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**Review Manuscript**

# A Survey in the Different Designs of Passive Exoskeletons for Lower Extremities

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## ABSTRACT

Assistance exoskeletons are among the requirements for those suffering from strokes, post-polio complications, injuries, osteoarthritis and multiple other health issues. These exoskeletons could also be beneficial for individuals who exert heavy physical activities on a regular basis. Consequently, various academic as well as commercial projects are available in the market in the field of lower limb exoskeletons. The purpose of this article is to investigate passive and quasi-passive lower limb exoskeletons with a focus on knees and categorize these exoskeletons and moreover introduce their basic structures. It is concluded that ppassive exoskeletons are among the most essential subjects of this field due to their simplicity and cost efficiency. The basis of these types of exoskeletons is grounded on energy storage while the knee is in flexion (stored energy to be released in the extension phase). Furthermore, passive exoskeleton designs endeavor to sustain/endure some of the weight force with the aim of reducing pressure on the knee joint. One of the important parameters in choosing an exoskeleton is the user's comfort when using the exoskeleton, which depends on two factors, the first is how the exoskeleton connects to the body and the second is the changes in metabolic energy consumption as a result of using this exoskeleton.

**Keywords**: Passive Exoskeletons, Lower Extremities, Quasi-passive exoskeletons, Rehabilitation

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## INTRODUCTION

Being able to walk, sit and stand up on your own feet are among the most important indicators of personal independence. The knee joint, as the largest joint in the body, plays a key role in such activities. Subsequently, this joint is exposed to various injuries in the workplace, sports and accidents due to the large forces it can withstand in addition to illnesses such as arthritis rheumatoid and osteoarthritis. Changing lifestyles and the rising elderly population are effective in increasing these injuries (1). Those suffering from these injuries will require assistance devices to compensate for their disabilities. With the advancement of technology, various gadgets and systems have been built to compensate for disability or increase people's performance. Exoskeletons are examples of such systems. They can be categorized in various aspects. In terms of their location on the body, they are divided into three main groups of exoskeletons: upper limb exoskeletons, lower limb exoskeletons and full-body exoskeletons. In regards to energy consumption, they are divided into three categories: active, quasi-passive and passive. Most of the reputable exoskeletons are of the active type (2). The purpose of this review article is to examine the advantages and disadvantages as well as compare the mechanisms and mechanical designs of passive systems related to the lower limb. On the other hand, due to the fact that the knee joint plays an essential role in daily human movements, in the present study, more focus has been placed on systems that play a supporting, strengthening or rehabilitation role on this joint.

To the best of our knowledge, even though research teams are working on exoskeletons in most research institutions, to date, no review article has been published on passive exoskeletons for knees and lower limbs. This article is organized hereinafter, as follows: In the second chapter, the research method shall be described. In the third chapter, exoskeletons are categorized and passive exoskeleton systems for the knee are classified. In the fourth chapter, the mechanisms utilized in passive and quasi-passive knee exoskeletons that have been introduced in articles or offered by companies are evaluated. Chapter 5 discusses the limitations and benefits of each of these exoskeletons and provides guidance on how to proceed. In cchapter 6, a conclusion is proffered. This article provide an up-to-date information in the field of passive exoskeletons.

## METHODOOGY

### Research Strategy

Research databases of this article are exclusively English-based articles, published between 2010-2020, inclusive of articles published in journals, conferences, as well as industrial products offered in this field. Science direct, Scopus, Google scholar and Pubmed databases were searched using the following keywords: passive knee exoskeleton, lower extremity exoskeleton, passive knee braces and passive knee orthoses. Next, the articles were selected by reviewing and assessing their titles and abstracts.

### Inclusion & Exclusion Criteria

This article’s primary focus is on passive lower limb exoskeletons, especially ppassive knee-aassistance eexoskeletons. The selected articles and products are limited to those related to passive and semi-passive lower limb exoskeletons. As a result, articles related to active exoskeletons and also clinical examinations of active exoskeletons were removed.

## RESEARCH FINDINGS

Using the keywords mentioned above, 492 articles were identified in the first stage, including 236 articles from Google scholar, 65 from Science direct, 156 from Scopus and 35 from PubMed. After reviewing the titles and abstracts of these articles and applying selection criteria, we excluded some of them, such as articles related to active exoskeletons and those related to active exoskeleton controlling systems. Large number of excluded articles were those that specialized on medical fields unrelated to mobility aiding technologies (e.g. physiology, surgery, orthopedics). Ultimately, only 32 research papers remained, which are reviewed and cited here.

**External Skeleton Classification**

In this chapter, exoskeletons are divided into general categories and thereafter multiple types of knee-related exoskeletons are introduced.

**Exoskeleton Types in Terms of Energy Source:**

A) Active B) Passive & C) Quasi-Passive

**Active Exoskeletons:** Active exoskeletons used as an external energy source to help the user move or to increase a person's abilities and endurance. The main medical (nonmilitary) usage of this exoskeleton type is to aid physically-handicapped patients and individuals with spinal cord injuries regain mobility. The main disadvantage of this type is its dependence on a large and heavy external energy source, curtailing the patient's movement range and duration of use. Another main problem with this type is its exorbitant expense due to censoring and controlling costs (3). Most of the well-known exoskeletons are the active ones (4, 5) .

**Passive Exoskeletons:** Passive exoskeletons do not require an external energy source and their energy source is limited to the energy they derive from the user. As a result, usually these exoskeletons do not include censors and control systems. From advantages of this type, the primary ones are their simplicity and affordability, making them have a larger target audience. On the other hand, the main problem with this type of product is their lack of functionality for physically-handicapped patients.

**Quasi-Passive Exoskeletons:** Quasi-passive exoskeletons are intermediates between the two types above. These exoskeletons do not provide external mobility that provides energy to the user but they have a small energy source for control systems, clutches and dampers.

**Exoskeleton Categorization in Terms of Target Organ:**

-Upper Limb Exoskeletons
-Lower Limb Exoskeletons
-Full-Body Exoskeletons

**Categorization of Knee-Assistance Exoskeletons in Terms of Application:**

-Performance Augmentation & Assistance Knee Braces
-Exoskeletons with Usage in Rehabilitation Programs
-Assistance Exoskeleton for Industrial Purposes
-Stance Control Knee-Ankle Foot Orthosis
-Prophylactic Knee Braces
-Unloader Braces
-Functional Braces

**Description of Knee Exoskeleton Mechanism:** In this chapter, the types of passive and quasi-passive exoskeleton mechanisms of the knee that have been introduced in articles or offered by companies are examined based on the above category.

**Performance Augmentation & Walking-Assistance Exoskeleton (WAE)**

These exoskeletons usually store the kinetic energy of the organs of the body in one part of a movement cycle and utilize it in another part, and by reducing the metabolism energy, they increase ability and endurance during walking and running (1, 6) .

**Exoskeleton Xped2(7)**

Van Dijk and Van Der Kooij introduced a passive exoskeleton called Xped2 to help with walking. This exoskeleton is displayed in Figure 1. The assisting strategy in this device is based on reducing the required torque in the joints with the help of elastic components. These elastic components are called Exo tendons, supplied by Van den Bogert (8, 9). These Exo tendons contain elastic cables that provide mechanical functions similar to that found in the muscles and tendons of a horse's foot. In these animals, muscles and tendons effectively store energy and transfer it to several joints. The intention of XPED2 creation was to test Exo tendons efficiency. The XPED2 skeleton utilizes a rigid frame that is parallel to the wearer's legs. The frame is attached to the pelvis and rods are provided to connect the cables. At the top of the frame is a rotating lever around the pelvis, and at the bottom of the frame a spring extends from the sole of the foot to the back of the tenon. A hinge-like joint and a pulley are used in the knee. A number of Dyneema cables (a special polyethylene with a resistance of about fifteen times of steel) have been utilized to make the Exo tendon. Exo tendons store energy and transfer it to the joints. Exo tendons start at the pelvis lever, pass over the pulley of the knee, and end at the foot leaf spring at the end of the foot. The cables are arranged in such a way that the Exo tendon is stretched during hip extension and dorsiflexion of the ankle. It is released in the opposite direction, so the cable stores elastic energy during one support and releases this energy when two supports. The auxiliary torque supplied to the joints reduces the required torque by about 12.1%. But the energy consumption (Emetabolic) when walking with Xped2 is about 27.3% higher than without this exoskeleton. The total weight of this exoskeleton is about 6.91 kg.

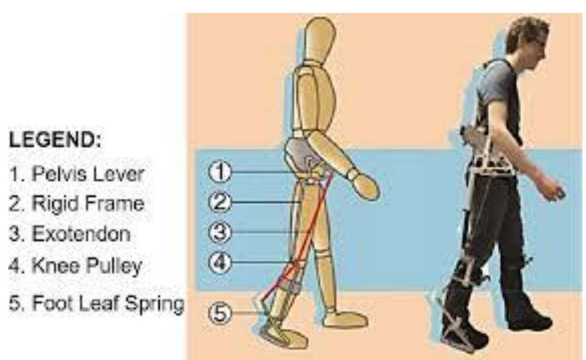



**Figure 1.** Schematic Of XPED2 Conceptual Design, Introduction Components & Skeleton Worn by User (7)

**A Passive Weight-Support Lower-Extremity-Exoskeleton with Compliant Knee-Joint (10)**
Wang and Lee built an auxiliary passive external skeleton to aid in walking, which is shown in Figure 2. The purpose of this exoskeleton is to reduce the internal load on the knee for those affected by a mild form of osteoarthritis. The assist strategy in this tool includes a compliant structure with the legs that carries a percentage of body weight. The device is placed between the user's legs and the user's weight is transferred to the skeleton by a bicycle saddle while walking. The structure of the legs are made by two adjustable links (quasi-thigh and quasi-leg). The structures are attached to the saddle of the bicycle with a joint allowing two degrees of freedom. This 2 DOF joint offers sagittal and frontal motion to the hip. Adjustable straps are fastened to the top of the user's thigh to keep the saddle in place between the user's legs. The knee unit only allows motion about the sagittal plane. A body-compatible knee made of two rings is placed on both support bases. The outer ring is attached to the thigh link and the inner ring is attached to the shank link. The design of these rings is such that these rings are rigid in one direction and can be rotated in the other direction. At the beginning of the heel contact (walking cycle), the upper link is in a state of excessive stretching and at a 5 degree angle. In this position, the two rings are aligned in the weight support position. This mode is demonstrated in Figure 2. In this situation, the skeletal structure resembles a rigid lever. A rigid spring is attached to the end of the leg connector, which transmits the force applied to the saddle to the foot plate. In pre-swing, the knee-compatible joint changes position to create proper movement with the swing phase. The user is wearing his/her shoe. In the middle of this shoe, a plate has been installed to transfer the load to the ground. The total weight of this structure is 2.36 kg and pursuant to installing a pressure sensor in the shoe, it was observed that about 27% of the body weight is carried by this exoskeleton.

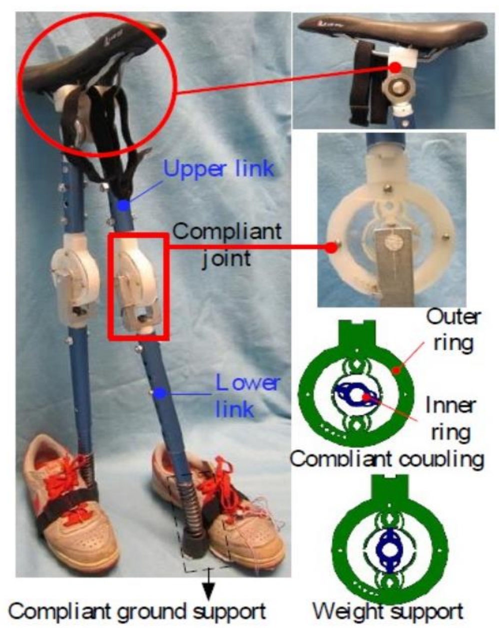



**Figure 2.** External Skeleton Supporting Body Weight, The Seat and Knee Components In Two Positions (10)

**A Walking Assistance Exoskeleton with Upward Force Assist** (11)

According to Figure 3, the design proposed by Zlatko and et al., includes a two-legged skeleton and a chair aiming to carry at least 20% of the weight of the wearer. This exoskeleton consists of nine parts. The seat consists of a seat and elastic straps. These straps pass in front of the seat frame and pass through the seat, wrapping around the two pulleys on the hips and attaching a tension spring attached to the thigh strap.

A torsional mechanical spring is selected to passively support the seat mechanism. This spring is simple and available in different ranges of stiffness. When the seat is lowered by the weight of the user, the tension of the elastic straps increases, and as a result of this increasing in tension, an upward force is produced. In the stance phase, both straps (left and right) apply equal upward force to the seat. When walking, the reaction of each belt is shifted according to which leg is in the stand position. Due to the distinctive design of the seat mechanism, it is ensured that the upward force is always vertical and has no horizontal component and the user will not be unstable due to the horizontal force. The support leg fits the combination of the four units, the Thigh Link Unit (TLU), the Knee Joint Unit (KJU), the Shank Link Unit (SLU), and the Foot Plate Unit (FPU). Each leg in support uses a locking mechanism for the knee joint unit (KJ) similar to the sckafo brace. During the stance phase, the KJU is locked to ensure that the Seat Unit (SU) and the Elastic Wire Unit (EWU) provide assistance. Via a trigger mechanism by a cable with leg circulation at the end of the stance phase, the KJU is activated by the user. In this system, there are only two places of contact and connection between the device and the user (seat & sole). Below the seat is a Rubber Stopper Unit (RSU), a key component in the final design. This piece interacts with both parts of the TLU during walking. The function of this piece is to limit the rotation of the seat frame relative to the Hip Joint Unit (HJU). Otherwise, applying weight to the seat will cause the seat frame to collapse. To test the performance, a sample of aluminum and polyethylene (HDPE) was made. After the experiment, the findings were satisfactory and it was observed that due to the stiffness of the spring and the position of walking, between 9-27% of the body weight is carried by this skeleton. The final prototype weighed 5.68 kg.

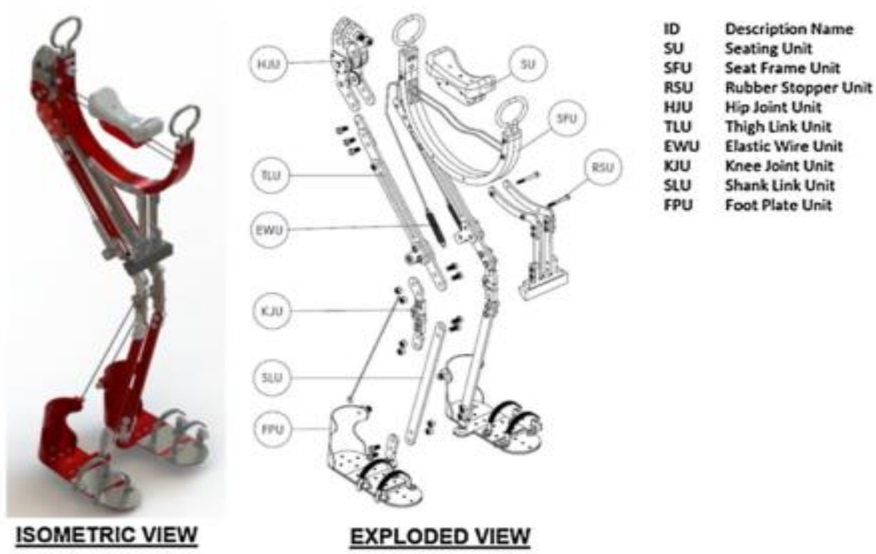



**Figure 3.** Isometric View and Explosion Map Of WAE Passive Skeleton CAD Model (11)

**Knee-Braced Energy Harvester (12)**
Langan Xie and et al., built an energy picker to extract kinetic energy for walking. This device helps the knee torque with the energy collected. The energy harvester is installed adjacent to the knee , and simulates the "Spring-Damping" mechanism using a spiral spring and a generator. This mechanism will have a function similar to the function of the hamstring muscle during walking by reducing the knee's biomechanical torque and power. Thus, the total metabolic energy utilized for walking will be reduced while generating electrical energy at the same time. A prototype was built for performance testing. The test findings indicated that by walking at a speed of 4.2 km/h while the spring stiffness was 2 newton/radians, the energy harvester could reduce the metabolic energy consumption rate by 3.6% and the average electrical energy produced in this process was 2.4 watts.

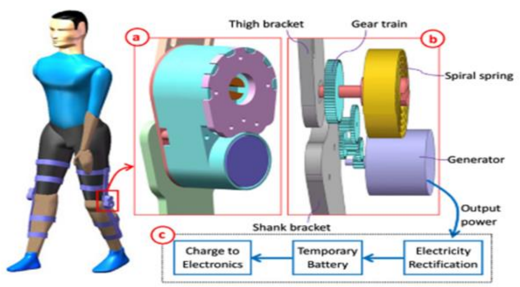



**Figure 4.** Image and CAD Model Of Harvester Energy System Made Via Rapid Prototyping Method (12)

**Spring Loaded Technology (Levitation) (13)**
The Canadian company Spring Loaded Technology Inc. has introduced a system as shown in Figure 5. In this system, the upper and lower parts are connected by a multi-center hinge. The hinge is multi-piece and a cam with a variable radius is placed between the two side pieces. On this cam, a cable rotates and due to the changes in the radius of the cam, different torques can be had at various angles. As demonstrated in Figure 5-B, the function of this cable, connected on one side to a bridge above the piston cylinders and on the other side to a pulley, is to actuate the springs and jacks. Torque can also be adjusted by turning the pulley. If you need to loosen the cable, for example when sitting on a chair while the leg is being extended, this can be done with the aid of a pulley, so that the leg does not need to apply opposite torque. In this system, inspired by the aircraft landing gear system (to absorb and store energy), springs and hydraulic jacks with compressible fluid have been utilized. The company claims that the common fluids in the market have not been optimal for proper performance and that the company has invented the appropriate fluid itself. The weight of each knee brace is about 990 grams and the total weight is about 2 kg.

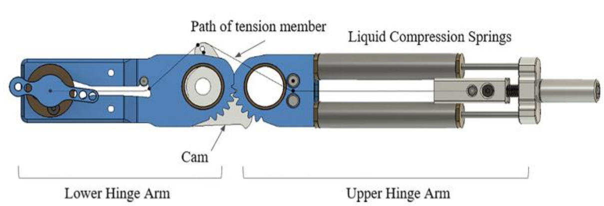




**Figure 5.** (A) Spring Loaded Knee Brace; (B) Hinge and Energy Storage Mechanism (14, 15)

**REHABILITATOR™ (GUARDIAN**) (16)

The Guardian Co. has introduced knee braces under the OA rehabilitator brand. This knee brace uses a series of balloon-like components. The mechanism of this knee brace has been patented in the United States under the numbers (7,608,051 / 7,963,933 / 8,057,414 / 8,308,669 / 8,376,947). In this knee brace, each pressure on the pump is equivalent to blowing 30 cc of air inside the balloon-like chambers, for normal activities each balloon should be about 60 cc and for heavier activities up to 90 cc. This knee brace is assisted in the oscillation phase by using elastic straps embedded in the knee brace hinge. This assistance is provided by damping the pressure on the knee during the flexion phase and helping the knee at the end of the oscillation phase and during extension, At the end of the swing phase, the hamstring muscle must work extraordinarily to control the knee tension because the straps cause the knee to expand quickly, and in the stance phase when the quadriceps muscle bears the load, it must work extraordinarily to stretch the strap. Auxiliaries overcome the extension and cause knee flexion.

Clinical trials have shown the positive benefits of this knee brace as follows:

- Reduction of knee abduction moment (KAM) up to 48%
- Increase quadriceps strength up to 54% and hamstrings up to 27%
- Significant reduction in knee pain

**Figure 6.** OA Rehabilitator (16)

The following diagram compares the auxiliary torque provided by the Guardian Volvitation knee braces. As observable, Levitation's knee brace can provide variable torque due to the utilization of a variable radius cam.

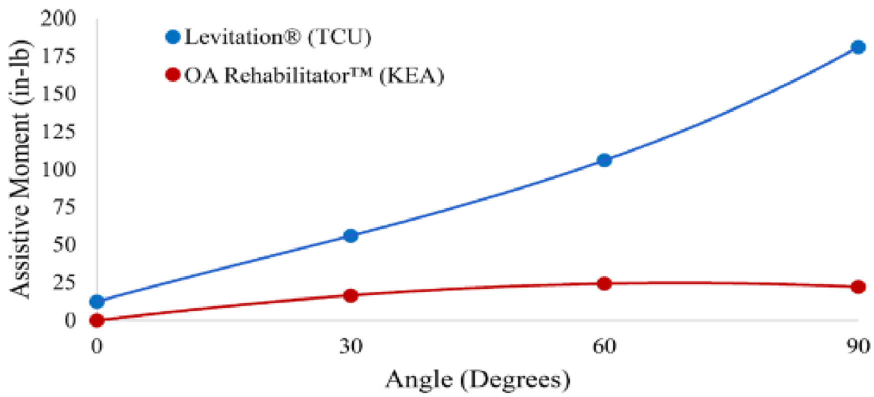



**Figure 7.** Comparison Of Guardian and Levitation Auxiliary Torque Knee Joint (13)

**Power Knee Stabilizer Pads (17)**

The system shown in Figure 8 is marketed by several companies. Simplicity and inexpensiveness are important advantages of this system. Manufacturers claim that this product is designed to help with daily tasks and reduce pain. Moreover, this knee brace decreases the possibility of knee injury in heavy movements. Each knee brace reduces the load on the knee by a maximum of about 20 kg. The function of this knee brace is similar to that of a person lifting a wearer. This knee brace is suitable for the elderly when climbing stairs, athletes as well as workers lifting heavy loads.

Advantages & disadvantages:

- Using this knee brace has no effect on the abduction moment in the braced legs.

- In the stance phase, the pressure is not reduced on the knee and only helps during the swing phase.

- Connection to the leg is via only two straps. Hence, there is no complete connection and consequently the pressure on the leg is more concentrated than for example when four knee straps are connected to the leg.
- Due to the phenomenon of spring fatigue, the life of the spring is limited, therefore, in most brands, additional and spare springs are also provided. Also, due to sweating, this knee brace is usually washed frequently, and this washing due to the constant pressure on the knee brace, makes the lifecycle of this system limited.

This system weighs approx. 800-900 grams (for a pair).

**Figure 8.** Image of Power Knee Stabilizer Pad System (17)

**Assistance Exoskeleton for Industrial Purposes**

Most exoskeletons used for helping workers in industrial areas are upper limb exoskeletons and their function is usually to reduce the burden on the spine. However, in some activities where the employee must be constantly standing or between sitting and standing, such as surgeons and assembly line workers, wear exoskeletons to reduce work pressure and protect the user from issues such as varicose veins (18). Several companies have designed and built skeletons such as the following.


**Figure 9.** Noonee AG-Designed Chairless Exoskeleton for Production Line Workers Who Toil in Poor Conditions (19)

The Chairless design provided by Noonee AG can be classified as quasi-passive exoskeletons. The Swiss startup, a subsidiary of faulhaber micromo, LLC, launched these chairs in 2016. In this design, a stepper motor opens and closes the inlet and outlet valves of the jacks. This chair was originally made of titanium and then the body material was modified to carbon fiber (19).

Another passive exoskeleton design is the Fortis Exoskeleton, which is supplied by Lockheed Martin. This exoskeleton is designed to reduce worker fatigue and increase safety and efficiency. This system transmits the weight of heavy tools directly to the ground. In this system, the gimbal mechanism has been utilized to ensure the rotation and flexibility of the tool in all directions.

**Figure 10.** Lockheed Martin-Designed Fortis Exoskeleton for Workers Using Heavy Tools (20)

**Auxiliary Exoskeletons for Rehabilitation**

Working in rehabilitation clinics can be difficult and tedious, and the patient's recovery depends on the continuation of rehabilitation operations. Therefore, wearable exoskeletons can help to reduce the work pressure on the staff of these clinics. In this regard, various passive and active exoskeletons have been constructed. It should be noted that the design of such skeletons requires sufficient information about physiology and robotics. Rehabilitation robotics is an interdisciplinary and multidisciplinary field. In fact, in addition to a thorough knowledge of robotics, research and development in robotic rehabilitation devices requires a deep understanding of the biomechanics of the human body and the human nervous and cognitive systems. In fact, rehabilitation robots that are not designed with sufficient knowledge of joint movements can disrupt the rehabilitation process or even damage human joints (21). Here are some examples of these exoskeletons.

**Moon Walker(22)**

This exoskeleton is shown in Figure 11. It is a quasi-passive exoskeleton built by Kurt & Associates. The main idea when designing the Moon Walker was to propose an exoskeleton that could apply a vertical upward force to the user's pelvis to reduce the weight of the body applied to the legs. In this exoskeleton, external energy is utilized only to control some components. This device helps users who have leg problems by carrying a part of the body weight. Moon Walker's design approach is very similar to conventional body weight bearing (BWS), turning it into a mobile device (common in rehab centers).

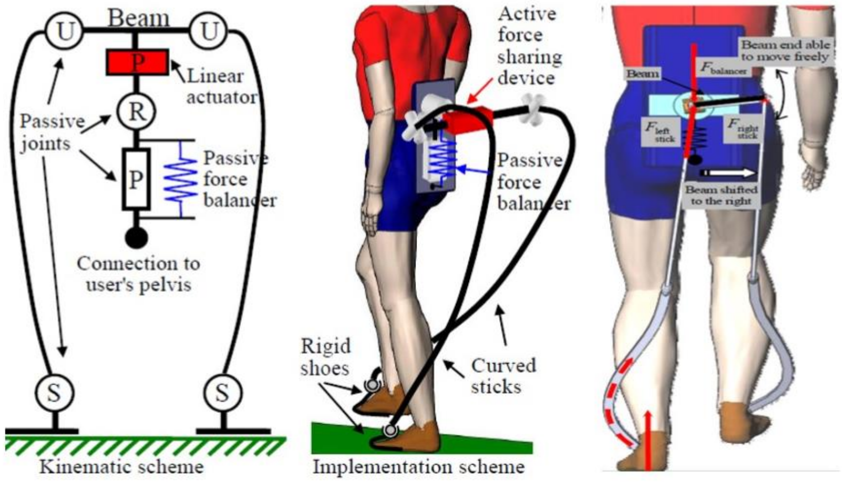



**Figure 11.** Moon Walker Schematic Image (22)

This device consists of four parts: (a) 2 foot-like structures, (b) 2 custom shoes, (c) a force balancer, (d) a force distribution mechanism. Two foot-like structures were made curved so as not to collide with the user's leg during the walking cycle. Spherical joints were used in the ankle enabling the user to have a full range of motion. The upper end of each foot-like structure is attached to a rigid beam, which is part of the force distribution mechanism. During the movement, a linear actuator moves the rigid beam towards the foot-like support. Thus, part of the ground reaction force is transmitted to the foot-like structure as a support, and this force is transmitted directly to the user's pelvis. Pressure sensors placed in special and custom shoes are used to detect the ground reaction force (GRF). An external computer reads the data sent by the sensor and controls the movement of the linear operator. A drive joint connects the force distribution mechanism and the force balancer. The force balancer is mounted on a rigid plate and fastened to the user with restraining straps to be put on. The force balancer consists of a linear slider joint and a spring. The force balancing function allows adequate vertical displacement relative to the pelvis when transmitting the upward force created in the quasi-leg structure. The prototype was built and tested to reveal an upward force of 320 Newton’s in the middle of the stance phase. During the test, it was observed that this system is noisy and unbalanced.

**Compatible Mechanical Device for Foot Rehabilitation (23)**

This system was created by Dmitry Fedorov and Lionel Birglen. The aim of this project was to correct the patient's gait with the help of a mechanical device that did not require external energy and was cost-effective/inexpensive. This system is shown in Figure 12. In this system, using a cable-based system, the weight applied to the leg is reduced. To restore normal gait to the patient, whenever movement on the sagittal plane deviates from the normal gait pattern, the device should be able to gently apply corrective forces on the patient's leg. The orthosis has two degrees of freedom (DOF), it coordinates the flexion and stretching movements of the pelvic and knee joints, and it moreover creates corrective forces when there is an abnormal movement between the pelvic and knee. The production of corrective forces is undertaken by several coordinated components and is equivalent to creating a potential energy field. The system utilized two sets of cable transmissions and pulleys connected by gears to connect the elongation of the two cables to the user according to the angular positions of the hip and knee joints. In this design, there is no need to use a sensor or an actuator. Also, lightness and cost-efficiency have been taken into account (for rehabilitation). At the same time, by minimizing the interaction forces between the system and the user, if the user follows the path predicted, it is expected that a patient's dependence on external care will decrease while his/her independence will increase.

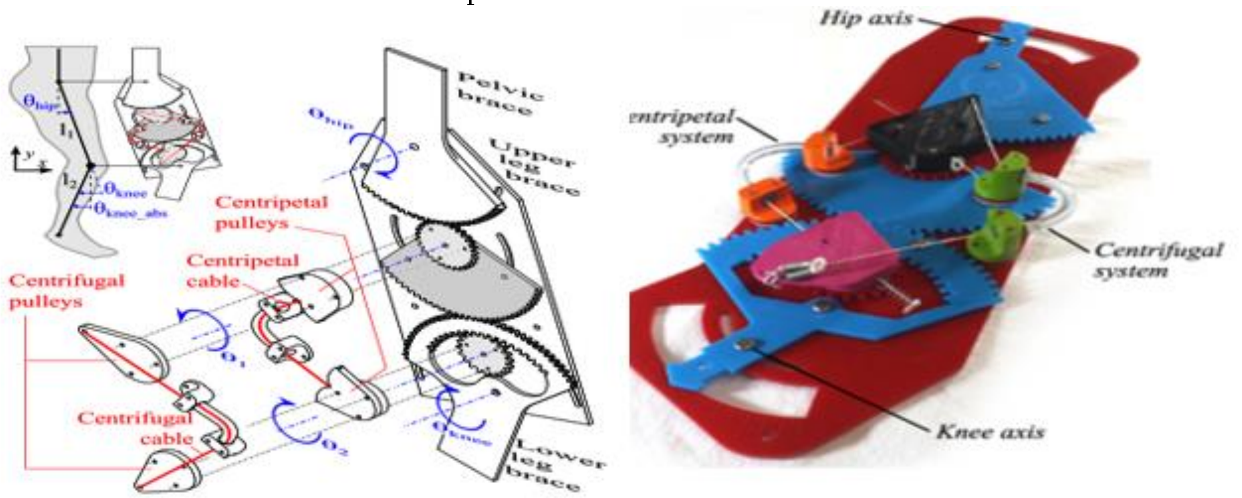



**Figure 12.** Isometric Images of Left Prototype Mechanism and Right Rapid Prototype (23)

This exoskeleton is a quasi-passive exoskeleton, invented by Roland Oberger and et al. In this system, only the control system requires electrical energy. The primary components of this exoskeleton are shown in Figure 13. The microcontroller and battery are housed in a side compartment. The joint is designed to be in maximum fit with the wearer's body. The joint in the direction of the frontal plane must be fixed, To accomplish this, the middle part of the body (medial) is utilized. This way, the joint carries a large part of the knee's load. Also, this design have been made for ankle joints as well. In this design, a custom spring is made of composite for the leg, which rotates to store energy in the stance phase (STP) and returns this energy at the beginning of the swing phase (SWP). Because significant loads are transferred between the brace and the user's leg, in addition to the anatomical suitability of the interface components, these parts need to have the necessary strength. Therefore, the interface parts displayed in Figure 4 are made of carbon fiber composites and compliant with the patient anatomy casting models. The exoskeleton leg in this system is attached to the user's body with adhesive straps.

Knee joint design: A microprocessor installed in the knee joint, which is an independent functional unit, controls and supports leg movement. The knee joint includes the hydraulic unit, sensors, battery and a control circuit. A hydraulic cylinder is used to control the movement of the knee joint and according to Figure 13-A, the hydraulic cylinder is converted into a rotational movement of the knee joint with the help of a linear motion lever. The hydraulic force is controlled by a microprocessor via a "servo valve". In this valve, there are two separate valves for two directions of movement. This induces the hydraulic to have high resistance in one direction (for example, bending the knee) and low resistance in the other direction (return of the knee to original position). The geometry of the knee joint and the lever arm is designed to transmit maximum angle-dependent torque. When walking, the maximum flexion angle is usually about 20 degrees. Hence, for a person weighing one hundred kilograms, the maximum knee torque is estimated at 120 Nm. This hydraulic system can apply up to 160 Nm (maximum).

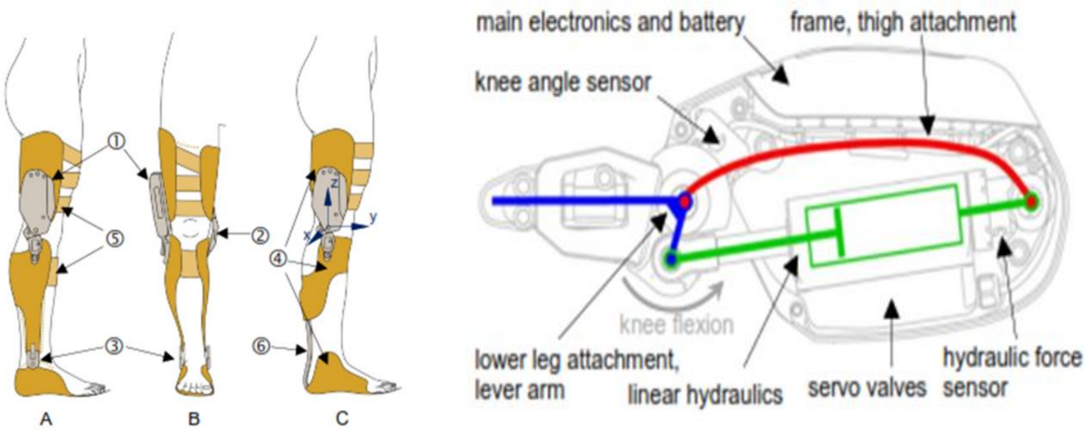


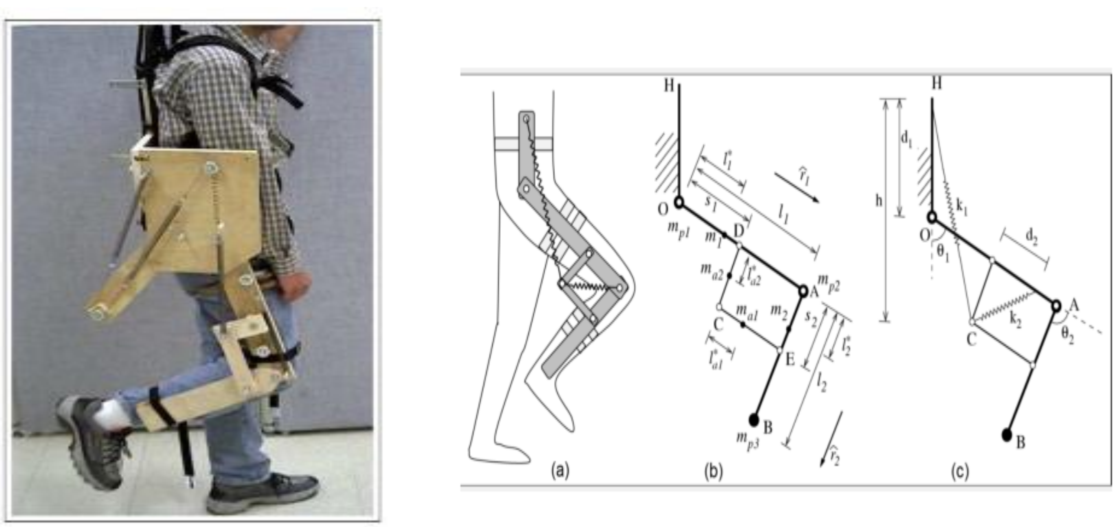

**Figure 13.** Pictures (A) and (B); Knee Joint Mechanism and Skeleton Outline (23)

### Gravity Balancing Passive Exoskeleton(24)

Agrawal and et al., at the University of Delaware have designed and built a pilot model to help rehabilitation centers. This exoskeleton is a simple and mechanical device that consists of arms, joints and springs and can be adjusted according to the geometry and inertia of the person who wears it. This skeleton is passive and does not use any motor or controller, but it can lift the weight from the joints in the leg's entire range of motion. The basic principles of gravitational balance skeleton operation are based on keeping the potential energy of the entire system constant, and for this purpose, the following two steps must be performed:

(A) To determine the mass center of the combined system of the human leg and the external skeleton.

(B) By adding springs to the exoskeleton, one between the center of mass of the entire system (frame's center of mass representing the trunk) and the other between the links (interfaces). Hence, the potential energy of the entire system is always kept constant.




(b) (a)

**Figure 14.** Image (a): Primary Components and Connection Mechanism; Image (b): Wooden Prototype (24)

**Designed Exoskeleton for Gait Rehabilitation (25)**
A virtual model of the exoskeleton, consisting of two legs connected to an upper frame and a chain transmitter for each leg was designed in the SolidWorks software and the motion was simulated in MSC.ADAMS software. The left links are 180 degrees opposite to right links.
The proposed exoskeleton mechanism is distinguished by certain new features. Compared to other rehabilitation exoskeletons, the current proposed design has only one stimulus. A rotary actuator (DC gear motor) is utilized. The motor speed is controlled with a hardware architecture based on pulse wave modulation method (PWM). This design does not require complex hardware in the command-and-control section, and it is a low cost, operational/functional and simple solution, and creates an acceptable gait (hence gait planning is not necessary).

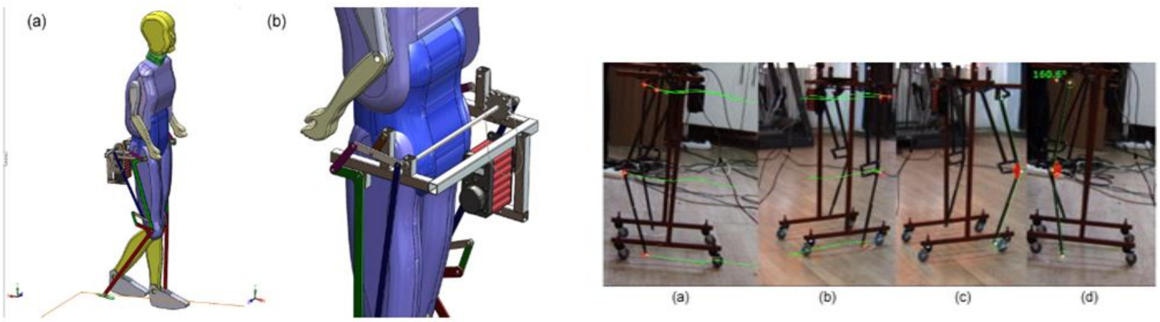
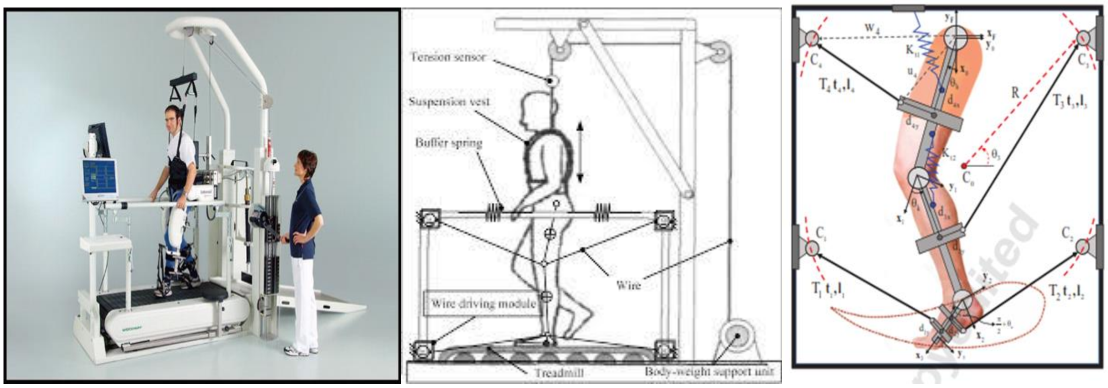



**Figure 15.** Virtual Model of Worn Skeleton and Performance Evaluation of Constructed Skeleton Prototype

In the following, the cable-based system is introduced. Even though the operator is used in this system and it’s not a passive exoskeleton, however, due to the simplicity of this system and its extensive utilization in rehab centers, its specifications are briefly described here under:

**Cable-Based Joint Rehabilitation System for Walk Training (26)**
Problems with the rehabilitation process have motivated researchers to develop walking treadmills that support body weight to provide continuous walking. Normally, while walking on a treadmill, physiotherapists should help the person maintain balance. The physical abilities and personal experience of therapists usually limit this training. One solution to this problem which has become commercialized and common, is "Driven Gait Orthosis (DGO)". This device moves the patient's legs physiologically on a moving treadmill. Cable-guided rehabilitation systems are offered in various forms by various companies. The main challenge in any project is to control the "cable robot" and be satisfied with the stress conditions, this means making sure that all cables are always in tension. Manipulation is via increasing and decreasing the length of cables connected to the end component. To estimate the cable tension, the number of extra cables can be augmented. However, this increases the interference of the cables in the workspace. Therefore, some plans have been presented to optimize the connection of these cables, including Alamdari and et al. In this design, unlike traditional cable robots, where several cables are connected to one point from several points on the ground, the cables are connected to various connections of the multibody system from several points on the ground.




(a) (b) (c)

**Figure 16. (a):** Hocoma AG's Lokomat; (b) and (c): Alamdari Proposed Cable-Based Robot Design (27)

**Anti-Gravity Treadmill (28)**

AlterG's patented Differential Air Pressure (DAP) technology was originally developed for NASA. As astronauts were spending increasing periods of time in zero-gravity environments, an unintended consequence emerged – a loss of weight and bone density. An ingenious NASA engineer sought a solution to help astronauts maintain their strength and bone density while in space by utilizing a pressurized air chamber to simulate gravitational load. Recognizing that the converse reduction of gravity's effects on people on earth could have significant benefits in a vast array of applications, the solution was reverse engineered to create the Differential Air Pressure system used in the AlterG Anti-Gravity Treadmill today.

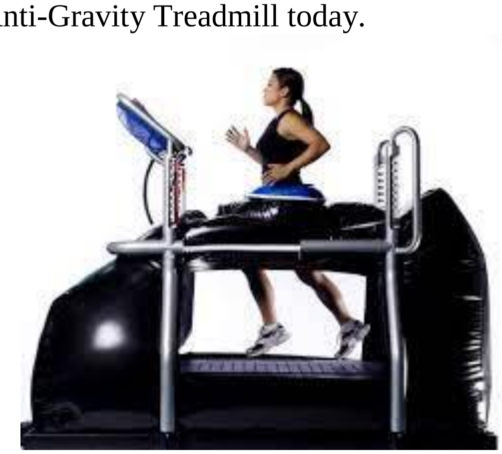


**Figure 17.** Anti-Gravity Treadmill (28)

**STANCE-CONTROL KNEE-ANKLE-FOOT ORTHOSIS (SCKAFO) (29)**

This orthosis usually helps people with knee injuries and patients with limited spinal cord injuries and allows them to walk with a cane. These braces restrict knee movement in the stance phase. When the knee cannot flex, it is difficult to climb (up and down) stairs and move on sloping surfaces. When walking with a fully extended knee, there is less balance and you are more likely to fall. Therefore, an attempt has been made to design a new orthosis that is easier to walk than KAFOs (where knees are locked). For this purpose, a new type of KAFO has appeared in the orthopedic markets, enabling the wearer to bend when moving their leg forward, while preventing the knee from bending while bearing weight in the stance phase, and allows the knee to bend in the swing phase. This new design is commonly known in the orthostatic community as localized stance control knee and ankle orthoses (SCKAFOs) (29). With the development of rapid prototyping methods and 3D printers, the additive manufacturing method is deployed to optimally adapt these braces to the wearer's body (30).

The high bending torque that the knee must carry while moving remains a challenging engineering problem. This torque is estimated at 1.04 Nm/kg body mass (at normal) and 1.67 Nm/g body mass (at fast motion) and 1.71 Nm/kg body mass (when climbing stairs) (31). The peak knee joint moment during ramp ascent is 0.64 Nm/kg for an 8.5° incline.

The knee joint or any other alternative mechanism must support this flexural torque as described above. The specifications of an ideal orthosis can be listed as follows: Being quiet, having a very fast reaction time (less than 6 milliseconds), being relatively cheap in terms of production, and if it is electromechanical, it can be used with a single charge for at least 1 day. It should also have minimal dimensions and be as light as possible. Because a typical KAFO can weigh 5 pounds (2.3 kg), an SCKAFO should be as light as a regular KAFO. This design is a difficult challenge because the components of the exoskeleton of the knee joint, highly resistant to failure and with an acceptable degree of safety, are usually not light and small [26]. Otto Bock HealthCare's Free Walk and UTX Becker both utilize ratchet/pawl. When a knee is fully extended before the heel strokes, the knee spring automatically locks the figure (17), stretching a cable attached to the toe with a dorsiflexion of about 10 degrees, and releases the lock to eliminate the bending moment in the knee. The leg should be in the extension position at the same time and the ankle should be less than ten degrees in the dorsiflexion position. Because full knee traction is required to lock the knee, the orthosis does not support the knee if it is bent when force is applied. Pressure on a bent knee usually occurs when users walk on stairs, slopes, or uneven ground. Because the separation mechanism requires 10 degrees of dorsiflexion, the device cannot be used for patients with ankle problems or biomechanical issues (limiting dorsiflexion). Similar designs include the Horton Stance Control Orthosis and the Fillauer Swing Phase Lock. The schematic of these three designs is displayed in Figure 17.

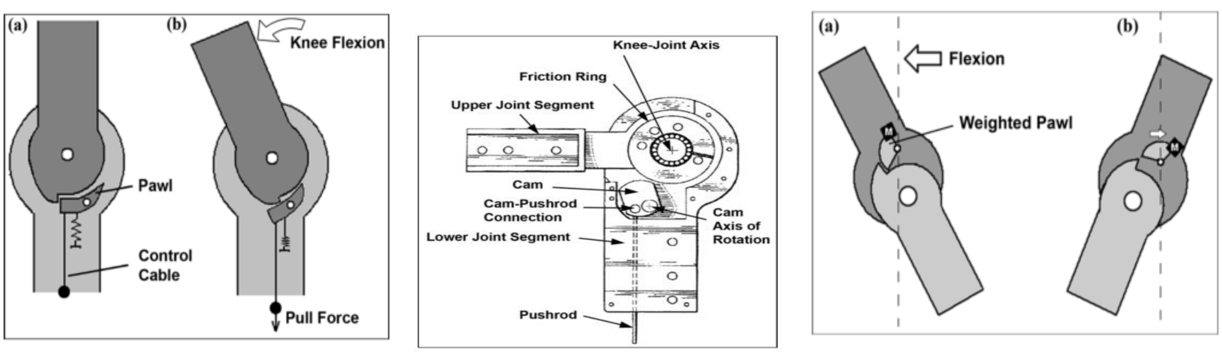



**Figure 18.** Locking System Design of Ratchet/Pawl In Spring and Weight (32)

**Prophylactic Brace**

These types of braces prevent damage to knees and ligaments. They are commonly used by athletes to preclude the cruciate ligament from rupturing.


**Figure 19.** A Prophylactic Brace (33)

**Unloader Knee Brace**

Individuals with congenital issues such as flat feet, which causes a deflection torque or KAM (Knee Abduction Moment), intensifying cartilage wear on one side. The unloader brace is worn with the objective of removing this deflection torque. This brace helps to deal with the deflection torque, reduces pain and enhances stability (while standing). In some models of this brace, a designed mechanism helps the leg return to its original (straight) position (34) .

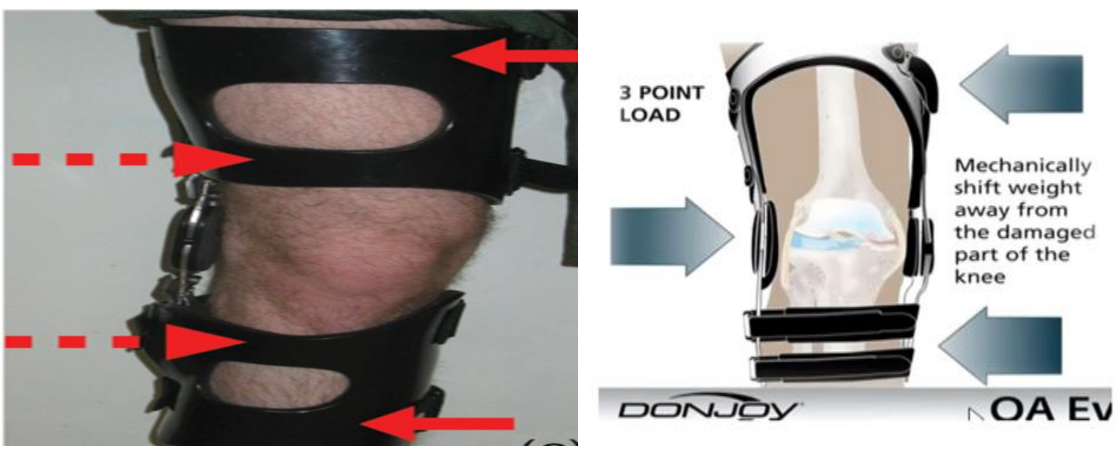



**Figure 20.** Unloader Knee Brace (33)

**Functional Knee Brace**

These braces are quite similar in appearance to Unloader knee Braces, but in addition to reducing the pressure on the knee, they control the knee’s ROM (Range Of Motion) in flexion and extension and control its stability. These braces are often utilized after an injury or knee surgery to reduce pressure on the knee and for faster recovery to the damaged part of the knee. However, their effectiveness is controversial and there is no verifiable evidence attesting to their effectiveness (35).


**Figure 21.** Functional Exoskeleton Image (36)

## DISCUSSION

The knee joint, as the largest joint in the body that must carry a high bending torque while moving and is exposed to various injuries (workplace, sports, accidents, etc.). Moreover it can withstand diseases such as arthritis, rheumatoid and osteoarthritis. A summary of the currently available and previously-mentioned knee exoskeletons is presented in Tables 1 and 2.

**Table 1.** Comparison between Various Walk Assistant Passive Knee Exoskeletons

| | Name | Producer | Energy source | Weight(Kg) | Mechanism | Reduction of load on knee | Reduction of knee torque | Metabolic energy consumption |
|---|---|---|---|---|---|---|---|---|
| 1 | Xped2 | Van Dijk, and H. Van der Kooij, | Passive | 6.91 | Exo Tendon (Dyneema) | NA | about 12.1% | 27.3% |
| 2 | A passive weight- support | Lee, K.-M. & D. Wang | Passive | 2.31 | Spring& Elastic strap | 27% | NA | NA |
| 3 | A Walking Assist Exoskeleton | Z. Lovrenovic &M.Doumit | Passive | 5.68 | Spring& Elastic strap | 20% | NA | NA |
| 4 | Knee-braced energy harvester | Xie, L., et al, | Passive | NA | Spring & Generator | NA | 4% | NA |
| 5 | Levitation | Spring Loaded Technology Inc. | Passive | 2 | Hydraulics &Spring | 22% | From 25to 180 (Ib-in) 3-20 N.M | NA |
| 6 | REHABILITATOR™ | Guardian | Passive | 1.8 | Air- Balloon | NA | About 25 (Ib-in) 3 N.M | NA |
| 7 | Power Knee Stabilizer Pads | Various company | Passive | 1 | Spring | Zero in stance phase | Average about 10 N.M | NA |

NA: Information Not Available

**Table 2.** Comparison Between Various Passive Auxiliary Exoskeletons in Rehabilitation

| | Name | Producer | Energy source | Weight(Kg) | Mechanism | Reduction of load on knee | Reduction of knee torque | Metabolic energy consumption |
|---|---|---|---|---|---|---|---|---|
| 1 | Moon walker | Kurt et al | Quasi-passive | NA | force balancer | 320 Newtons | 0 | NA |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2 | Compatible mechanical | Dmitry Fedorov and Lionel Birglen | Passive | prototype 0.36 kg | Cable-based system | NA | NA | NA |
| 3 | Intelligent passive exoskeleton | Roland Oberger et al | Quasi-passive | NA | Spring | NA | Max. 160 N.M | NA |
| 4 | A Gravity Balancing | Agrawal and colleagues | Passive | prototype | keeping the potential energy | NA | NA | NA |
| 5 | Exoskeleton for gait rehabilitation | Ionut Geonia and Daniela Tarnita | Quasi-passive | NA | DC gear motor | NA | NA | NA |
| 6 | Cable-based joint rehabilitation system for walking training | Various company | Quasi-passive | ------- | Cable-based system | Adjustable | Adjustable | NA |

NA: Information Not Available

The primary issue with research-based exoskeletons is their excess weight and inertia, causing amplification in metabolic energy consumption, hence in commercial exoskeletons, lightness and low inertia is among the design objectives. What's more, one of the important parameters that should be considered in design is ergonomics and proper coordination of the exoskeleton with the wearer (usually not taken into account in research projects) (37).

Another important factor that should be taken into consideration while designing the knee exoskeleton is how to connect this external skeleton to the wearer's body. As mentioned, one of the most important tasks of these exoskeletons is to reduce the weight applied on the knee so the exoskeleton's connection to the wearer's body must be such that the most possible portion of the person's weight is transferred to the exoskeleton. Elsewhere, Honda has also utilized this design in a commercialized active external skeleton.

Comparing the three commercial exoskeletons:

The stabilizing pads have limited lifespans and no control tools to increase or decrease the assist torque, and have little effect on a knee's small bending angle and moreover do not carry a load during the stance phase. However, due to affordability (compared to exoskeletons offered by Levitation and the Guardian), these pads are now widely used.

Even though academic designs are theoretically desirable, the efficiency and complexity of use and durability of these systems have not been thoroughly studied. Except for the Agriwal research project, the remainder of the exoskeletons and orthoses utilized for rehabilitation are active or quasi passive (due to the percentage of active disability), which is logical since patients lack control over their body.

In conclusion, it is desirable for an exoskeleton to have following characteristics:

Strengthen User's Performance: The skeleton should increase the wearer's ability, endurance, speed and etc in order to enabling them to undertake actions they previously could not.

Low Inertia: The exoskeleton should not impede the natural movement of the user.

Natural Relationship: The exoskeleton should provide a natural, visual, and transparent interface whereby users feel that the exoskeleton is a true extension of their body.

Long Service Life: The exoskeleton should have sufficient use time and in active exoskeleton the time between charging and a fast and easy charging method.

Comfort: The exoskeleton should be comfortable and safe.

**CONCLUSION:** With the ever-increasing numbers of knee disorder patients, several external skeletons for the knee have hit the market in order to rehabilitate patients and help them with their mobility and hence improve their quality of life. In addition, it is notable that the external skeletons of the knee are utilized in everyday life to enhance human performance in normal walking, carrying loads, running, and etc. In this study, as an initial step the exoskeletons were divided and then the functions of the research-based exoskeletons and commercialized ones were described. Finally, the authors discussed the limitations of knee exoskeletons plus their future research and development paths. According to the authors of this article, among the most significant parameters in assistance external skeleton utilization is their ease of use, meaning customers feel comfortable when putting on the exoskeleton. Users' sense of comfort can be attributed to two factors: first, how the exoskeleton connects to the body, and second, the amount of metabolic energy consumption as a result of its use.

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# مروری بر طراحی اسکلت های خارجی غیر فعال جهت نیم تنه پایین

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**چکیده:**

اسکلت های خارجی کمکی از جمله سامانه های ضروری جهت بهبود شرایط زندگی برای کسانی می باشد که ازعوارض بیماریهایی نظیر سکته مغزی ، فلج اطفال ، آستئوآرتریت ،سوانح و تصادفات و یا بیماری هایی نظیر اینها رنج می برند .همچنین این اسکلت‌های خارجی می‌توانند برای افرادی که فعالیت‌های بدنی سنگین را به طور منظم انجام می‌دهند نیز مفید باشد. در نتیجه پروژه های مختلف دانشگاهی و تجاری در زمینه اسکلت خارجی انجام شده است.هدف این مقاله بررسی انواع اسکلت خارجی اندام تحتانی غیرفعال و شبه فعال با تمرکز بر روی اسکلت خارجی مربوط به زانو می باشد. در این مقاله اسکلت های خارجی را دسته بندی و ساختار اصلی آنها را معرفی می کنیم. با بررسی انواع اسکلت های خارجی نتیجه گیری می شود که اسکلت خارجی غیرفعال به دلیل سادگی و مقرون به صرفه بودن از بهترین گزینه های این نوع سامانه ها می باشد. اساس کار این نوع اسکلت های خارجی ذخیره انرژی در یک فاز حرکت و آزاد کردن انرژی ذخیره شده در فاز دیگر می باشد ، هنگامی که زانو در حالت خم شدن است انرژی ذخیره شده و در فاز دیگر حرکتی این انرژی آزاد می گردد. علاوه بر این، اسکلت خارجی با هدف کاستن از فشار روی مفصل زانو ناشی از نیروی وزن و یا حمل بارهای سنگین در صدی از این نیرو را حمل می کند. و از پارامترهای مهم در انتخاب یک اسکلت خارجی احساس راحتی کاربرهنگام استفاده از اسکلت خارجی می باشد که به دو عامل بستگی دارد ، اول نحوه اتصال اسکلت خارجی به بدن و دوم تغییرات مصرف انرژی متابولیک در نتیجه استفاده از این اسکلت خارجی می باشد.

**کلمات کلیدی:** اسکلت خارجی غیر فعال ، نیم تنه پایین ، اسکلت خارجی نیمه فعال، توانبخشی