far, some exoskeletons allow for a semi- seated and relaxed position which eliminates the need for an individual to sit or drop his/her rucksack. This creates an increase in individual mobility, and hence that of the group, bringing greater manoeuvrability. Which is an absolute necessity and is vital in combat.[13] Moreover, it leaves room for extending a mission as indicated above or increasing the units outreach.

Similarly, fire-fighters, disaster rescuers and other critical operation workers are exposed to heavy physical exertion. To prolong action time, these professions need to enhance his/her performance: endurance, mobility and load capacity. Hence, equipment for helping carry loads is a great advantage both to hold out and remain effective in his/her effort.

3. Related Work

There are several publications focused on lower limb exoskeletons. A substantial portion of research reviewed assistive and rehabilitative exoskeletons.[1,14–18] Empowering lower limbs exoskeletons are also included in some research. But none of this research is directly aimed at reviewing empowering exoskeletons. Those that are available are general reviews on exoskeleton topics,[8,19,20] technologies related to exoskeletons,[21,22] exoskeleton control systems.[23] Unlike these reviews, this paper focuses solely on active empowering exoskeletons and outlines a probable future for the field.

4. Concepts of Exoskeleton Structure

Depending on the design structure of the rotation axis alignment of the exoskeleton joint and the rotation axis of the human joint, the exoskeleton may be classified as anthropomorphic, quasi-anthropomorphic or non-anthropomorphic.[24]

An anthropomorphic exoskeletons structure is aligned with the operators lower limbs (Fig. 1A). Moreover, the joint rotation axes are in alignment with human joints rotation axes. This arrangement allows the operator movement traction so that the exoskeleton makes the same motions as the operator.

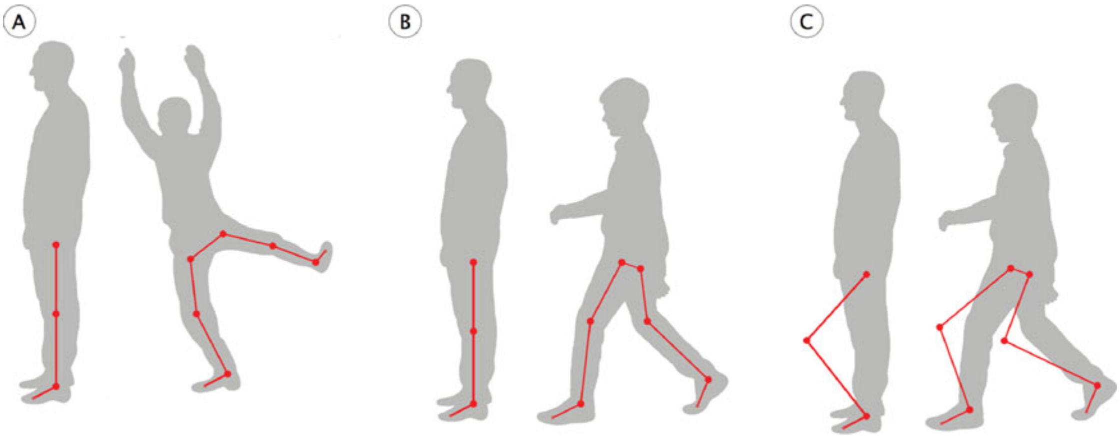

Fig. 1. Exoskeletons structure. Anthropomorphic (A), quasi-anthropomorphic (B), non-anthropomorphic (C).

Anthropomorphic mechanical structure simplifies the control of exoskeletons movements in such way that they imitate human movement in terms of range of movement and degrees of freedom (DOF). Thus, it is not necessary to prevent collision between the human and the exoskeleton. On the other hand, inter-subject variability in limb/body morphology, modelling approximations and slippage of exoskeleton fixations over the body during motion hinder the perfect alignment of human joints with the matching exoskeleton structures.[25] Such misalignments result in the exchange of unwanted interaction forces at the sites of contact between the human and the robot and subsequently may cause discomfort or even pain for the operator.[26,27]

In contrast to anthropomorphic design, quasi-anthropomorphic (also called pseudo-anthropomorphic), does not allow for the exact same motions, but it allows similar motions as the operator. The structures are designed in alignment with the operators limbs but the types of joints, i.e. types of kinematic pairs, or joints rotation axes of operator and that of exoskeleton are different (Fig. 1B). This arrangement is usually robust against alignment errors, but its control is more challenging in terms of the analysis of the relationship between corresponding joints range of movement.

In the later, non-anthropomorphic design, links and joints positions, i.e. types and number of kinematic pairs, do not correspond to that of the operator (Fig. 1C). Non-anthropomorphic structure benefits from the lack of the anthropomorphism by the opportunity of optimising the intrinsic dynamics of the robot, e.g. through a proper distribution of masses.[25] This unnatural structure focuses on the optimisation of specific tasks performance, precision or power consumption.

Based on the differences in joint mechanical properties, exoskeletons can be categorised into three types: active (powered), quasi-passive and passive exoskeletons. The first category includes those which have actuated joints. These exoskeletons generally implement electronic control systems that can modulate exoskeletal behaviours for different conditions. Segments of active exoskeletons are directly moved by actuators. Actuators convert a source of energy into mechanical motion. Currently, electric, hydraulic and pneumatic actuators are predominantly used in active exoskeletons.[28] Movement is created based on electromagnetic motors and/or variable volume pressure chambers that use electricity, pressurised liquid or pressurised gas.

An exoskeleton is quasi-passive, when it does not contain an active actuator. Support for the operator is based on controlling the release of energy stored in structural elements during specific phases of movement (e.g. gait cycle). This approach is less heavy and could reduce the metabolic cost of movement. Examples of elements utilised in quasi-passive joints are springs and variable dampers.[29,30] Passive exoskeletons contain neither actuators for the power supply nor quasi-passive elements. Therefore, passive exoskeletons[31,32] are often lightweight. On the other hand, their controllability is limited due to their lack of electronics. However, which type of joint mechanical property is selected considerably affects the structural complexity, and therefore the final price of the exoskeleton. Without an active actuator, quasi-passive and passive exoskeletons are not able to provide high enough levels of positive power that would overcome the negative metabolic effects of added device mass.[29,31,33]

5. Operator–Exoskeleton Interaction

The interaction between the operator and exoskeleton is usually bidirectional. The operator determines the movement (task) that should be performed, and the exoskeleton provides the mechanical power and feedback information to the operator. Before providing mechanical power, it is necessary to distinguish the operators intent. This is done by interpreting data acquired from various sensors placed on the operators body, exoskeleton or between both of these. In the case of a stationary device, a data acquisition system can also be placed outside the operators body and exoskeleton. Based on measured data, the control algorithm instructs the actuators to act.

Signals measured by such sensors are used as input for the exoskeleton controller. These signals can be classified as biosignals and physical signals. Generally, biosignals are bioelectrical signals that include brain activity, muscle activity, etc. Physical signals are, in this case, the results from the operators or exoskeleton movement.

First, we will limit the scope of biosignals to muscle activity signals, because this is the only one used when relating to empowering lower limb exoskeletons. EMG sensors, which are widely used across all biomedical applications, are used to direct the measurement of muscular activity. Although these sensors are recommended to be used in cognitive human–robot interaction as an input to recognise the operators intent,[34,35] these sensors have some disadvantages: They must be attached directly to the skin, and it is difficult to quantify the signal.[34] Therefore, other sensors are developed that measure the physical properties of muscles, e.g. muscle stiffness sensor.[36]

The later, represents kinematics and kinetics of the subject movement. Physical signals including pressure, force, acceleration, speed, position, etc. are measured by potentiometers, strain gauges, piezoelectric sensors, capacitive sensors, accelerometers, gyroscopes, etc. These signals are more reliable than biomedical signals. Physical signal sensors are not usually attached directly to the operators skin. Rather, they are attached to the exoskeleton or to the connection points between the operator and exoskeleton or environment (for example, limit switches or sensors between the shoes and the floor).

In the case of wearable active exoskeletons, motion is controlled by an embedded microcomputer. As mentioned above, the control mechanism estimates the operators intent and gives instructions to the actuators. The appropriate control mechanism is applied according to the purpose of the exoskeleton. There are various control strategies: sensitivity amplification, predefined gait trajectory control, predefined action based on gait pattern, model-based control, adaptive oscillators-based control, fuzzy control (i.e. artificial intelligence control), hybrid assistive strategy, etc.[37] For a more detailed description of the control strategies, the reader is referred to Marchal–Crespo and Reinkensmeyer,[38] Anam and Al-Jumaily,[23] Yan *et al.*[37] and Tucker *et al.*[39]

In the control system of the active exoskeletons, sensitivity amplification usually relies on the inverse dynamic model of the exoskeleton. The force exerted by the operator on the exoskeleton is set on a positive feedback loop for the controller and could be scaled down by an amplification.[40] Currently, this kind of controller is only used for empowering exoskeletons.

Predefined gait trajectory control is based on desired pre-recorded exoskeleton states (e.g. joint angles). The pre-recorded states are then replayed on the exoskeleton. Rehabilitation exoskeletons usually address this control method.[2,3,41]

Under predefined action based on gait pattern, the exoskeleton joints operate synchronically with expected gait events. This control method is characteristic for quasi- passive exoskeletons. For example, energy is stored during the swing phase and released during stance phase. The strategy of predefined actions based on gait pattern is similar to the predefined gait trajectory control. Based on the actual state of the user and the exoskeleton (i.e. gait pattern), the following body segment movement is introduced.[42]

Model-based control utilises the operator–exoskeleton model, considering gravity and other effects of the environment (e.g. inertial, coriolis and centrifugal). Model-based control strategy can be obtained by modelling the exoskeleton theoretically based on the physical characteristics of the system. From this point of view, sensitivity amplification can be seen as a special case of model-based control strategy. Besides, muscle models can be employed in this class of exoskeleton control strategies. In contrast to mathematical models, muscle models are able to predict muscle forces deployed by the muscles as the function of muscle neural activities and the joint kinematics.[43] Model-based control strategy is used for empowering[36,44] and assistive exoskeletons.[45]

Adaptive oscillator-based control is founded on adaptive learning of kinematics and kinetics variable (or EMG signal) profiles in periodic tasks. Usually the variables are measured by assistive joints which are also used as actuators. Users perform an activity and the control system adapts to the activity which is being performed. If the task is altered and the existing assistive behaviour becomes inadequate, the exoskeleton gradually adapts to the new task execution. The advantage of this proposed method is that it does not require biomechanical or dynamical models. This method appeared recently for assistive and rehabilitation exoskeletons.[37,46]

Fuzzy controllers applied fuzzy rules and inferential mechanism to formulate intuitive knowledge[47] and to induce the target exoskeleton positions. Fuzzy rules are designed by experts or automatically inferred using experimentally measured data by MoCap systems. These controllers are employed especially for assistive exoskeletons.[48–50] Similarly, there are also used methods based on neural networks. Neural networks are learned based on the previous state (measured by MoCap systems or assistive joints) and after learning about the neural networks, expected states are inferred. The inferred state can be used to control the actuators of the exoskeleton.[51]

Hybrid assistive strategy combines various control methods for different phases of the gait cycle. For example, the exoskeleton utilises a model-based controller in the stance phase and a predefined trajectory controller in the swing phase.[52]

6. Lower Limbs Exoskeletons

Lower limb exoskeletons can be classified into full and partial lower limb exoskeletons. The distinguishing criterion is the number of human body joints that a device runs parallel to. A number of active (powered), quasi-passive and passive wearable and stationary systems have been developed, especially in the field of rehabilitation and assistive devices. Given the focus of this paper, the remaining part of our research will focus on the state of wearable full lower limb exoskeletons with active joints only, or active joints complemented by quasi-passive and passive joints. We will just mention here that although we focus on full lower limbs exoskeletons in this paper, there is considerable research on the topic of partial lower limbs exoskeletons. Examples of such devices are RoboKnee,[53] Knee Stress Release Device[54,55] or MITs quasi-passive knee.[14] Recently, Mooney and Herr published a powered ankle exoskeleton.[56]

Regarding the development of active exoskeletons, one of the initial attempts to construct an active exoskeleton was called Hardiman, which was developed in 1968.[57,58] Hardiman was a huge full-body exoskeleton designed for military purposes. The exoskeleton consisted of two lower extremities and two upper extremities with a total of 30 DoFs and a weight of 680 kg. Although Hardiman was able to significantly increase the operators strength (about 25-fold), the project was finally abandoned because of a lack of interest by potential users. Hardiman was followed by the development of similar exoskeletons that are obsolete today.[59,60]

Since 2001, a group led by H. Kazerooni has worked on the development of BLEEX (Berkeley Lower Extremity EXoskeleton).[40,61,62] BLEEX (Fig. 2) is composed of two main parts: lower extremity exoskeletons and a back part that is intended to bear a heavy backpack. The exoskeleton movements are based only on measurements of the current state of the exoskeleton, in contrast with the movement of other advanced exoskeletons, which are based on the direct measurement obtained from the operator (e.g. EMG and joint angles). To achieve this, BLEEX is equipped with 45 sensors and a control method called sensitivity amplification control. BLEEX is hydraulically actuated, and each exoskeleton limb supports seven DoFs (only four of which are active: hip flexion/extension and abduction/adduction, knee and ankle flexion/extension). The operator is able to walk at speeds up to 1.3 m/s. Moreover, the exoskeleton allows an operator to comfortably squat, bend, sway from side to side, twist, and run on ascending and descending slopes, and step over and under obstacles while carrying equipment and supplies.[24] The system allows for passive torso and metatarsal flexion. The license agreement for all BLEEX technologies developed at the University of California was obtained by Berkeley Bionics which continued its development and introduced the exoskeleton and its variants into the market under the names ExoHiker,[63] ExoClimber[64] and Human Universal Load Carrier.[65] Availability of detail information about these exoskeletons is limited (see Table III).

An exoskeleton designed to aid nurses was the product of academic research at Kanawaga Institute of Technology (Japan).[36,69] The device consists of four active construction parts: shoulders, back, lower limbs and upper limbs. All four parts are pneumatically actuated and controlled based on muscle

Fig. 2. Empowering exoskeletons. BLEEX[66] (left), HULC[67] (middle), XOS® 2 (right).

stiffness measurement (instead of muscle activity measurement). To allow better contact between the nurse and patient, no mechanical structures were placed on the frontal part of the exoskeleton. The exoskeleton was tested carrying a 60 kg person.

The higher the number of active joints, the greater the weight and complexity of the control system. For this reason, the MIT lower limbs exoskeleton[70,71] actively actuates hip flexion/extension, while the rest of DoF are quasi-passive (one DoF at knee) or passive (two DoF at hip, two DoF at ankle and one DoF at foot). Walking experiments were conducted with the exoskeleton loaded with a 35 kg payload.

A team at Hanyang University (Korea) used quasi-passive instead of active joints at the hip and ankle.[72] Their exoskeleton had four DoFs: an active knee joint (one DoF) to support flexion/extension and quasi-passive hip (two DoFs) and ankle (one DoF) joints. Movement control for the exoskeleton is based on the data transmitted from four muscle-stiffness sensors.

A wearable device, called Agri-Robot, was developed at the Tokyo University of Agriculture and Technology (Japan) to decrease the labour of farmers.[73] Agri-Robot is a full-body exoskeleton with a total of 10 joints. The active joints at the shoulders, elbows, hips and knees, and the passive joints at the ankles enable the operator to move at desired trajectories, though the ranges of motion are limited. There are two modes of control of the exoskeleton. The first mode is used for memorising operations, i.e. storage information about joint angles that are currently being used. The second mode is used for the repetition of these joint angles. The exoskeleton is voice controlled, i.e. input operations are performed using the voice, and the status of their execution is displayed on the monitor.

A fully actuated, quasi-anthropomorphic body extender that can amplify the force of a human operator, called PERCRO BE, was designed, realised and preliminary tested in a laboratory in Italy.[74] This full-body exoskeleton has four limbs and a central body which weighs 160 kg and has a total of 22 DOFs (six DOFs for each robotic leg, each of them is independently actuated).

Recently, the lower extremity exoskeleton Hanyang Exoskeleton Assistive Robot CR50 (HEXAR-CR50) was developed.[75] The exoskeleton consists of seven DOFs per leg. The hip and knee extension/flexion joints were selected to be active. Ankle dorsiflexion/plantarflexion joints were selected to be quasi-passive mechanisms and the remaining joints were selected to be passive. The weight is 23 kg, and the system is designed to carry a payload of 20–30 kg.

For a summary and comparison of developed exoskeletons, as described above, see Tables I and II.

Several other wearable robot systems are in an early stage of active development.[77,78] In addition, several proposals have been made.[78–80] Unfortunately, no further references are available for these projects.

In addition to the above-mentioned lower limbs exoskeletons mainly developed under university research, there also exist a number of commercially developed and available empowering exoskeletons. As explicit specifications of the commercial exoskeletons are not published, information must be gathered from corporation webpages and product brochures. Thus, these exoskeletons will only be briefly introduced.

Table I. Full lower limbs exoskeletons: actively and quasi-passively supported joints, comparison to human DoFs.

Exoskeleton	Hip	Knee	Ankle	Structure
BLEEX[61,76]	2 (A)	1 (A)	1 (A)	QA
Nursing exoskeleton[36,69]	–	1 (A)	–	QA
MIT exoskeleton[70,71]	1 (A)	1 (QP)	–	QA
Hanyang University exoskeleton[72]	2 (QP)	1 (A)	1 (QP)	QA
Agri-Robot[73]	1 (A)	1 (A)	–	QA
PERCRO BE[44]	3 (A)	1 (A)	2 (A)	NA
HEXAR-CR50[75]	1 (A)	1 (A)	1 (QP)	QU
Human	3	1	3	

DoF: A - active, QP - quasi-passive. Structure: A - anthropomorphic, QA - quasi-anthropomorphic, NA - non-anthropomorphic.

Table II. Full lower limbs exoskeletons: control methods, employed sensors and actuators.

Exoskeleton	Control method	Actuators	Sensors	Weight (kg)	Payload (kg)
BLEEX[61,76]	SA, H	H	Accelerometers, encoders	45	30
Nursing exoskeleton[36,69]	M	P	Muscle stiffness sensors	30	60
MIT exoskeleton[70,71]	P	SEA	Potentiometers, strain gauges, force sensors	N/A	34
Hanyang University exoskeleton[72]	M	E	muscle-stiffness sensors	10	20
Agri-Robot[73]	H	E	Angle sensors, gyro sensors, force sensors	30	20
PERCRO BE[44]	M	E	Force/torque sensors, accelerometer	160[FB]	100
HEXAR- CR50[75]	M	E	Force/torque sensors acceleration sensors, reaction force sensors	23 23[FB]	30

Control method: SA - sensitivity amplification, M - model-based control, P - predefined action based on gait pattern, H - hybrid assistive strategy. Actuators: H - hydraulic, E - electric, P - pneumatic, SEA - Series Elastic Actuator. Status: A - Under active development (the last reference to active development is not older than 5 years ago), Ab - Abandoned. Weight: FB - full body exoskeleton, N/A - information is not available.

In 2009, Activelink presented the Power Loader, the full-body exoskeleton for lifting heavy objects.[81] In April 2014, Activelink announced its offshoot lower limbs exoskeleton Power Loader Light which have actuators at the hips, knees and ankles that are controlled by signals sent by six-axis force sensors located under the feet. When wearing the PPL, an operator can handle approximately 40 kg of extra weight.

The development of the XOS® exoskeleton (Sarcos Corp.) as well as the development of BLEEX was funded by DARPAs project Exoskeletons and Human Performance Augmentation under the umbrella of DARPA.[82] The hydraulically actuated XOS® is a full-body device (with upper extremity exoskeletons incorporated into it). There are only a few published technical reports on the design and control of XOS®. The second-generation exoskeleton (XOS® 2) was unveiled in 2010. XOS® 2 (Fig. 2) is lighter, stronger and faster than its predecessor, yet uses 50% less power.[83] Although technical reports are not publicly available, it can be collected from medially available information that XOS® 2 should comprise of 23 actuated joints (six for each leg, one for the trunk and five for each arm) and weights 95 kg.

Recently, Sarcos Robotics introduced untethered, battery-powered exoskeletons Guardian™ XO® and XO® MAX.[84] These exoskeletons are successors of XOS® 2 are capable support 36 kg (80 lbs) and 90 kg (200 lbs), respectively. Working time is 4 h for XO® and 8 h for XO® MAX. Both versions are currently under development and are expected to be commercially available in 2019.

Table III. Commercially available empowering exoskeletons. Exoskeleton BLEEX (not commercially available) added for comparison with its newer models ExoHiker, ExoClimber and HULC.

Exoskeleton	Weight (kg)	Payload (kg)	Speed (km/h)	Battery life (h)
BLEEX	40	34	4.6	N/A
ExoHiker[63]	14	68	4	21
ExoClimber[64]	23	68	N/A	N/A
HULC[65]	N/A	68	4.8 march, up to 16 burst	N/A
Power Loader Light[81]	N/A	40	N/A	N/A
XOS® 2[83]	95 (full body)	N/A	N/A	N/A
Guardian™ XO®[84]	N/A	36	N/A	4
Guardian™ XO® MAX[84]	N/A	90	N/A	8
Hercule[68]	30	N/A	N/A	N/A
Power Assist Suit[86]	39	40	N/A	N/A

N/A - information is not available.

Fig. 3. Empowering exoskeletons. Hercule.[68]

In 2012, the French company RB3D presented the Hercule (Fig. 3), an electrically actuated lower limbs exoskeleton.[68] Although Hercule development was initiated by the French Ministry of Defense with their RAPID program and presented as a military exoskeleton, the latest version (v3) is dedicated to civilian use. It weighs 30 kg and has 14 DOFs among which four are actuated. In contrast to other exoskeletons that have a payload placed on the back, Hercule v3 is equipped with a counter for transfer payload on the front part.

Besides the HAL-5 (Hybrid Assistive Limb, version 5) proposed as the assistive exoskeleton, the Cyberdyne Inc and University of Tsukuba developed its empowering full-body offshoot and recently full-body offshoot for disaster recovery.[85] Assuming the same mechanical structure, these versions employ actuated hip and knee joints. The weight of a full-body exoskeleton is 23 kg, of which 15 kg is for the lower body part. Further, HAL for disaster recovery equips a radiation shielding jacket, an operator cooling system and a vital sensing system. The development of this version was abandoned in 2018 and it is not available on the market.

In 2015, Mitsubishi Heavy Industries and Japan Atomic Power Company exhibited a prototype of electrically powered exoskeleton for nuclear disasters named Power Assist Suit (PAS).[86] The primary function is to assist in holding tools. The PAS includes active joints at hip, knee and ankle. The control relies on pressure sensors embedded in the exoskeleton foot plates. PAS weighs 39 kg and allows an extra load of up to 40 kg.

For basic characteristics of exoskeletons available in the marketplace, see Table III.

7. Discussion

Exoskeletons are complex mechatronic devices. The area of exoskeleton development is related to the research field of control methods and hardware including, among other things, sensors and actuators, and control strategy. That is why we discuss each of them separately. The challenges for exoskeletons as a complex are also addressed.

From the point of view of concepts of structure, empowering exoskeletons are mainly quasi-anthropomorphic or non-anthropomorphic. Although the description of all these classes is provided,[24] there is no widely spread consensus about classification. As a result, some exoskeletons are misclassified, e.g. BLEEX is classified as anthropomorphic in some studies even though their mechanical structure differs from a human in joint rotation axes. Now, division and classification are properly reported in Table I. Because of missing standards, empowering exoskeletons on the marketplace are not quantitatively comparable because some technical details are not officially published (e.g. battery life).

In contrast to rehabilitation exoskeletons, practical applications of empowering exoskeletons, for example, for military purposes, require autonomous devices where the operator carries its own source of energy and control. Regardless of its purpose, autonomous exoskeletons face the same challenge: long battery life. Energy efficiency should be improved to prolong the operation time. Since human motion is rich in kinetic energy, energy harvesting based on human motion[87,88] can be utilised in exoskeletons.

Above that, exoskeletons utilised in critical operations must be lightweight, collapsible and portable, e.g. in case the battery runs out. Components of current actuation systems are designed especially for industrial applications, not interacting with and being worn by humans.[28] It often results in heavy, rigid and bulky actuators. However, these attributes do not meet the demands for exoskeletons employed in critical operations (lightweight, collapsible and portable).

To recognise the human intent is essential in empowering exoskeleton–operator interaction. The intent can be estimated via a wide range of sensors. In the context of empowering exoskeletons that are intended to be used for military, fire service or disaster rescue operations, practical applicability should be considered. Putting on the exoskeleton should take minimal operators effort and should not be time consuming. Similarly, calibration and personification of empowering exoskeletons, should not take a lot of time. For these reasons, sensors that need to be attached directly to the skin are not suitable. Next, workers in these professions are often exposed to a dirty environment. Thus, the sensors as same as actuators must be reliable and durable despite unfavourable circumstances.

Owing to rapid progress in the field of exoskeletons development the standards, governing operators safety and technical requirements, fall short of commercially available exoskeletons. Generally, exoskeletons are human-centred robotic devices. Thus, the operators (human) full control over their gait along with safety must be ensured. Most of the exoskeletons realise safety via mechanical design only. This is accomplished by physical stops which limits the joints range of motion. Apart from range of motion, the velocity and acceleration of each body part should be carefully handled. As the safety of the operator is a crucial issue, it should be implemented in different levels simultaneously, e.g. mechanical design and control strategy. The development of the control system of empowering exoskeleton must meet several considerations and demands. First, it must be able to produce augmentation for the operator as needed according to his physical status (e.g. fatigue). Next, natural movement and unconstrained motion flexibility is necessary in some target application (e.g. soldiers and fire workers). Another demand is to anticipate the operators intent. Control strategies based on EMG signal (muscle models) are capable of predicting the operators intention, but EMG signal and appropriate sensors are subject to a number of problems. Some of these issues can be solved by new sensing techniques. For example, the ultrasonic imaging of dynamic muscle activity, which is known as sonomyography, could be investigated to lower limbs exoskeletons control. This method was already examined in gait analysis[89] and proposed to control upper limb powered prosthesis.[90]

Overall, constraints in life threatening operations using exoskeletons are nonetheless very high. They should not restrict the operator from their basic functions (ability to move—often urgently). In this respect, the burden is also one of the main obstacles in using exoskeletons in real-world scenarios. In fact, limited joint amplitudes currently impair executing various reflex actions. In case of injury, it is essential to remove it quickly and in a very simple way. A push button releasing it in a few seconds would be the best solution in this case. Based on the above, it would be appropriate to use sensors and systems for long time monitoring the psychological and physical condition of users. However, these systems are not used in empowering lower limbs exoskeletons for workers. Systems for long time monitoring of the psychological and physical condition of users are used only in the construction of rehabilitation exoskeletons. These include the following sensors: respiratory rate sensors, temperature sensors, perspiration sensors, etc. Although these sensors must usually be in direct contact with the body, we can overcome the disadvantages of such sensors using special suits, etc. Thus, the advantages of using sensors can overcome the disadvantages of their use. Using systems for monitoring the psychological and physical condition of user exoskeleton will be able to automatically prevent the user from dangerous situations. For example, various reflex actions can be implemented into exoskeleton control system.

Another obstacle in using exoskeletons in operational missions can be considered that each exoskeleton must be customised before any use so that it can be adapted to an individuals morphology. This machine configuration phase requires time for fine adjustments to be made through several iterations, enhancing its use to utmost comfort.[91] This means an operator will need to train with his/her own equipment and follow predefined exercises, including functional testing.

Additionally, in the case of military exoskeletons, a high stealth level and transportability is also needed to avoid detections by enemy forces. In this respect, the noise level must be kept to a minimum when using it. The transport of exoskeletons raises serious issues that can imperil their current use. In fact, little room is left for new equipment in a military vehicle as its free space is both rare and scarce.

We may note that nowadays, a new class of empowering wearable robotics is arising. This class is called exosuits, which overcomes many of the above-mentioned disadvantages. In contrast to exoskeletons which use rigid structures, these devices use textiles and interface to the operators body. Exosuits apply joint torques via tensile forces over the outside of the body in parallel with muscles, utilising the bone structure to support loads.[92] This class of empowering robotics might be a serious competitor to endurance augmentation exoskeletons in the future.

8. Conclusion

In this paper, we have provided an overview of various empowering exoskeletons, focusing on full lower limbs, and active ones. Along with lower limb exoskeletons, we briefly described its different concepts of design and control strategies.

A large amount of research on active lower limbs exoskeletons was found. This research includes laboratory development describing exoskeleton characteristics in detail, and commercial development which publicly presents much less technical detail. Based on collected and compared available information, we can conclude that most of the empowering exoskeletons are designed quasi-anthropomorphically. All of them support knee joint (one DoF), most of them support hip joint (various DoFs) and only a few of them support ankle joint (one or two DoFs). From the point of view of which sensors are used, exoskeletons vary as they utilise wide range of sensors. Electric actuators are usually employed. Finally, we discussed key points considering exoskeleton classification, development and standardisation. However, this study is not only a summary of the current state, but also points to weaknesses of current empowering lower limbs exoskeletons, such as energy harvesting, materials and sensors that meet demands of hard-workers environments and critical operations (customisation, durability, lightweight, collapsibility, portability and transportability), and outlines possible improvements.

Acknowledgements

This work was supported by Ministry of Health of the Czech Republic, AZV Grant no. 16-28119a "Analysis of movement disorders for the study of extrapyramidal diseases mechanism using motion capture camera systems".

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