

# Past, Present and Future of Assistive Robotic Lower Limb Exoskeletons

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**Abstract.** Many research teams have developed various innovations in the field of assistive robotic exoskeletons for human lower limbs. Especially in the recent years, because of the expeditious technological development, much work has been done and published in the scientific communities. However, in the publications, for different reasons and constraints, the information available is in bits and pieces. Most papers only could manage to speak of the individual aspects like the mechanical design or state machine or interface or another control scenario, etc. This is why an attempt of bringing scientific aspects together is done in this work. This is achieved by considering the most popular and various kinds of exoskeletons. Therefore, in this chapter an overview on the aspects of mechanical design and electrical control, and simultaneously their algorithms were discussed. Coming to analytical simulations like forward and inverse kinematics, dynamic simulation of the moments of the multibody system, etc., were performed in ADAMS and OpenSim simulation platforms. Better solutions were proposed and awaiting challenges were discussed for each aspect of the robotic exoskeleton.

## 1 Introduction

In the beginning of the computer era nobody would have thought or imagined that such advancements could occur in the history of science. Today Technology has advanced to manufacture devices which are helping people with lower body disability to stand up straight on their feet and on the other side assisting people in load carrying in the industries etc., Thanks to advancements in engineering and technology which contributed outmost for the development of robotic exoskeletons[29].

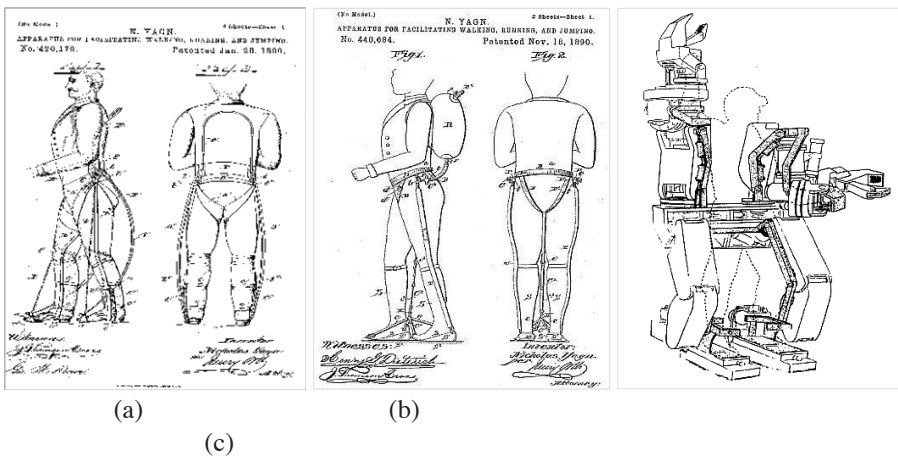
Basically, robotic exoskeleton is a wearable device which helps the wearer in different ways. The exoskeletons can be for the single limb, upper body, lower body or full body. These have very wide applications. The interest in this area of study had never decreased from the beginning of 21<sup>st</sup> century. Most precisely in the domains of medical, military, industrial and entertainment has greater scope. When designing the exoskeleton major factors like reduction of metabolic cost, weight, cost of the device, safety and comfort etc., are decisive. [30]

This work is more inclined towards medical or rehabilitation applications. Human mobility is often affected with sensory paralysis, involuntary muscle contraction, cerebral paralysis, spinal cord injury, crouch gait, stroke and post-polio syndrome etc., Stroke is an effect of the brain function due to discontinuity in blood supply to the brain. The consequence of this is paralysis of one or more limbs [19]. Cerebral palsy is very common problem with which many people suffer [1]. However, if people do not have any of the above gait disorders, mobility is even being affected by aging. To bring such people back to independent life this kind of mobility devices are must. Efficiency of the robotic exoskeleton proved its need in case hemiplegic patients' rehabilitation with convincing results [25].

Medical application exoskeletons are personalized on basis of the requirement of the patient or individual. This field has very increasing interest in research as there are different kinds of mobility disorders. For example, crouch gait; person with crouch gait has different gait pattern. For people with complete paralyzed lower limbs, they need fully automated exoskeleton. In case of hemiplegia the working limb is in closed loop with the control system and guides the paralyzed limb using exoskeleton. These are some different case scenarios among many. The complexity of the exoskeletons is challenging because of human safety.

## 2 Evolution of the exoskeletons

The earliest exoskeleton like device came into existence in 1890 by Nicholas Yagn, of Russia, designed a set of walking, jumping, and running assisted apparatus **Fig. 1(a)**. An earlier version used a giant bow spring. The final version used compressed gas bags to store the energy **Fig. 1(b)**. It is an initiative of a passive and human-powered exoskeleton. [37]



**Fig. 1.**(a), (b) Nicholas Yagn's assisted-walking device[37]; (c) Hardiman exoskeleton[38].

The early exoskeleton was co-developed by General Electric and United States military named 'Hardiman' in the mid 1960's. Although it weighed 680 kilograms, consisting 26 force reflecting servos and worked under external power source. Its ability is to lift a weight of 100kgs with the wearer's perception of 5kgs **Fig. 1(c)**. [23]

In 1986, exoskeleton called LIFESUIT was designed by Monty Reed, who suffered spine damage during his service in US Army. He could regain his mobility and returned to

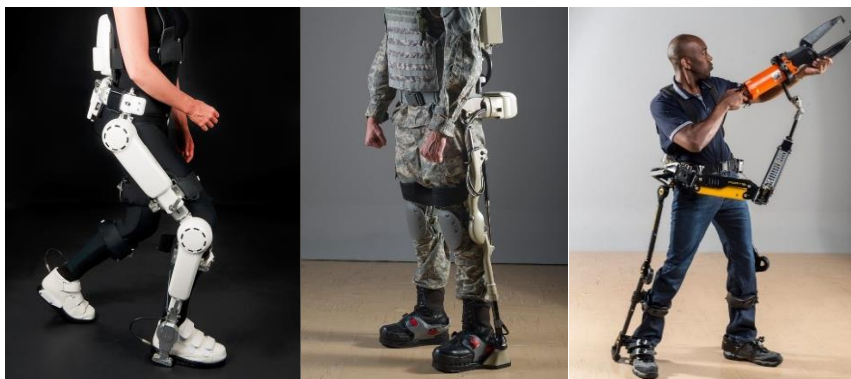
normal life with the help of LIFESUIT exoskeleton. ‘LIFESUIT 14’ has capacity to carry individuals weighing up to 92 kgs [8].

### 2.1 Body weight supported treadmill training (BWSTT)

In the second half of 1990’s BWSTT or **Driven gait orthosis (DGO)** was developed and performed under the supervision of high qualified therapists. The therapy must be performed in a systematic phase manner to reduce risk and for better results. Initial phase must be done in a manual way and with two therapists at least must assist the patient. This increased the labor cost and effort of the individuals [5].

### 2.2 State of the art

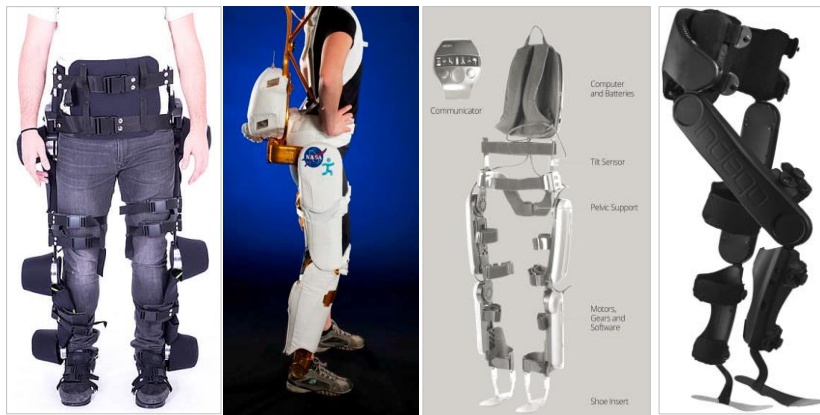
Coming to 21<sup>st</sup> century, HAL (Hybrid assistive limb) was developed (2003-2008) by Cyberdyne (Japan) played a key role in exoskeletons. It is a light weight power assistive device which is available in different versions depending on the uses of the exoskeleton as full body, lower body, and one-legged exoskeletons [2,4]. These also have different applications including heavy labor support and for rehabilitation. The lower body version of HAL weighs about 15 kilograms. Surface electromyography signals and ground reaction force sensors play their role in controlling the electric actuators of knee and hip joints[15].



**Fig. 2.** HAL, HULC, FORTIS respectively.

HULC (Human universal load carrier): Berkeley bionics (now called Ekso Bionics) licensed HULC exoskeleton for Lockheed martin which is playing an important role in exoskeleton development. It is a load carrier exoskeleton which transfers the load to the ground. It is designed for the military application. It recorded maximum speed of 11km/h in long distances. FORTIS is also a development of Lockheed martin. It is unpowered exoskeleton which is used for the industrial purpose. The weight is grounded and load is reduced on the wearer while carrying heavy loads. The load is counter balanced with a weight behind the back where in exoskeleton’s leg acts as middle support for a seesaw construction and wearer’s leg directs the exoskeleton’s leg while moving. During motion as one leg always stays in contact with the ground weight is always grounded. HANK or H2 exoskeleton was developed together with GOGO in Spain, is a rehabilitation exoskeleton which can carry a weight of 100kgs. The weight of the device is 12kgs including battery pack. It has 6 degrees of freedom (DOF)[4].

X1 exoskeleton is co-developed by NASA (National Aeronautics and Space Administration) and IHMC (Institute of Human and Machine Cognition). It is used as a mobility device and also as a supportive exercise training for the Astronauts to help in preventing muscle degradation in microgravity. It has modes for eccentric and concentric force applications which makes it unique in usage, both on the earth and in space [7]. ReWalk exoskeleton (ReWalk™; Argo Medical Technologies, Inc, Marlborough, MA, USA) has 4 degrees of freedom and it weighs around 20-25kgs. All the joint angles can be personalized according to the user and with the computer in the backpack. Device is used with crutches for more stability [2-3].



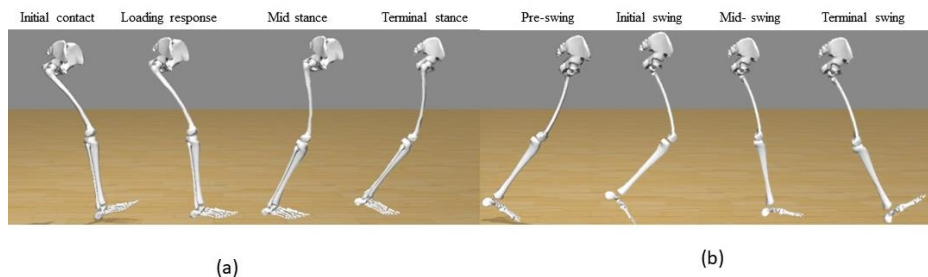
**Fig. 3.** HANK or H2, X1 exoskeleton, ReWalk and Indego respectively.

Indego powered exoskeleton (Parker Hannifin Corporation, Macedonia, OH) also has 4 degrees of freedom like ReWalk. The weight of the device is 12kgs including the battery [28].

### 3 Gait analogy

Basically, human gait is a periodic movement of the lower body segments. It is repetitive motion and to understand periodic walking course better and easier, the gait phase must be divided into different phases.

“Analysis of the human walking pattern by phases more directly identifies the functional significance of the different motions generated at the individual joints and segments. In the following figure, a normal walking gait cycle is divided into eight different gait phases, that is, initial contact, loading response, midstance, terminal stance, pre-swing, initial swing, mid-swing, and terminal swing. Detailed definitions of the gait phases are described in the following;



**Fig. 4.**Gait phases in a normal gait cycle in OpenSim.(a) Gait phases of the stance period; (b) Gait phase of the swing period.

- (1) Initial contact: This phase comprises the moment when the foot touches the floor. The joint postures presented at this time determine the limb’s loading response pattern.
- (2) Loading response: This phase is the initial double-stance period. The phase begins with initial floor contact and continues until the other foot is lifted for swing. Using the heel as a rocker, the knee is flexed for shock absorption. Ankle plantar flexion limits the heel rocker through forefoot contact with the floor.
- (3) Midstance: This phase is the first half of the single-limb support interval. In this phase, the limb advances over the stationary foot through ankle dorsiflexion (ankle rocker), while the knee and hip extend. Midstance begins when the other foot is lifted and continues until body weight is aligned over the forefoot.
- (4) Terminal stance: This phase completes the single-limb support. The stance begins with the heel rising and continues until the other foot strikes the ground, in which the heel rises and the limb advances over the forefoot rocker. Throughout this phase, body weight moves ahead of the forefoot.
- (5) Pre-swing: This final phase of stance is the second double-stance interval in the gait cycle. Pre-swing begins with the initial contact of the opposite limb and ends with the ipsilateral toe-off. The objective of this phase is to position the limb for swing.
- (6) Initial swing: This phase is approximately one-third of the swing period, beginning with a lift of the foot from the floor and ending when the swinging foot is opposite the stance foot. In this phase, the foot is lifted, and the limb is advanced by hip flexion and increased knee flexion.
- (7) Mid-swing: This phase begins as the swinging limb is opposite the stance limb and ends when the swinging limb is forward and the tibia is vertical (i.e., hip and knee flexion postures are equal). The knee is allowed to extend in response to gravity, while the ankle continues dorsiflexion to neutral.
- (8) Terminal swing: This final phase of swing begins with a vertical tibia and ends when the foot strikes the floor. Limb advancement is completed as the leg (shank) moves ahead of the thigh. In this phase, limb advancement is completed through knee extension. The hip maintains its earlier flexion and the ankle remains dorsiflexed to neutral.”[16]

In general, the human leg can be considered as a 7 DOF structure, with three rotational DOFs at the hip, one at the knee, and three at the ankle [17].The gait analysis is used in designing a human machine model in simulation software’s like OpenSim, Visual 3-D, Anybody, ADAMS (Automated Dynamic Analysis of Mechanical Systems)etc., which are widely used in medical diagnosis, rehabilitation, industries and sports etc.,

## 4 Importance of Simulation software

Computer simulations are taking a leap in every field of science, they are playing a crucial role to solve complex problems by dealing with “what if” conditions and helping in decision making. [14]. The complexity is visualized on the computer graphical user interface and important outcomes can be predicted in advance. Working with the human mobility disorders is in timiding task. All the outcomes must be very seriously analyzed. In such analogy musculoskeletal modelling simulations can help in better foreseeing the results. Especially once the raw data is collected initially from an individual, that data can be dynamically analyzed and optimized in different case scenarios with in the computer simulation platform.

Dynamic simulation of movements can alsoanalyze the treatment for different pathologicalproblems. Among the biomechanical simulation platforms like Anybody, Visual 3-D,OpenSim etc.,OpenSimallows to change the source code.This helps in personalizing experimentations according to the individual [18]. Muscle forces can be analyzed, which will be an asset in designing a Multibody machine simulation in ADAMS.OpenSim contributed in the following work in comparing and testing the results that are obtained in ADAMS.

### 4.1 Multibody simulation using ADAMS

The product outcome can be foreseen using a dynamic machine simulation. Without which there are high risks of error which are unknow till the very end. ADAMS is designed to solve complex problems. So, a human dynamic simulation model is designed for better understanding of the exoskeleton. The following model is designed to simulate the human motion with the exoskeleton for better understanding of the machine dynamics. The design is as follows:

#### Construction

Human lower limb consists of Hip, Thigh, shank, and foot as the major parts. The actual movement of lower limb during various activities is challenging to model and simulate. In this work a simplified model is presented with 1DOF and 2DOF connection of the segments at the joints. The lengths of the segments are taken as follows:

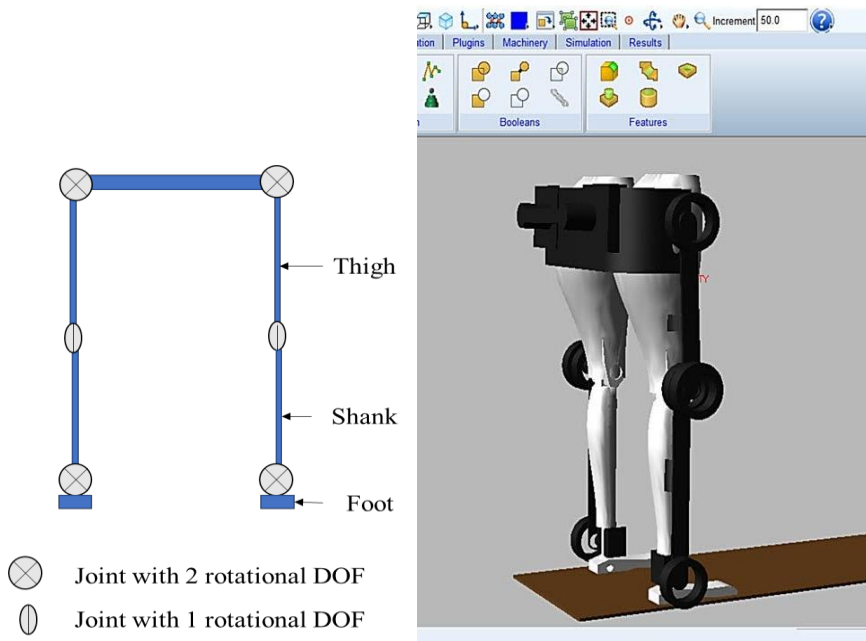
**Table 1.** Length of lower limb parts of male [20].

Sr. no	Segment	Longitudinal Length (mm)
1	thigh	520.20
2	shank	393.40
3	foot	258.48

The basic schematic of lower limb is represented in **Fig. 6**.by considering, the CAD (Computer aided design) model was created. The dimensions for cad model were given according to the data obtained from [20].

MSC ADAMS (version 2020) model was created to simulate the multibody dynamics of human motion during activity e.g. gait cycle. The main objective of the study was to visualize and correlate the behavior of system in concern with the actual human motion.

The input data for the torque exerted by joints were obtained from [9]. The hip joint has 2 rotational DOF with which thigh can rotate in XY as well YZ plane. Knee joint has only one rotational DOF. It can rotate along Z axis. Ankle joint is also having 2 rotational DOF. In ADAMS Spherical joint was used to state 2 rotational DOF. the contact between foot and road was modelled in ADAMS. The solid to solid type of contact was used. In which coulomb friction was also considered. The frictional coefficient for steady state was 0.45 and for dynamic condition it was taken as 0.2. To model the rotational stiffness of knee joint and ankle joint, torsional springs were attached between the parts. The stiffness of the torsional spring was stated according to the values obtained from literature [9]

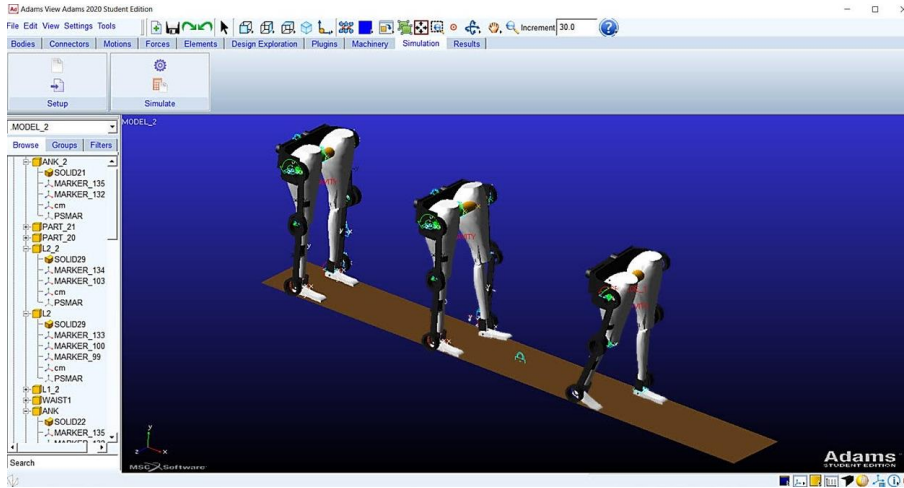


**Fig. 5.** Schematic of human lower limb (Right) and ADAMS Model of lower limb with exoskeleton design(Left).

**Table 2.** Stiffness of joints of human lower limb.

S No	Joint	Stiffness (Nm/rad)
1	hip	5770
2	knee	5770
3	ankle	5770

### Imitating human motion with multibody simulation



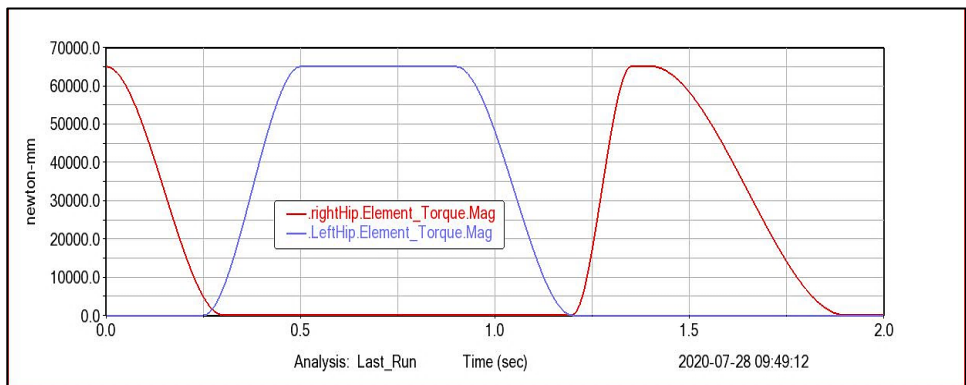
**Fig. 6.** Replicating human motion with exoskeleton using machine modelling (Level Walking Simulation in MSC. ADAMS).

After specifying all the joints and constrains, the model was given the actuations to perform activities. The model was made to perform a single gait cycle. input was given in form of torques at joints. Values of torque were obtained from literature [21].

**Table 3.** Maximum absolute torques at joint during various activities [3].

Task	Hip max.	Knee max	Ankle max.
level walking	65Nm	40Nm	125Nm
stair ascent	40Nm	90Nm	105Nm
stair descent	50Nm	105Nm	90Nm
sit-to-stand	50Nm	70Nm	45Nm

The torques on joints were applied by developing a series of step function in ADAMS function builder.



**Fig. 7.** variation of input torque vs time.

The above ADAMS multibody dynamic simulation helps in better understanding the human motion and with the exoskeleton.

## 5 Different engineering contribution for exoskeleton

### 5.1 Actuators

Hydraulic, pneumatic, electric and series elastic actuators (SEA) are majorly used actuators for the mimicking of human motion in exoskeletons. Widely used one's in the design among these are electric brushless direct current (DC) motors. Popular exoskeletons like ReWalk, HAL, HANK and Indego used Electric actuators [13]. Hydraulic actuators are used for lifting heavy loads mostly in military and industrial applications. The early exoskeleton "Hardiman" was made of hydraulic actuators. The exoskeleton weighed about 680kgs.

Although pneumatic actuation yields a good result but the output is not stable which is dependent on temperature. SEA [12] are also used in some researches like MIT active ankle-foot orthosis device[24] but couldn't take it's stand because of its limitations like safety, control etc., Electric motors are the best choice for the exoskeletons because of energy consumption, safety and accuracy.

### 5.2 Sensors

Force resistive sensors FRFs, EMG (Electromyography) sensors are often used as force sensors. FRF's serve as an input to the control system to know the phase change from stance to swing and vice versa [35]. HAL used EMG as a control input and is also a very well commercialized devise [26]. To better understand the kinematics of the exoskeleton; accelerometer and gyroscopes are used. Foot, knee and hip angular information is sensed through the kinematic sensors and serve as an input for the stride [11,16]. However, EEG (Electroencephalography) is not yet used in this field of study. This can be a game changer for quadriplegia patients. Although it is expensive but is a possible way to assist in the mobility of the patient.

### 5.3 Control

It is the brain and a major variant for every design and version of the exoskeleton. Sensory information acts as an input for the control system which directs the motion of the actuators accordingly. The devices which are existing now in the market are designed with various control systems and advanced algorithms within the system. But there is a greater scope as well for improving the control algorithm with present Artificial intelligence [36].

Initially HAL came up with smart multiple algorithms considering safety of the wearer. Hybrid control is necessary for the stability of the device. It has both voluntary and Autonomous control [22,27]. Voluntary control is unchanged and fixed control in all the times of gait to maintain the stability of the device with the wearer. Whereas autonomous control is the one which varies according to the sensory information.

Subsequently different exoskeletons also emerged with better control systems. Control systems like EMG signal control, finite State machine, impedance and proportional integral derivative (PID) controllers are used according to the existing evidences. Where in PID or Kinematic and Direct force are most commonly used control systems. [11]. Exoskeletons must be made with multiple algorithms and also with chance of modifying the joint angles, forces etc., ReWalk exoskeleton is used in rehabilitation, with inbuilt computer in the backpack and this can be personalized according to the individual's necessity [0,10]. It is approved by FDA (Food and drug Administration). Exoskeletons like HAL and ReWalk has huge demand. X1 exoskeletons has all the four control systems mentioned above and it is a multiutility device designed to assist both on earth and also in zero gravity for the astronauts to maintain the muscle mass [7]. In the upcoming devices the autonomous control like in HAL can be improved with the present developments in sensory and actuating technology.

### 6 Future projections

When the literature published in different scientific communities is taken into account this field of study has increasing demand [11]. "The global exoskeleton market size is anticipated to reach USD 4.2 billion by 2027, expanding at a CAGR (Compound annual growth rate) of 26.3% over the forecast period" [33]. Moreover, Artificial intelligence is gaining strength day by day, "the global AI market is around 260 billion USD in 2016 and it is estimated to exceed 3 trillion by 2024" [31] which gives a greater scope for better exoskeletons in the near future. Unpowered exoskeletons like FORTIS must also be taken into consideration for such will have a greater demand for industrial sector [32]. 3D printing of exoskeletons parts is becoming an effective method of manufacturing exoskeletons [34]. Engineers must better understand the biomechanics of the human beings, which makes possible for better innovations. Costs must be taken into account when designing an exoskeleton as the present exoskeleton's costs are sky high and unaffordable for common man. And for outreach, doctors, rehabilitation physicians and industrialists must be conducted with seminars for the awareness of advanced technology time to time.

### 7 Conclusion

A detailed evolution, state of the art and applications of the assistive exoskeletons were discussed. Gait analogy and ADAMS multibody dynamic simulation model were done for the better understanding and contribute to the exoskeleton development. In which

importance of the simulation environment was also discussed. An overview of the engineering contributions was discussed with suggestions. Future projections were outlined at the end.

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