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State of the Art Lower Limb Robotic Exoskeletons for Elderly Assistance

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ABSTRACT The number of elderly populations is rapidly increasing. Majority of elderly people face difficulties while walking because the muscular activity or other gait-related parameters start to deteriorate with aging. Therefore, the quality of life among them can be suffered. To make their life more comfortable, service providing robotic solutions in terms of wearable powered exoskeletons should be realized. Assistive powered exoskeletons are capable of providing additional torque to support various activities, such as walking, sit to stand, and stand to sit motions to subjects with mobility impairments. Specifically, the powered exoskeletons try to maintain and keep subjects' limbs on the specified motion trajectory. The state of the art of currently available lower limb assistive exoskeletons for weak and elderly people is presented in this paper. The technology employed in the assistive devices, such as actuation and power supply types, control strategies, their functional abilities, and the mechanism design, is thoroughly described. The outcome of studied literature reveals that there is still much work to be done in the improvement of assistive exoskeletons in terms of their technological aspects, such as choosing proper and effective control methods, developing user friendly interfaces, and decreasing the costs of device to make it more affordable, meanwhile ensuring safe interaction for the end-users.

INDEX TERMS Lower limb assistance, actuation, exoskeleton, wearable robots, mechanism design, elderly.

I. INTRODUCTION

Beginning from the late of the 20th century when the vast research has started developing robotic systems to increase physical capabilities or to rehabilitate patients, people started to use expression "wearable robotics" [1]. Based on the designation of wearable robotic exoskeletons, they are designed towards assisting people with gait abnormalities in their locomotion, increasing physical capabilities of people to allow them carry or lift heavy loads, and rehabilitate patients after surgery or patients suffering from various neurological disorders which causes gait impairments to some extent. Moreover, exoskeletons may also come in handy in assisting people with motor impairments in their limbs performing their daily activities, such as walking, standing, sitting and lifting various objects. Until now, majority of research is concentrated on developing rehabilitation exoskeletons for stroke survivors, individuals with spinal cord injuries (SCI) and military personnel to augment their combat capabilities and increase their mobility.

Nowadays, the elderly population is rapidly increasing [2]. It is estimated that the number of people who were older than 65 years old in 1996 was more than 300 million and by 2010 the population has increased up to 440 million and now it is predicted that the number of elderly population will reach 1.5 billion by 2050 [2], [3]. Since the locomotion capability among elderly people declines, it causes them various inconveniences in their everyday life. In addition, restricted locomotion may also have negative effects on the mental and emotional constituents of a person. Therefore in order to help elderly people maintaining good quality lifestyle, there is a need to develop robotic assistive exoskeletons [4]. According to Paterson unrestricted locomotion is a major thing which allows person to stay at home independently [5]. When the crutches and walkers are not enough to support walking of people with gait impairments, wheelchairs are considered to

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be one of the safest tools to move around. However, because aged people usually have weak health condition, the usage of wheelchairs for them is difficult process, therefore they are not able to perform usual daily activities [4]. In addition, if person spends much time sitting on wheelchair, the muscular inactivity may bring negative consequences and worsen general health condition. Another risky case that elderly face during walking is falling down. Around half of the falls occur due to the problems with locomotion [6]. It was reported in the work done by Moylan and Binder that one third of people older than 65 years old have fallen down at least once a year [7]. There is a highly increasing trend of falls' occurrence as the person gets older. Every year around 3 million of elderly are accepted in hospitals due to fall injuries [8]. Falls' after effects are different and mostly negative [7]–[9]. One of the most spread consequences after fall are bone fracturing either on upper limb, lower limb or both, injuries and trauma to head. Moreover, it is explored that falls cause around 9 times more deaths among elderly rather than car crashes [6]. Therefore, taking into consideration that falls among elderly is dangerous, new innovative solutions have to be introduced to reduce the risk of falls. People who are moving around home easily and do not have any locomotion problems can maintain comfortable lifestyle. Exoskeletons can be useful tools to allow and assist elderly in moving around freely and easily and perform daily activities without facing any physical difficulties, which also might have positive impact on society in general.

Extensive research is being done towards developing assistive robot-based solutions which will have positive impact on health care services. Recent review papers on lower-limb wearable exoskeletons have generally covered and classified all types of exoskeletons based on their use either medical or non-medical, discussed their performance, type of user interfaces and their disadvantages [10]–[12].

The aim of the current paper is to present the state of the art of existing exoskeletons for lower limb which can be used by elderly people. The mechanism design, sensors, actuation and control types and other describing key features of exoskeletons are described.

II. LOWER LIMB BIOMECHANICS AND WALKING OF ELDERLY

It is crucial to study and understand the biomechanics of lower limb part in order to develop and construct robot-based gait exoskeleton. Sufficient study and description of lower limb biomechanics have been done in the literature [13]–[16].

In general, lower limb consists of three main regions, they are hip, knee and ankle. Hip movement is described with spherical joint which has 3 Degrees of freedom (DoFs) consisting of flexion and extension, abduction and adduction, and internal and external rotational movements. The knee joint has one DoF for flexion and extension and the ankle joint allows 3 DoFs. In overall, there are around 30 bones that compose lower limb. The major ones are femur, patella, tibia, fibula tarsal bones, metatarsal bones, and phalanges as depicted in figure 1.

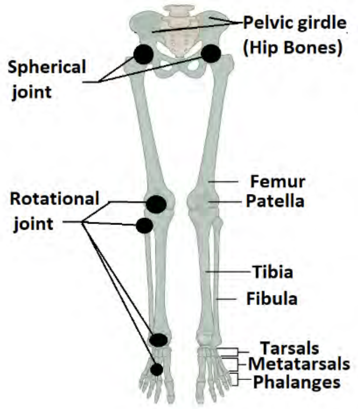


FIGURE 1. Lower limb bones with kinematic chain. The hip movement is described with spherical joint of 3 DOF, knee movement by rotational Joint with 1 DOF allowing flexion and extension. Adapted from OpenStax, 2013 [17].

The range of motions (ROM) of lower limb start to alter with ageing and the gait performance of people is also degraded. It causes instability in walking and increases the risks of falls [18]–[20]. In the work done by Zhou, comparison of the lower limb motions of elderly and younger group of population has been made during kneeling activity. The results revealed that elderly apply higher hip flexion angles in comparison to the younger group, however there is no much difference has been found on ankle and knee joints' movement [21]. During walking and running conditions, it was revealed that toe clearance among elderly is lowered in comparison to young adults, moreover there are differences in kinematic characteristics of knee and kinetic parameters of hip and ankle movements [22], [23].

III. ASSISTIVE LOWER LIMB EXOSKELETONS

Usually, elderly people experience motor deficits in their lower limbs' performance, therefore the control over their legs become a challenging process. The probability of fall occurrence is increasing as the degree of abnormality in walking performance enlarges. In general, elderly use various passive supporting devices such as crutches to assist them in balancing, walking, sit to stand and stand to sit activities. However, one of the main drawbacks of crutches' usage is that it requires involvement of healthy upper limbs which has to take control over the crutches' manipulation. Robotic exoskeletons are able to provide assistance during walking by exerting additional forces and torques to compensate the muscles' inactivity in the weak parts of the lower limbs. Assistive exoskeletons are designed and constructed such that they can keep motions of joints or limbs of subjects within correct predefined trajectory. One of the examples of assistive exoskeleton named ''AUTONOMYO'' shown in figure 2 (a) is presented in the work done by Ortlieb *et al.* [24]. It has 6 DoFs which is dedicated for elderly people and people suffering from neuromuscular diseases and multiple sclerosis. Exoskeleton provides compensational forces and complementary torques using electromagnetic actuation located on the back side of the user, which makes the system have ergonomic design. The hip flexion and extension activities are performed with the use of cable driven methodology. The ball-screw provides the hip abduction and adduction motions. The estimated level of assistance of ''AUTONOMYO'' exoskeleton for sit to stand activities was varying from 50-100%.

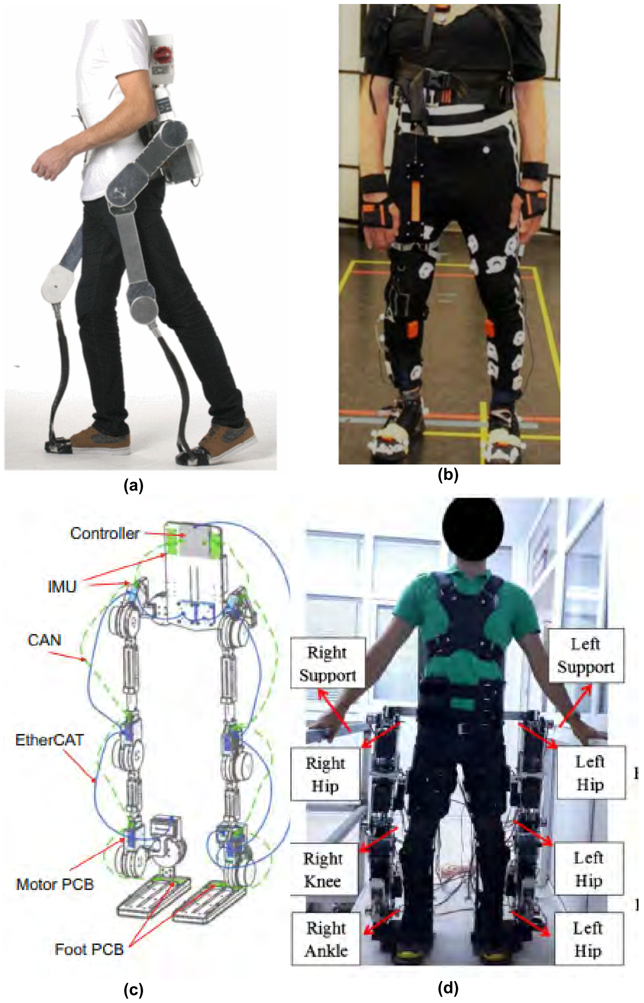


FIGURE 2. **(a) AUTONOMYO [28]. (b) XoSOFT EU project [25]. (c) Auto-LEE schematics [26]. (d) BioComEx [27].**

The results for assistance level of 13% in the hip movement and compensational 7% have been achieved by the lower limb exoskeleton in [25]. This wearable exoskeleton depicted in figure 2 (b) with modular actuation was designed to provide physical assistance to elderly persons during walking. The contribution of the related work lies in the inclusion of quasi-passive elements into the system. Another recent assistive exoskeleton called Auto-LEE on figure 2 (c) has been presented in the work [26]. In comparison to previously developed devices, this exoskeleton has 10 DoFs which higher from usual ones. In addition, it applies direct current motors to actuate each joint separately. Also, the system has integrated the human-robot interface. With the integrated interface and the modular structure, the proposed exoskeleton provides variety of control methods such as electroencephalograph (EEG) and the joystick to manipulate the system. The exoskeleton called ''BioComEx'' described in the work by Baser et al. represented in figure 2 (d), assists walking of people with paralyzed limbs or healthy people by reducing the load [27]. Basically, it applies series elastic type of actuation for the knee and hip joints, however for the ankle joint variable stiffness actuator has been employed. Using the force sensors on each segment of the limb, closed loop type of control has been achieved. Since the robot can be used for rehabilitation and reducing the load for healthy people, it will also be beneficial for elderly people with lower limb motor impairments.

Assistive wearable robot based exosuits compensate deficit of lower limb muscles by providing additional torques to enable full and correct locomotion of elderly people or patients experiencing gait disorders. Moreover, they can help in performing usual daily activities such as standing and sitting similar to healthy people's performance [29], [30]. Active Assisted Living (AAL) program running in Europe is aimed at making quality of life for elderly better [31]. Therefore, one of its project has developed device which can assist elderly people during their daily life activities named Exo-legs [32]. The exoskeleton assists elderly in sit to stand movements, assures straight locomotion and provides stable standing. It provides up to 30% of power for assisting the person. Company called Superflex is developing assistive soft exoskeletons dedicated to the elderly group of people. The objective of the company is to develop so called ''powered clothing'' (figure 3) which will have onboard electric muscles to support hip and knee motions during sit to stand activities [33], [34].

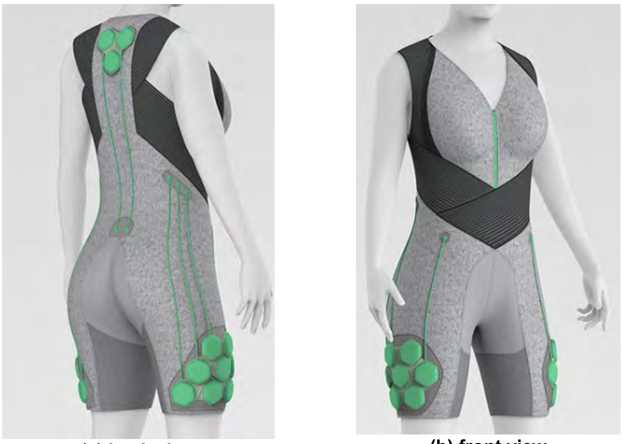

(a) back view (b) front view

FIGURE 3. **Powered clothing concept (Superflex) [35].**

Another assistive robotic device named active pelvis orthosis (*i.e.* exoskeleton) (APO) shown in figure 4 (a) was designed to assist people in locomotion by guiding the hip

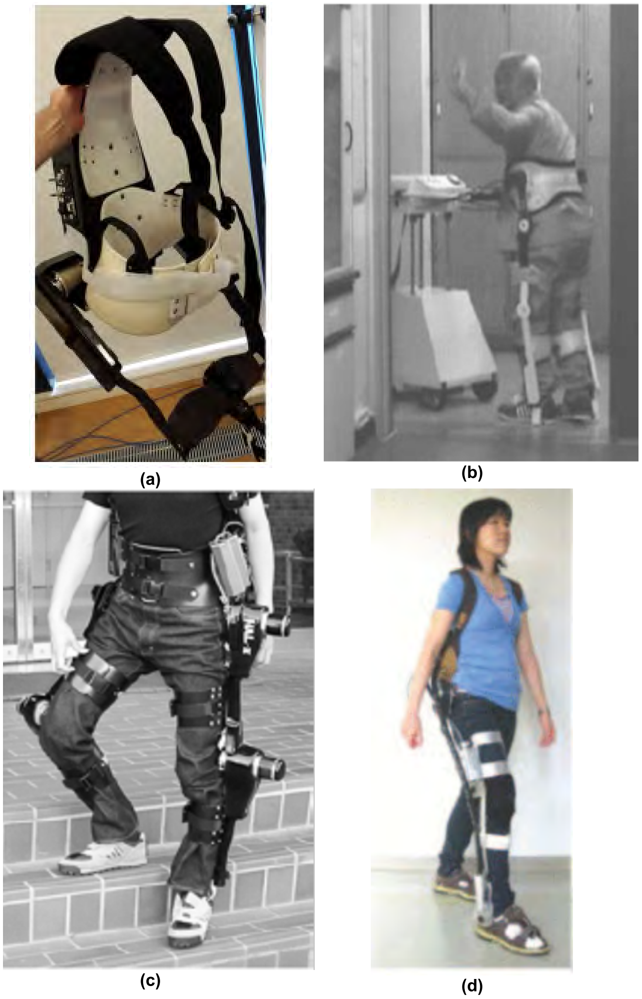


FIGURE 4. (a) Active pelvis orthosis (APO) [37]. (b) EXPOS (Sogang University) [39]. (c) HAL-3 [40]. (d) Exoskeleton [41].

flexion and extension motions, which was proposed in the work [36]. The orthosis is worn at the waist. Device weighs around 5 kg which is not much. Sensors installed onboard detect when the balance is lost and automatically turns on "assistive mode". The system is also able to detect and counteract against slippage. This type of mode will enable people to avoid falls and keep balance during walking. Moreover, APO performance has been quantified and the results demonstrated that less energy is spent while using the exoskeleton during walking conditions [37]. The ergonomic assessment of APO and human interaction has been proved to be effective and reliable [38]. Today APO can be considered to be the best existing robotic device intended for the elderly group of people.

Assistive system which consists of exoskeleton and caster walker with 4 active joints for elderly locomotion assistance has been proposed by Sogang University named EXPOS (Figure 4 (b) [39]. The purpose of the research was to make light weight system which has lower volume to enable comfortable use of it during daily life activities. The total weight of the exoskeleton does not exceed 3 kg. All the heavy parts such as motor, battery and controllers are placed in the castler walker.

Wearable exoskeleton named Hybrid Assistive Limb (HAL-3) exoskeleton has been proposed by Tsukuba University and Cyberdyne in Japan shown in figure 4 (c) [40]. The main purpose of the device was to assist elderly in locomotion. Assistive torque in hip and knee joints is generated with the help of DC motor. The system has various sensors onboard such as force sensor, EMG to monitor the muscle contractions and measure reaction forces from the foot's sole. The device is certified and is also being used as a medical device and has been tested and reported in several research works [42], [46]. Besides assistive purposes there are also other models of HAL which can be useful in the case when person has to receive rehabilitation of the lower limbs. However, this device is not cheap and therefore not many people can afford it. Additional information regarding HAL exoskeleton is presented in the table 1.

Exoskeleton by Ikehara is actuated using hybrid actuation in the hip and knee joints depicted in figure 4 (d) has been built with the use of worm gear and flexible shaft. Its purpose is to help elderly people who do not have symmetrical leg length which causes unstable walking [41].

One more example of exoskeleton which provides assistive torque in walking has been developed for enhancing the walking performance of disabled and elderly people is called Wearable Walking Helper (WWH) [47]. Numerous experiments have been conducted to test the feasibility of the given exoskeleton, the results demonstrated that the heart rate of subjects has been reduced while using the exoskeleton in stair ascending/descending experimental procedures.

Exoskeleton presented in the work done by Chen *et al.*, Walking Power Assist Leg (WPAL) can also help old people normalize their walking and assist patients suffering from SCI [48]. Clinical evaluation of WPAL demonstrated the benefits of patients from using the device and the feasibility of its use among them has been proved [49].

ReWalk demonstrated in figure 5 (a) is considered to be one of the old and well known wearable robotic exoskeletons [50]. It is designed to train and rehabilitate the hip and knee joints for individuals having SCI, it also allows subject to stand, walk, turn around and go up on stairs [30]. More information about ReWalk is shown in table 1. Nowadays, ReWalk Robotics Incorporation has two rehabilitation systems, one is ReWalk and another is ReStore shown in figure 5 (b) [51]. The objective of ReStore exosuit is to train and rehabilitate the performance of lower limbs of post-stroke patients. There were some clinical trials conducted with ReWalk in the works [30], [50], [52]. It was revealed that ReWalk has some drawbacks in the difficulty of using wrist control, since the system is quite complicated. Besides its rehabilitation purpose, ReWalk may also assist walking of elderly people, however, it is very bulky to be used in their daily life activities.

Lower limb exoskeletons which are developed to increase the physical capabilities can be also applied in order to augment physical capabilities of weak people such as elderly.

TABLE 1. Existing lower limb exoskeletons for rehabilitation and assistive purposes.

Name of the device	Targeted group (Use)	Actuator type and Output force	Price	Sensors	Joint movements and DOF	Control modes	Availability
1. Ekso[83]	Locomotion assistance for individuals with Spinal Cord Injury (SCI), Paraplegia	Maximum output torque 150 N-m, Hydraulic actuator	High price-around 100.000 USD	Battery, computer and portable compressor in bag pack Encoders and linear accelerometers	6DOF, Hip flexion/extension, knee flexion/extension, both legs	Configurable assistance levels "Variable assist"	Purchasing only for hospitals
2. ReWalk [50]	Locomotion assistance to people with SCI, Paraplegia	DC motors a battery unit, and a computer-based controller contained in a backpack, a wireless mode selector	High price-around 70.000 USD, crutches are required	Various sensors that measure upper-body tilt angle, joint angles, and ground contact	Hip flexion/extension, knee flexion/extension, both legs	A closed-loop algorithm software control, normal walking mode, sit–stand, stand–sit, up steps and down steps	Commercially available system, approved for hospital usage
3. Indego [85]	Locomotion assistance for individuals with Spinal Cord Injury (SCI), Paraplegia. Can be split into three pieces and then coupled	DC brushless motor	High price-around 140,000 USD,	Developed control system that calculates the user's center of pressure (CoP)	Powered movement of bilateral hip and knee joints in the sagittal plane	Lightweight system with reduced assistance and fewer control functions Wireless operation	Commercially available system
4. Rex [86]	Locomotion assistance to individuals with a complete SCI up to the C4/C5 level	Linear actuators	High price-around 150,000 USD	No information	Sit, stand, walk and turn	Non- invasive brain interface, joystick for control self-balancing system, stand up, walk, sit down, ascend and descend stairs, and turn without the need for crutches	Commercially available system
5. HAL-hybrid assistive limb[75]	Locomotion assistance and rehabilitation for individuals with incomplete SCI or who have paralysis due to a stroke	Electric DC actuation	$1,950 per annum (Rent)	Bioelectrical sensors, angular sensors, acceleration sensors, and floor reaction force sensors. Rotary encoders and strain gages	Hip flexion/extension, knee flexion/extension, double legs, Shoulder flexion/extension and elbow flexion,/ extension	EMG used to control, Phased sequence control which generates series of assistive motions with the exoskeleton being the Master in a master/slave system.	Only exoskeleton to get global safety certification
6. 8. Atalante [87]	Assist in walking individuals with paraplegics (people with lower limb paralysis)	Brushless DC motor	33.000 USD	digital encoder is mounted on each motor to estimate joint position and velocity. Sensors installed in the feet allow for impact detection when the feet hit the ground.	12 DoFs (6 per leg)	No use of crutches, joystick, dynamic balancing control Intel Core i7-equipped microcomputer	Commercially available
7. 9. Exoatlet [88]	Assist in walking and gait rehabilitation of individuals with paraplegics or after stroke, injury, or unsuccessful operation.	Electric actuator	No information	EMG and torque sensors for control, electrical stimulation system, and physiological sensors	Hip flexion/extension, knee flexion/extension, knee flexion/extension (both legs)	Can be controlled with the app on tablet when used in clinics. Experienced user of ExoAtlet use "thinking" crutch for control	Commercially available
8. Vanderbilt exoskeleton [89]	Locomotion assistance to people with paraplegia	Electric actuator	No information	using sensors estimation of the location of the user's center of pressure (CoP)	Hip flexion/extension & knee flexion/extension (double legs)	Controlled by on-board electronics on a host computer	No information
9. 11. CUHK-EXO [90]	Locomotion assistance to patients paralyzed due to stroke, spinal cord injury, or other related diseases	Electric actuator	No information	Multiple sensor system, encoders, potentiometers, inertial measurement units, FSR sensors.	7DoFs, Hip flexion/extension & knee flexion/extension (double legs	Controlled through HMI, smart-phone app and a pair of smart crutches	No information
10. MindWalker[91]	Empower people with	Linear electric actuators,	No information	1 motor encoder, 2 analogue-to-digital (ADC) channels, 1 spring encoder, 2	5 DOF at each leg,	Works on user command Centre of mass control strategy for	No information

TABLE 1. *(Continued.)* **Existing lower limb exoskeletons for rehabilitation and assistive purposes.**

	paraplegics to stand and walk	100Nm torque		joint encoders, 1 load cell, and 1 IMU	hip flexion/ extension, abduction/adduction and knee flexion/extension	walking, developing brain neural computer interface-based control	
11. Lower limb orthosis [92]	rehabilitation of paraplegia patients and hemiplegia patients and spinal-cord-injury victims	Bilateral hydraulic servo actuators	No information	Potentiometer for position control, embedded pressure sensors in shoes to stabilize posture,	4 DOF per leg	Pulse width modulation (PWM) control system	No information
12. ETH knee perturbator [93]	Compensate gait deviations	Brushless and flat actuator, Max. torque 80 N-m	No information	knee angle potentiometer, a string potentiometer (Celesco SP1-4), torque and screw encoder, Optical encoder, pressure sensors	Range of motion 0-120 knee flexion Five-degree extension and flexion perturbations	Wireless data acquisition , controlled with software Simulink Real-Time Toolbox (The MathWorks, Natick, Massachusetts)	No information
13. Arke [94]	Compensation to people with paraplegics	No information	No information	No information	hip joints allowed 3 DOF, knees allowed 1 DOF (flexion-extension), and ankles allowed 2 DOF (plantar/dorsi flexion, inversion/eversion).	controlled by an app on a tablet	No information
14. EXPOS [39]	Assisting elderly and patients	Tendon-connecting motors and pulleys	Under research, feas	Potentiometers, pressure sensors, EMG sensor	4 active joints, 1 DOF for hip and knee joints, 2 DOFs for both ankle joints	Fuzzy controller	Under research stage


(a) Rewalk (b)Restore

FIGURE 5. **(a) ReWalk [50]. (b) ReStore [51].**

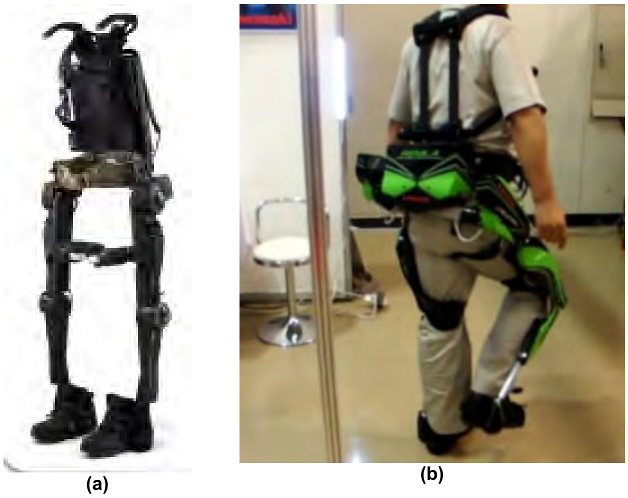
Basically, exoskeletons developed for the augmentation of strength can increase the endurance during walking, allow people to perform various hard tasks which usually person without exoskeleton cannot perform. The reason why force augmentation robotic exoskeletons are also considered in this work is because they are capable of providing additional forces for the users which may be beneficial for elderly, very bulky and large exoskeletons which are difficult to wear were not considered.

One of the famous and popular exoskeletons intended to augment physical capabilities have been developed by Defense Advanced Research Projects Agency (DARPA) in the U.S. The objective of the agency is to augment the strength among people to exceed usual human's one. Exoskeletons developed by DARPA include BLEEX [53]–[55], Human Universal Load Carrier, ExoHiker, and Exo-Climber [56]. Another popular exoskeleton called Human Universal Load Carrier (HULC) has been developed to enable to lift and transfer various objects. The results of testing first prototypes on people demonstrated that metabolic energy rate was increased among them and the gait performance has been altered limiting the functional mobility [57]. There are also other exoskeletons available which also help in lifting and carrying heavy objects, they are Exo-climber which allows to quickly go up on stairs while carrying some stuff [58], Sarcos XOS2 is compliant and environmentally resistant, the user of the device is even able to kick soccer with it [59]. South Korea has also introduced its own exoskeleton called Hanyang Exoskeleton Assistive Robot (HEXAR) (Figure 6 (a)) [60]. It has 15 DOFs and actuated using 2 electric motors.

Wearable Kawasaki robotic exoskeleton shown in figure 6 (b) can enable users to lift objects which weigh up to 30-40 kilograms without exerting any own muscles' force [61].

Sensors located on board are able to detect when the subject is trying to life heavy weight and then the signals are transferred to the motors to actuate them.

The design of mechanism is crucial part during exoskeleton development stage, since the latter performance will highly depend on it. Majority of exoskeletons share similar structure even if the targeted group and the design objectives are different. Full lower limb exoskeletons usually comprised of 5 and more DoFs and have rotational joints to provide hip flexion/extension and abduction/adduction, knee flexion/extension functions. For the insight of the systems,


(a)

(b)

FIGURE 6. **(a) HEXAR [62]. (b) Kawasaki [61].**

exoskeleton developers have to choose proper actuators, decide which sensors, what type of materials, power supply methods should be integrated in the system based on what exoskeleton's designation is. The following subsections provide the description of design insights in terms of power sources, material, sensors and actuation types for existing exoskeletons and number of DoFs robot can provide.

A. ACTUATION TYPES

Choosing right actuation type for the exoskeleton was always important part during the construction stage. The characteristics of the motors in terms of weight, size and power have always limited the robotic exoskeletons. The first difficulties in the application of pneumatic and electric actuation has been documented in the works by Vukobratovic [63], [64]. Improper selection of the actuation type may result in the ineffective performance of the system. There are 3 types of actuation systems which are spread among exoskeletons: electric motor, hydraulic and pneumatic actuators. Each type of actuations has its own drawbacks and benefits.

DC motors are widely used in the robotic actuation systems. DC motors are categorized into two types: brushless DC motors and synchronous AC motors. The benefits of electric actuators lie in their high power capacity, torque to weight ratio, precision and the others. In addition, they are usually more silent in comparison to pneumatic or hydraulic ones. The feedback and response time from them is usually short. However, because the locomotion requires relatively high speed in the leg joint motions, the gear ratios cannot be made high, which means that the electric motor will not be able to provide enough torques. In the industrial or military application when heavy lifting tasks are required to be performed hydraulic actuators can come in handy.

Hydraulic actuators are able to provide large output force; they have highest power to mass ratio which varies in the range of 300–600 W/kg, in comparison to electric or pneumatic actuation which usually has ratios in-between 100–200 W/kg [65]. However, hydraulic actuators require lots of energy to be supplied from the power source. In the case of failure of hydraulic system, the leakage of liquid can occur, and if the operating temperature is high, the system exploitation becomes dangerous for the end user.

The pneumatic actuators are compliant and selected due to their light weight. As an example University of Auckland has proposed compliant robotic orthosis which is actuated using pneumatic muscles. The robot provides motions in the sagittal plane allowing the hip and knee joint rotations [66]. However, as a drawback the control of pneumatic actuators is difficult process. The usage of either pneumatic or hydraulic actuators make exoskeletons not portable, heavy and hard to manipulate. Besides their drawbacks, there are still number of successful implementations of them in the system [54], [67].

HAL-3 exoskeleton, Walking Power Assist Leg (WPAL) exoskeleton have used DC actuators to provide required torque for knee and hip motions [40], [48].

B. SENSOR AND SENSING SYSTEM

Sensors allow us to receive the feedback from the exoskeleton, control it, actuate necessary and relevant movements of specific joint in a given time. All exoskeletons presented in this work have at least one mechanical sensor which allows to control position, force and torque. Without sensors the exoskeletons will not be able to assist or treat people. Modern exoskeletons incorporate in itself different sensors such as encoders, accelerometers, inertial measurement units (IMU), gyroscopes, EMG, EEG, pressure and torque sensors, potentiometers which allow us to measure various physical characteristics such as joint angles, position, ground contact, center of pressure, exerted force, torque and the others. For example, muscle movements and joint angles are measured using potentiometers, pressure sensors in EXPOS exoskeleton [68]. HAL-3 integrated in itself force sensors attached below the foot to measure reaction forces and EMG to track muscle contractions [40]. EMG sensor can also be used to recognize and classify different limb motions such as standing, sitting and walking, such system has been tested on assistive lower limb exoskeleton for aged people which has four bar mechanism and the results demonstrated high recognition accuracy [69].

C. ENERGY SOURCE

Batteries are required to supply energy to exoskeletons. If the load on exoskeleton is high, more energy is needed to be supplied from battery. Basically, functionality of the exoskeleton is highly correlated with the capacity of source of energy. It is straightforward that large capacity batteries usually need more space allocation, they are heavy weight which reduces its usage effectiveness. Majority of developed exoskeletons use batteries to supply power to the motors.

Lithium-ion batteries enabled lots of robotic devices to run for several hours. Sometimes the energy expenditure can be reduced by realizing the mechanical stuff such as springs or dampers to compensate the required forces from the actuators. There is still much research work remaining on developing techniques which will allow the energy to be exploited less and effectively.

D. TYPE OF MATERIALS

One of the important things in building the exoskeleton is the selection of proper material. Since, later it will have an effect on the weight, bulk and its convenient usability. The structure of the exoskeleton should be designed such that all necessary parts like motors, sensors and controllers can be attached meanwhile providing ergonomic interface for the subject. In general, it is desired to have strong, stiff and lightweight material for the exoskeleton to allow necessary torque to be applied in the joints. Depending on the intended purpose of the exoskeleton material is also varied. The exoskeleton can be hard or soft. Usually, aluminum or aluminum alloy is preferred material for the exoskeleton's frame in hard exoskeletons. Titanium is better in terms of weight to strength ratio, however the price for it is higher than aluminum. Sometimes carbon fibers are used to create lightweight structures, but it is more difficult to create required shape from it rather than from metals.

Soft exoskeletons use textiles to reduce the weight and the Bowden cables are used to transfer the power. Assistive exoskeletons for elderly should be lightweight, not bulky, easy to wear and should have user friendly control interface, therefore it is recommended to make it soft, which will make it comfortable to use while performing daily life activities.

IV. CONTROL METHODS

The main purpose of control is to drive an exoskeleton along the trajectory of the healthy person's movement by providing additional torque and ensuring safety of the users.

There are many variations of control systems exist nowadays. The control strategies vary from one exoskeleton to another. Different control methods have been applied in the exoskeletons. Usually, the control input signals are generated from various sources such as EMG signals, biomechanical systems, central nervous and peripheral nervous system signals [70]. The effectiveness of controller highly depends on the structure of the exoskeleton.

Assist-as-needed (AAN) control methods are prevalent paradigms used to enhance user's involvement in the exoskeleton using process. This method provides additional assistive torques whenever the intention from the subject to move the limb is detected. Moreover, it implies adaptive strategy based on the needs of the user, such strategy are presented in the works [71]–[73].

Trajectory tracking control is usually implemented on the rehabilitation exoskeletons. They guide the paralyzed limbs of patients in a predefined gait trajectory. Since the participation of the paralyzed patient is absent, the effectiveness and relevance of the given treatment is also questionable [74]. In order to trigger the involvement of the intended patient into the rehabilitation process, an impedance control strategy is executed. When there is a deviation in the trajectory the controller compensates necessary force to help patient to get back on track.

The intentions of the user are detected using EMG and EEG sensors, in the AAN control mode, the robot helps to move the limbs when the subject does not have enough force to walk. There are many exoskeletons which integrated EMG sensors, some of them are Exoatlet (Exoatlet), HAL [75], KAFO [76] (Table 1). AAN based control enables the participation of user in the system. And it perfectly suits the assistive robotic devices intended to be used by elderly people.

In the work done by Rezage and Tokhi, FUZZY PID Control algorithm has been implemented on the exoskeleton which was designed for supporting hip and knee motions of elderly. The controller allowed the device to provide up to 40% of the general torque required to complete the gait cycle for the simulated humanoid which represented elderly person [77]. In the work done by Miranda-Linares Fuzzy PID controller and finite state machine have been implemented for the lower limb exoskeleton designed for elderly assistance, the controller allowed to assist during standing-up and walking motions providing up to 30% of required torque to complete the walking cycle [78]. Fuzzy controller has been integrated in EXPOS exoskeleton taking as the reference joints' angular velocity and torque [39].

EMG based control of the power assist exoskeleton designed for weak people has been introduced in the work [79]. For the adaptation of EMG signals, fuzzy-neuro control method has been implemented. The contribution of the given work is that it took into consideration precise subject's movement intension.

Another type of control for lower limb is implemented based on the impedance properties [80], [81]. It can be used as a substitute for EMG based control. EMG based control is considered to be complex task, since it requires periodical recalibration of the system. The main goal of active impedance control is to reduce the average muscle metabolic cost.

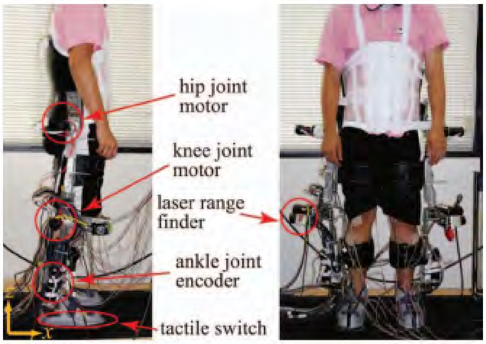


FIGURE 7. Lower limb exoskeleton with perception-assist [82].

Perception-assist method has been integrated in the lower limb exoskeleton (Figure 7) which helps elderly or weak people to walk safely [82]. Controller uses EMG signals to compute required amount of force to support the walking. The proposed methodology helps to prevent subjects from falls.

Various control methods of exoskeletons are presented in table 1. Ekso-bionics exoskeletons are worn as an assistive device which in long-term can rehabilitate the gait performance. It has ''Variable assist' control assistance levels which can be configured based on the user's preferences [83] in table 1. ReWalk exoskeleton intended to help weak people, people with SCI and paraplegia during walking. It has closed-loop algorithm software control which provides different locomotion assistance modes to sit to stand, stand to sit, going upstairs and downstairs activities [50] (Table 1).

In overall, lots of commercially available exoskeletons do not provide detailed information regarding what kind of control algorithms are applied in their systems, which makes it difficult to analyze the efficacy of controllers, make a comparison between them and decide which ones are better. Descriptive analysis on which control strategies implemented in exoskeletons are presented in the work done by Yan *et al.* [84].

V. DISCUSSION AND FUTURE PROSPECTIVE

The aim of the present work was to provide comprehensive state of the art of currently existing lower limb robotic exoskeletons which might be used by elderly people. Besides numerous numbers of research projects undergoing on lower limb exoskeletons there is still much work to be done in this promising field of science. Current developed assistive exoskeletons are expensive, heavy and bulky which makes it inconvenient to be used during daily life activities by elderly people. There are some projects of lightweight soft exosuits undergoing research stage, one such concept called Superflex. It can be worn with usual clothes and can assist elderly during walking, sitting and standing activities.

With the rapid increase in the population of elderly around the world, the realization and development of assistive robotic tools should be able to reduce the burden on human labor assistance and healthcare sector in general. Therefore, the focus should be made more on elaboration of assistive robot-based solutions which will allow free locomotion for ageing people. Assistive devices can effectively increase the mobility among aged people. There is also another type of robotic powered exoskeletons which allows to increase physical capabilities of a person. Strength augmentation exoskeletons are tangentially connected with assistive devices for elderly persons, since people become weak and additional or compensational torque is required for them to perform desired physical actions. Power increasing exoskeletons demonstrated to have high efficacy in enabling people lifting objects without putting in pressure their musculoskeletal structure and reducing metabolic cost.

Exoskeleton which increases physical capabilities can serve as a useful tool for elderly because the strength among them is usually diminished. Assistive exoskeletons support limbs' movements in a predefined trajectory by providing necessary torque in the specified joint. The work has also discussed and described the technological insight among these assistive devices. Specifically, technological aspects and design in terms of type of sensors, actuation methods, type of materials and power supply integrated on those exoskeletons are discussed. Moreover, the control strategies implied on these devices is also described. Usually, the targeted groups in the developed exoskeletons are multipurpose, which are used both for assisting and rehabilitation, therefore the lack of focus might lead to severe side effects, for example inappropriate usage of exoskeleton on a wrong target group might lead to injuring someone or worsen the progress made in the gait performance. It is still possible to apply some type of exoskeletons for elderly people which will assist them in their daily life activities, aiming at improving their life quality, however the potential effectiveness and drawbacks of usage of these exoskeletons among elderly was not researched properly. The technical characteristics requirements of exoskeletons for elderly will be different from people suffering from neurological disorders or people injured due to accidents. Therefore, the elderly group should be treated as a separate population.

The exoskeleton development should include studying common problems of what kind of sensory motor functions are impaired among ageing group of people. But still for the improvement of the currently existing exoskeletons for elderly from the technical perspective, more concentration is required in choosing proper actuators, sensors, type of materials, mechanism design, type of human robot interface, and the others, moreover existing exoskeletons are very bulky to be used in the daily activities, rather than that, it is better if robotic assistive system will come in a form of exosuit or soft exoskeleton which will be similar to clothes, taking less time and efforts to wear and take it off. Portability and assistance efficacy of powered exoskeletons should be improved. Each type of actuation has its own benefits and drawbacks. Electric motors are considered to be precise and easy to manipulate, however, their drawbacks lie in high price, heavy weight and not enough power. Pneumatic air muscle actuators are compliant, have high power to torque ratio, but their manipulation is challengeable thing, since exploitation of pneumatic muscles can give many errors, precision is suffered. Moreover, the level of assistance needed for the elderly person should be adjustable, so that every person can select proper assistance program based on what he needs.

The area of developing and constructing wearable robot based assistive solutions for elderly is becoming very demanding with the exponential increase in the elderly population around the world. From the economic and social perspectives, it is crucial for the government to have more people who can work. Future investments of governments or companies around the world should be made on developing robotic solutions to help elderly sustain good quality of life. Undoubtedly, it will have its own benefits in the financial and social spheres.

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