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Review

State of the Art Technologies for Exoskeleton Human Lower Extremity Rehabilitation Robots

***Sk. Khairul Hasan and Anoop Kumar Dhingra**

Department of Mechanical Engineering, University of Wisconsin Milwaukee, Milwaukee, WI 53211, USA

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Corresponding author:
S.K. Hasan
Department of Mechanical Engineering, University of Wisconsin Milwaukee, Milwaukee, WI 53211, USA
Email: skkhasan@uwm.edu

Abstract: The World Health Organization reports that about 1 billion people worldwide have some form of disability. Of these, 110-190 million people have significant difficulties in functioning. Providing rehabilitation services to a large number of disabled people with limited resources is quite challenging. Robot-based neurorehabilitation is an appealing solution for providing rehabilitation services without the downside of provider fatigue. Despite the importance of robot-based rehabilitation, a limited number of resources are readily available related to the technical challenges that need to be addressed in designing human lower extremity rehabilitation robots? This paper tries to fill up the technical gaps by explaining lower extremity anatomy, probable causes of lower extremity disability, rehabilitation protocols and fundamental safety and ergonomic features that need to be considered during the design/selection of an exoskeleton robot. A comprehensive review of the state-of-the-art sensing and actuation technologies involved in human lower extremity exoskeleton robots is also presented to familiarize the reader with current technologies. It is hoped that a comprehensive coverage of all relevant anatomical, anthropometric, actuation and sensing aspects of lower extremity exoskeleton robots will help the designer come up with the best possible solution for a specific application.

Keywords: Lower Extremity Exoskeleton Robot, Rehabilitation Protocol, Lower Extremity Anatomy, Rehabilitation Robot Sensing and Actuation System

Introduction

Physical disability is defined as a physical state that influences a person's mobility, physical capacity, endurance, or dexterity. It is a severe socio-economic problem in the world. Globally, approximately 15% of the total population is considered as physically disabled. Many people experience a temporary or permanent lower or upper limb impairment sometime in their lifetime. Exoskeleton robot-based exercises are a practical approach for neurorehabilitation. Exoskeleton robots offer an array of possibilities in human upper and lower extremity rehabilitation by providing customizable physiotherapy and evaluating performance during all stages of recovery.

In recent years, research in bio-robotics has received a lot of attention because of its effectiveness in the field of upper and lower extremity rehabilitation. Exoskeleton based physical therapy, prosthetics, artificial limbs are major applications of bio-robotics. This paper focuses on Human Lower Extremity (HLE) robotic rehabilitation which has been an area of active research during the last two decades.

A number of review papers have appeared over the last five years that address different aspects of lower extremity assistive devices. Yan *et al*. (2015) presented a comprehensive review of all HLE assistive devices developed after the 1990s. In their review, all analyzed devices were classified based on four criteria, namely, the robot control system, mechanical structure, validation with users and classification based on mechanical structures and sensory devices.

The review article by (Rupal *et al*., 2016) describes the construction and technological features of existing lower extremity exoskeleton robots and classifies them based on human power amplification and rehabilitation. The existing rehabilitation devices were further classified as commercial or prototype versions. Meng *et al*. (2015)

Science Publications

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reviewed recent developments in mechanisms and control strategies for robot-assisted lower limb rehabilitation. This work addressed comprehensively various control strategies for robot-assisted human lower limb rehabilitation. Chen *et al*. (2016) described developments in lower extremity exoskeletons, including their structure, control algorithms used, sensing technology to determine wearer's motion intention, as well as remaining challenges in this field.

The review article by (Chen *et al*., 2013) focuses on lower extremity assistive robotic exoskeletons used in rehabilitation therapy. The authors classified gait rehabilitation exoskeletons into two groups: Treadmill-based gait rehabilitation exoskeletons and exoskeletons for over ground gait training/assistance. Another comprehensive review by (Shi *et al*., 2019) summarizes the current state-of-the-art of HLE exoskeleton robots by focusing on human gait analysis, as well as actuation system design and control of the lower extremity exoskeleton robot.

Even though the review articles mentioned above summarize the state-of-the-art for HLE robots, it is seen that a majority of these articles have focused on an overall description of the robot, mechanism and control strategies, application (power assist or rehabilitation) and commercial aspects. Design considerations for these robots which are based on HLE anatomy, training methods and the state-of-the-art in sensing and actuation technologies have received limited attention in these works. To overcome these gaps in the literature, this review article addresses probable causes of HLE disability, rehabilitation protocol, lower extremity anatomy and basic safety and ergonomic design requirements that need to be considered during design/selection of an exoskeleton robot. A comprehensive review of the state-of-the-art sensing and actuation technologies is also presented to familiarize the readers with current technologies.

This paper is divided into nine sections. Section two discusses human lower extremity anatomy. An understanding of the lower extremity anatomy is important in understanding the causes of lower extremity disabilities and to design a suitable lower extremity assistive device. Section three describes the probable causes of human lower extremity disabilities. Fundamental safety and ergonomic features requirements for rehabilitation robots are discussed in section four. Section five describes the robot-assisted training methods, including active, passive, active assist and active resist forms of physiotherapy. Section six presents a review of existing exoskeleton robots. It includes a classification of existing 25 exoskeleton robots based on robot's Degrees of Freedom (DoF), actuator type, mechanical power transmission, feedback sensing method and control algorithm used. Sections seven and eight deal with actuators, drive systems and mechanical power transmission systems respectively. Lastly, section nine describes the intention sensing system that helps the user interact with the robot.

Human Lower Extremity Anatomy

Knowledge of HLE anatomy is essential to understanding the causes of lower extremity disability, developing a suitable rehabilitation protocol and designing an exoskeleton robot for HLE rehabilitation. Extracting features from the HLE anatomy serves as a starting point for an ergonomic exoskeleton rehabilitation robot. For designing, developing and performance evaluation of a HLE exoskeleton robot, the following information is needed: The structure of bones and joints, nervous system, muscle map for HLE, degrees of freedom, ranges of motion and anthropometric parameters. These aspects are discussed briefly in the next couple of subsections.

Bones and Joints

The HLE consists of three major segments: Thigh, shank and foot. Figure 1 shows the major bones and joints present in the HLE. The thigh connects with the vertebra (pelvis bone) through the hip joint, the shank connects with the thigh at the knee joint and the foot is attached to the shank at the ankle joint. The femur, the longest and heaviest bone in the human body, is located in the thigh segment. The shank consists of two parallel bones, the tibia and the fibula. Tibia is located on the medial side and fibula is located on the lateral side of the body. The foot consists of a total of 26 bones. The two significant bones in the foot are the talus and calcaneus. Tibia and fibula connect with the talus. Calcaneus is the largest bone in the foot joint and produces cushioned action during human movement. Figure 2 shows the ankle joint and bones in the foot.

Nervous System

The human body's nervous system is similar to the electrical wiring in a robot. It is a collection of different types of nerves that are made of neurons. There are two types of neurons: Sensory neurons and motor neurons. The role of the nervous system is to communicate between the Central Nervous System (CNS) and different parts of the body. Typically, it takes a fraction of a millisecond to transfer signals between two points. The complete nervous system divided into two parts, the CNS and the Peripheral Nervous System (PNS). Figure 3 shows the central and peripheral nervous systems of the body. The brain, spinal cord and retina of the eye together comprise the central nervous system, which works as the main controller of the body. The PNS communicates between the CNS and different parts of the body. The sensory nerves carry stimuli signals from different receptors of sensory organs to the brain, whereas the motor nerves carry activation signals from the brain to various muscles and glands.

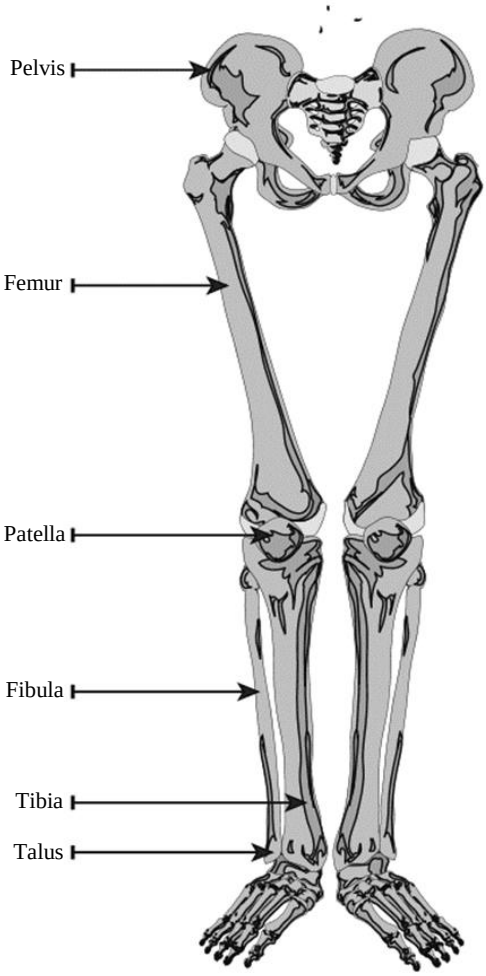


Fig. 1: Human lower extremity bones

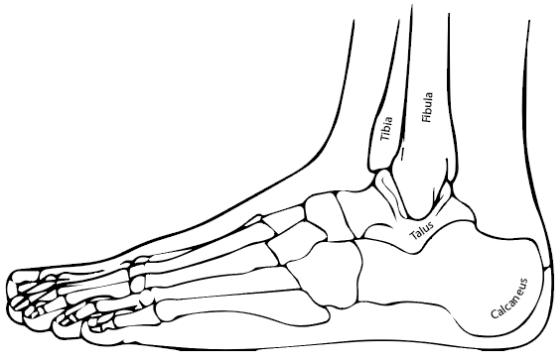


Fig. 2: Bones of the ankle joint and foot

Patients with nerve impairment may suffer from epilepsy, multiple sclerosis, amyotrophic lateral sclerosis, Huntington's disease, Alzheimer's disease, etc. The nervous system may also be affected by vascular disorders. Nervous system disorders may lead to upper or lower extremity disabilities.

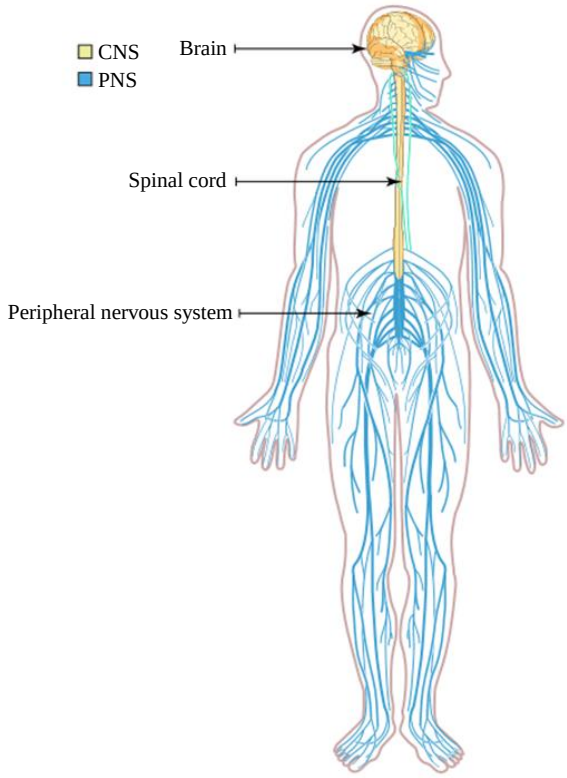


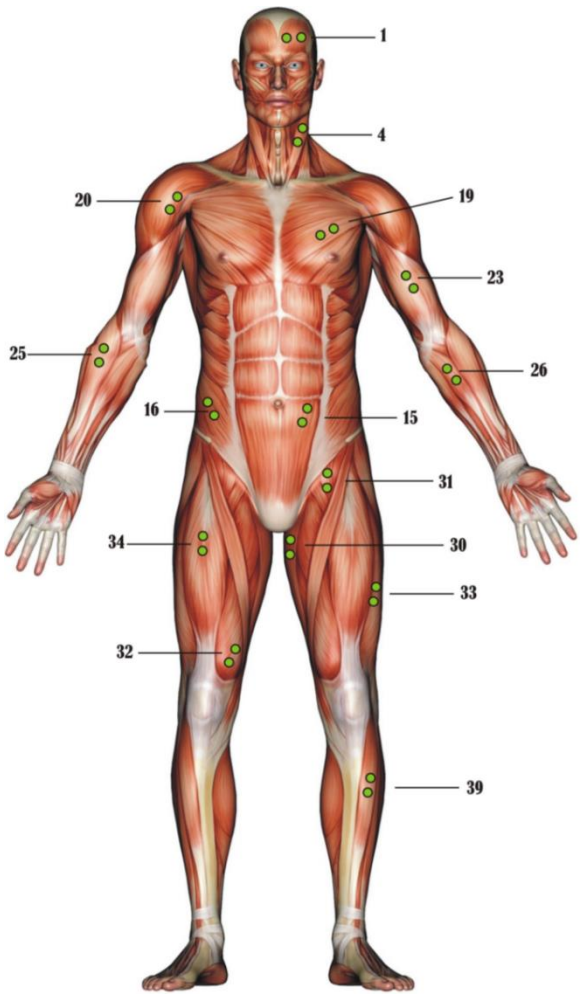
Fig. 3: Human body central and peripheral nervous system

Muscles

The muscles act similar to linear actuators and are made of soft tissue. The muscle cells consist of two protein filaments, actin and myosin, which can slide with respect to each other. The sliding of actin and myosin layers produces contraction that changes both the length and shape of the cell. Muscles produce forces and motion and are responsible for posture, locomotion and the movements of the internal organs. There are three types of muscles: Skeletal muscles, smooth muscles and cardiac muscles.

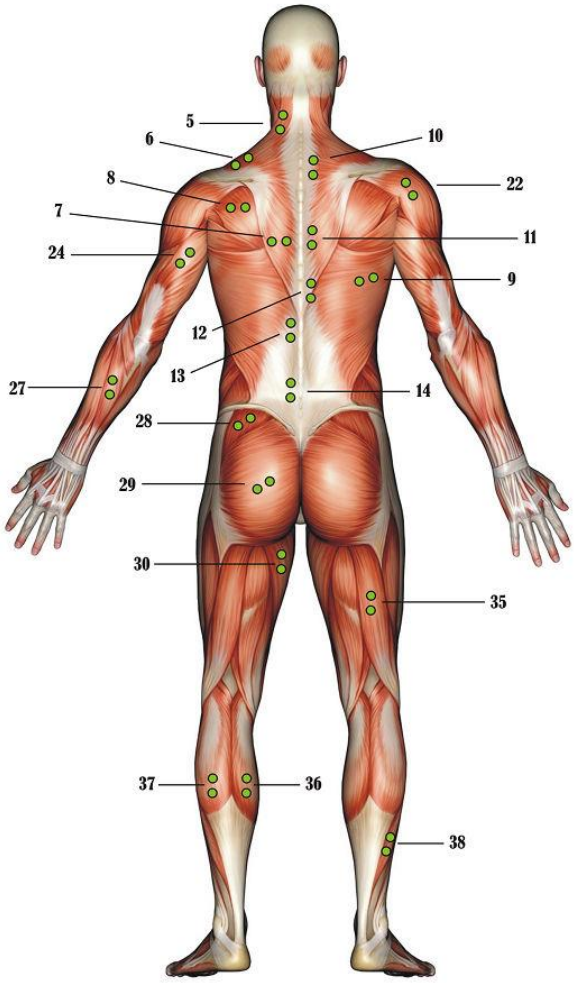
A skeletal muscle, also known as voluntary muscle, is attached to the bone by tendons and works for skeletal movements. Although postural control is often done by unconscious reflex, skeletal muscles are responsible for conscious control. Muscles receive actuation command from the brain via the motor neurons. To diagnose a lower extremity movement disorder, knowledge of muscle location and their contribution to different movements is needed. A list of all skeletal muscles involved in HLE movements is given in Fig. 4 to 6. Table 1 presents the human lower extremity DOF and their corresponding muscles. For examining the muscle's health, its activation level and the function of the corresponding nerves, muscle tone is measured using surface electromyography. For

proper placement of surface electromyography electrodes, the muscles need to be identified at their exact locations. Muscle activation levels can be used for triggering an active type of physical therapy.



#	Muscle name
1.	Frontalis
2.	Temporalis
3.	Masseter
4.	Sternocleidomastoid (SCM)
5.	C4 Cervical Paraspinals (CP)
6.	Upper Trapezius
7.	Lower Trapezius
8.	Infraspinatus
9.	Latissimus Dorsi
10.	T2 Paraspinals
11.	T8 Paraspinals
12.	T10 Paraspinals
13.	L1 Paraspinals
14.	L5 Paraspinals
15.	Rectus Abdominal
16.	Abdominal Oblique
17.	Internal Oblique
18.	Serratus Anterior
19.	Pectoralis Major
20.	Anterior Deltoid
21.	Lateral Deltoid
22.	Posterior Deltoid
23.	Biceps Brachii
24.	Triceps Branchii
25.	Brachioradialis
26.	Wrist Flexor
27.	Wrist Extensor
28.	Gluteus Medius
29.	Gluteus Maximus
30.	Hip Adductor
31.	Hip Flexor
32.	Vastus Medialis Oblique (VMO)
33.	Vastus Lateralis (VL)
34.	Quadriceps Femoris
35.	Medial Hamstring
36.	Medial Gastrocnemius
37.	Lateral Gastrocnemius
38.	Soleus
39.	Tibialis Anterior

Fig. 4: Frontal view of the human muscular system (Florimond, 2008)



#	Muscle name
1.	Frontalis
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4.	Sternocleidomastoid (SCM)
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9.	Latissimus Dorsi
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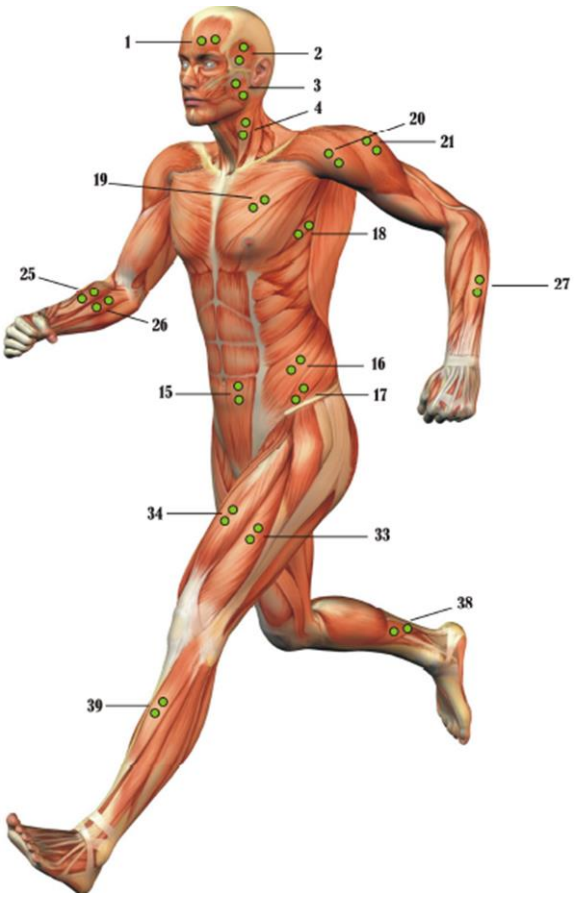
11.	T8 Paraspinals
12.	T10 Paraspinals
13.	L1 Paraspinals
14.	L5 Paraspinals
15.	Rectus Abdominal
16.	Abdominal Oblique
17.	Internal Oblique
18.	Serratus Anterior
19.	Pectoralis Major
20.	Anterior Deltoid
21.	Lateral Deltoid
22.	Posterior Deltoid
23.	Biceps Brachii
24.	Triceps Branchii
25.	Brachioradialis
26.	Wrist Flexor
27.	Wrist Extensor
28.	Gluteus Medius
29.	Gluteus Maximus
30.	Hip Adductor
31.	Hip Flexor
32.	Vastus Medialis Oblique (VMO)
33.	Vastus Lateralis (VL)
34.	Quadriceps Femoris
35.	Medial Hamstring
36.	Medial Gastrocnemius
37.	Lateral Gastrocnemius
38.	Soleus
39.	Tibialis Anterior

Fig. 5: Rear view of the human muscular system (Florimond, 2008)



#	Muscle name
1.	Frontalis
2.	Temporalis
3.	Masseter
4.	Sternocleidomastoid (SCM)
5.	C4 Cervical Paraspinals (CP)
6.	Upper Trapezius
7.	Lower Trapezius
8.	Infraspinatus
9.	Latissimus Dorsi
10.	T2 Paraspinals
11.	T8 Paraspinals
12.	T10 Paraspinals
13.	L1 Paraspinals
14.	L5 Paraspinals
15.	Rectus Abdominal
16.	Abdominal Oblique
17.	Internal Oblique
18.	Serratus Anterior
19.	Pectoralis Major
20.	Anterior Deltoid
21.	Lateral Deltoid
22.	Posterior Deltoid
23.	Biceps Brachii
24.	Triceps Branchii
25.	Brachioradialis
26.	Wrist Flexor
27.	Wrist Extensor
28.	Gluteus Medius
29.	Gluteus Maximus
30.	Hip Adductor
31.	Hip Flexor
32.	Vastus Medialis Oblique (VMO)
33.	Vastus Lateralis (VL)
34.	Quadriceps Femoris
35.	Medial Hamstring
36.	Medial Gastrocnemius
37.	Lateral Gastrocnemius
38.	Soleus
39.	Tibialis Anterior

Fig. 6: Lateral view of the human muscular system (Florimond, 2008)

Table 1: List of human lower extremity DoF and their corresponding muscles (Florimond, 2008)

Movement	Hip flexion	Hip extension
Muscles Involved	Adductor brevis, Adductor longus, Iliacus, Pectineus, Psoas major, Rectus femoris, Sartorius, Tensor Fascia latae	Adductor magnus, Biceps femoris, Gluteus maximus, Semimem branosus, Semitendinosus
Movement	Hip Abduction	Hip Adduction
Muscles Involved	Gemellus inferior, Gemellus superior, Gluteus maximus, Gluteus medius, Gluteus minimus, Piriformis, Tensor fascia latae	Adductor brevis, Adductor longus, Adductor magnus, Biceps femoris, Gluteus maximus, Gracilis, Pectineus, Psoas major
Movement	Hip Medial Rotation	Hip Lateral Rotation
Muscles Involved	Gluteus medius, Gluteus minimus, Tensor fascia latae	Adductor brevis, Adductor longus, Adductor magnus, Biceps femoris, Gemellus inferior, Gemellus superior, Gluteus maximus, Gluteus medius, Obturator externus, Obturator internus, Piriformis Quadratus femoris, Sartorius
Movement	Knee Flexion	Keen Extension
Muscles Involved	Biceps femoris, Gastrocnemius Gracilis, Popliteus, Sartorius, Semimembranosus, Semitendinorus	Rectus femoris, Tensor Fascia latae, Vastus intermedius, Vastus lateralis, Vastus medialis
Movement	Shank Medial Rotation	Shank Lateral Rotation
Muscles Involved	Gracilis, Popliteus, Sartorius, Semimembranosus, Semitendinorus	Biceps femoris
Movement	Ankle Dorsiflexion	Ankle Plantarflexion
Muscles Involved	Extensor digitorum longus, Extensor hallucis longus, Peroneus tertius, Tibialis anterior	Flexor digitorium longus, Flexor hallucis longus, Gastrocnemius, Peroneus brevis, Peroneus longus, Plantaris, Soleus, Tibialis posterior
Movement	Ankle Eversion/Supination	Ankle Inversion/Pronation
Muscles Involved	Extensor digitorum longus, Peroneus brevis, Peroneus longus, Peroneus tertius	Flexor digitorum longus, Tibialis anterior, Tibialis posterior

A smooth muscle, also known as an involuntary muscle, forms the walls of the organs such as the stomach, intestine, bronchi, uterus, bladder, blood vessels, etc. Smooth muscles are not under conscious control. Finally, the cardiac muscle is an "involuntary muscle," structurally similar to the skeletal muscle and is found only in the heart.

Human Lower Extremity Degrees of Freedom

The HLE has a total of 7 DoF. The femur attaches to the pelvis through a ball socket joint (Fig. 7) that allows it to rotate along 3 individual axes which allow for:

1. Hip abduction adduction
2. Hip flexion-extension
3. Hip internal and external rotation

At the knee joint, the femur connects with the tibia and fibula via an elliptical-shaped end called femoral condyle. Russell *et al*. (2018) presented the shape and size of the femoral condyle with its instantaneous center of rotation. As the connection surface has an elliptical shape, it allows for rotational as well as linear displacement at the knee joint. The leg length increases during flexion and decreases during extension (Hasan and Dhingra, 2020). Figure 8 shows all seven DoF of the HLE.

The knee joint provides 3 DOFs:

1. Knee flexion and extension
2. Knee linear displacement (passive DoF due to elliptical condyle end)
3. Shank internal and external rotation

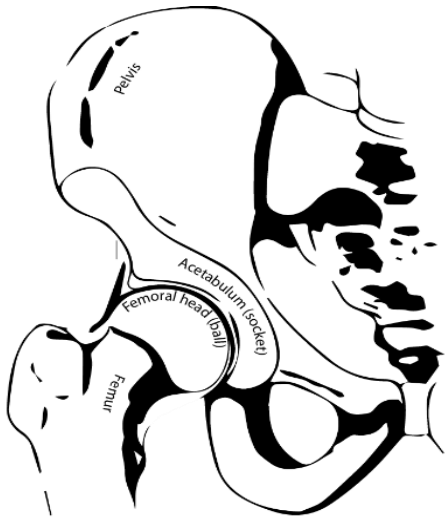


Fig. 7: Hip ball socket joint

The tibia and fibula are attached to the talus at their lower ends that provide 2 DOF. The allowed motions are:

1. Ankle flexion-extension
2. Ankle pronation and supination

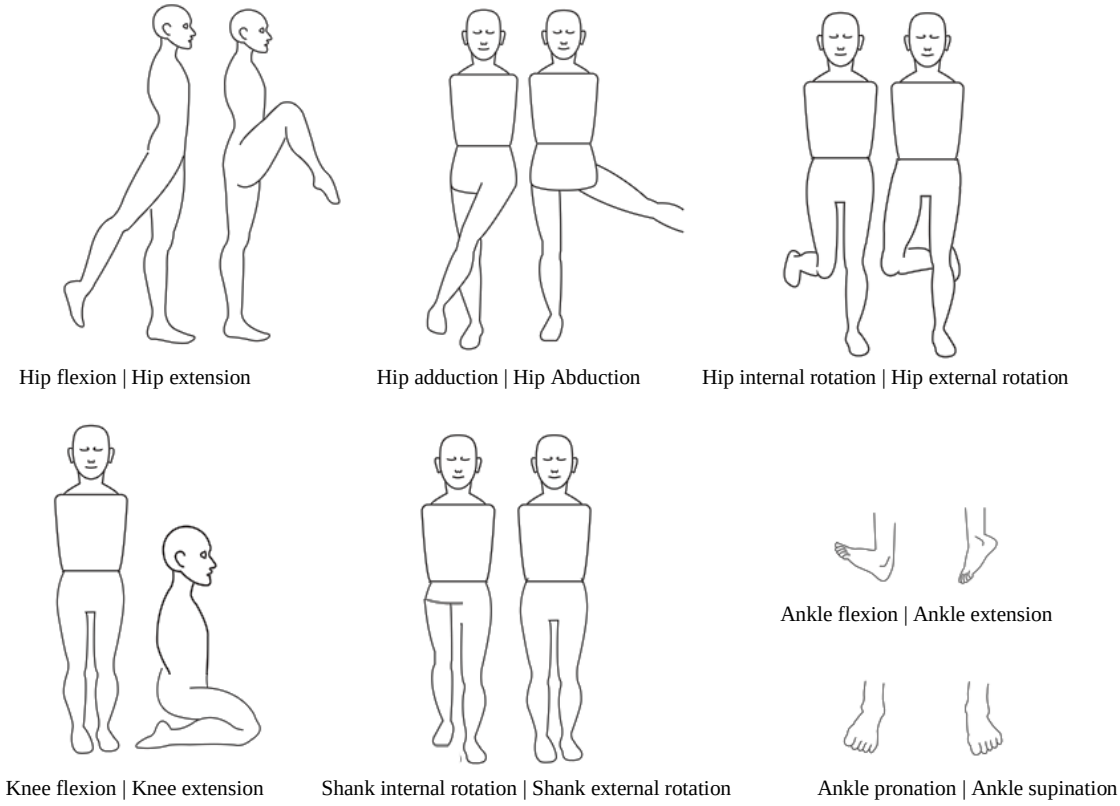


Fig. 8: Human Lower extremities degrees of freedom

Table 2: Human lower extremity ranges of motion

Joint	Movement	American Academy of Orthopedic Surgeons (1965)	Kendall *et al*. (2005)	American Medical Association	Kurz (2015)
Hip	Flexion	0-120°	0-125°	0-100°	0-130°
	Extension	0-30°	0-10°	0-30°	0-30°
	Abduction	0-45°	0-45°	0-40°	0-50°
	Adduction	0-30°	0-10°	0-20°	0-30°
	Internal Rotation	0-45°	0-45°	0-40°	0-40°
	External Rotation	0-45°	0-45°	0-50°	0-45°
Knee	Flexion	0-135°	0-140°	0-150°	0-130°
	Extension	-	-	-	0-15°
	Internal Rotation	-	-	-	0-10°
	External Rotation	-	-	-	0°
Ankle	Dorsiflexion	0-20°	0-20°	0-20°	0-20°
	Plantar flexion	0-50°	0-45°	0-40°	0-45°
	Inversion/Pronation	0-35°	0-35°	0-30°	0-30°
	Eversion/Supination	0-15°	0-20°	0-20°	0-20°

Range of Motion

Maintaining a proper Range of Motion (RoM) is essential for the exoskeleton robot. Most healthy people have a similar range of motion. In the case of physical therapy, the RoM varies with the patient's health condition. A failure to meet this criterion may result in serious adverse consequences. The reported HLE ranges of motion from various sources are given in Table 2.

Anthropometric Parameters

Anthropometrical properties play an essential role in the development of human lower extremity kinematic and dynamic models. Nikolova and Toshev (2008) reported the anthropometrical properties based on the data collected from 5290 individuals (2435 males and 2855 females).

Some empirical equations are also available in the literature to determine lower extremity anthropometrical

parameters based on the weight and height of the subject (Contini, 1972). Equation (1)-(21) are a set of empirical equations that can be used for calculating human lower extremity anthropometrical parameters based on the subject's weight and height:

$$B_d = 0.6905 + 0.0297C\frac{lb}{ft^3}, where C = HW^{-\frac{1}{3}}, \quad (1)$$

In Equation (1) B_d is the body density (lbs/ft^3), H is the height of the subject (*inch*), W is the body weight of the subject (*lbs*). The thigh, shank and foot densities are determined as follows,

$$T_d = 1.035 + 0.814 * B_d \frac{lb}{ft^3} \quad (2)$$

$$S_d = 1.065 + B_d \frac{lb}{ft^3} \quad (3)$$

$$F_d = 1.071 + B_d \frac{lb}{ft^3} \quad (4)$$

In Equation (2)-(4), T_d is the thigh density, S_d is the shank density and F_d is the foot density.

The whole body volume (B_v) is calculated using the body weight and body density

$$B_v = \frac{W}{B_d} ft^3 \quad (5)$$

The volumes of thigh, shank and foot were calculated as follows:

$$T_v = 0.0922 * B_v ft^3 \quad (6)$$

$$S_v = 0.0464 * B_v ft^3 \quad (7)$$

$$F_v = 0.0124 * B_v ft^3 \quad (8)$$

Approximate weights of the thigh, shank and foot were calculated as given in Equation (9)-(11):

$$T_m = T_v * T_d lbs \quad (9)$$

$$S_m = S_v * S_d lbs \quad (10)$$

$$F_m = F_v * F_d lbs \quad (11)$$

The length of the thigh (T_l), shank (S_l), foot (F_l) and ankle to lower face of the foot (A_g) were calculated as shown in Equation (12)-(15):

$$T_l = 0.245 * H \ inch, \quad (12)$$

$$S_l = 0.285 * H \ inch, \quad (13)$$

$$F_l = 0.152 * H \ inch, \quad (14)$$

$$A_g = 0.043 * H \ inch \quad (15)$$

The locations of the center of the mass from the proximal joint for the thigh (T_{cm}), shank (S_{cm}), foot (F_{cm}) are given by Equation (16)-(18):

$$T_{cm} = 0.41 * T_l \ inch, \quad (16)$$

$$S_{cm} = 0.393 * S_l \ inch, \quad (17)$$

$$F_{cm} = 0.445 * F_l \ inch \quad (18)$$

The empirical equations for the inertial properties of the thigh T_i, shank S_i and foot F_i are given in Equation (19)-(21):

$$T_i = \begin{bmatrix} T_m\left(0.124 * T_l\right)^2 & 0 & 0 \\ 0 & T_m\left(0.267 * T_l\right)^2 & 0 \\ 0 & 0 & T_m\left(0.267 * T_l\right)^2 \end{bmatrix} \quad (19)$$

$$S_i = \begin{bmatrix} S_m\left(0.281 * S_l\right)^2 & 0 & 0 \\ 0 & S_m\left(0.114 * S_l\right)^2 & 0 \\ 0 & 0 & S_m\left(0.275 * S_l\right)^2 \end{bmatrix} \quad (20)$$

$$F_i = \begin{bmatrix} F_m\left(0.124 * F_l\right)^2 & 0 & 0 \\ 0 & F_m\left(0.245 * F_l\right)^2 & 0 \\ 0 & 0 & F_m\left(0.257 * F_l\right)^2 \end{bmatrix} \quad (21)$$

Probable Causes of Physical Disability

The reasons behind physical disability can be classified into two categories: Hereditary/congenital or acquired. Congenital disability occurs before or during birth whereas acquired disability may appear at any moment during the lifetime. Congenital forms of disability are hard to overcome using physical therapy.

There are multiple causes for the acquired type of physical disability. Any kind of injury/damage in the nervous system may lead to acquired physical disability. These injuries may include injuries in the central nervous system (brain, spinal cord) or the peripheral nervous system. The primary causes that damage the central nervous system include accidental brain injuries, strokes, trauma, infections, insufficient oxygen supply to the brain cells, etc.

Stroke is a common cause of neurological injuries which often paralyzes one or more limbs of the body.

Physical therapy is the only treatment for post-stroke recovery (Gibson, 1990). Epilepsy, an abnormal electrical activity of the brain, causes short term or long-term physical disability (Brodie *et al*., 2012). Cerebral palsy is due to brain cell damage or malformation, which affects a person's movements and leads to physical disability. Cerebral palsy occurs during birth (due to obstructive labor), but the symptoms appear during early childhood (Harstad and Albers-Prock, 2011). Multiple sclerosis is an unpredictable disorder of the central nervous system, which freezes communication between the central nervous system and the peripheral nervous system (Waksman, 2020). Muscular dystrophy weakens the muscles; as a result, physical disability appears (Bushby and Marini-Bettolo, 2020).

Any type of fall that causes injuries to the central nervous system or peripheral nervous system also leads to long or short-term physical disability. Fall also causes fracture of the bones and often requires surgery; after surgery, the patient needs physical therapy to improve mobility disorders. Thus, any type of injury that disrupts communication between the CNS and PNS causes disability.

Requirements for Exoskeleton Rehabilitation Robot

Specific safety standards should be maintained for HLE exoskeleton robots to protect the user from any dangers. By following ergonomic design rules, both the user's comfort and the physiotherapy performance can be improved. The next two subsections briefly explain the desirable safety and ergonomic design features that need to be considered while designing an exoskeleton robot.

Safety

Safety is the most critical requirement for an exoskeleton or wearable robot. Exoskeleton robot interacts very closely with the human body. Any runtime failure in mechanical, electrical and electronics, or control algorithms may cause serious adverse consequences. Rehabilitation exoskeleton robot works parallel with the human joints with a corresponding range of motion for every joint. For healthy subjects, the RoMs have some standard values, whereas the RoM for impaired people are different, depending on the severity of impairment. Every exoskeleton robot should have a mechanism to limit the RoM of the joints. It may be in the form of a mechanical stopper or an electromechanical sensor-based stopping system. Further, every exoskeleton robot should also be equipped with an easily accessible emergency stop button. The function of the emergency stop button would be to stop the movement immediately and hold the robot against gravity.

Exoskeleton robots are designed by considering a maximum payload and exceeding the maximum limit may cause electrical or mechanical failures. A higher safety factor can reduce the chances of both electrical and mechanical failures. Robot payload specifications should be very clearly mentioned in the robot's user manual.

The robot should be operated at a low voltage to minimize the risk of electrocution. The severity of the electrical injuries depends on the amount of current flowing through the human body. The skin resistance varies with sweat gland activities and body temperature. Based on ohm's law, lower skin resistance allows more current flow through the body. While skin resistance is variable, the risk of electrocution can be reduced by avoiding higher operating voltages in a robot.

During the mechanical design of the robot, special attention should be given to avoid sharp edges and corners, which increase the risk of injuries. Dangling wires on moving parts increase the risk of an accident. The designer should allow a suitable passage for electrical wiring.

Ergonomic Mechanical Design

The utilization of ergonomic design rules improves the effectiveness of the rehabilitation exoskeleton robot. Since the exoskeleton robot is attached firmly to the wearer's body, an ergonomic design can improve the user's comfort and allow the user to exercise for a longer duration. The major focus of applying ergonomic design rules in rehabilitation exoskeleton robots are to minimize the macro and micro misalignments. The robot's axes of rotation should be closely aligned with the user's joint axes of rotation. Exoskeleton robots with anthropomorphic structures help to improve joint axes alignment (Cenciarini and Dollar, 2011). Careful consideration of all DoF helps to make the exoskeleton robot ergonomic. For instance, the knee joint is elliptical, which provides both rotational and linear movements to occur simultaneously. None of the existing 25 lower extremity exoskeletons reviewed in section 6 consider the linear motion of the knee; this affects the user's comfort and puts extra pressure on the knee joint during exercise (Hasan and Dhingra, 2020). The robot trajectories should be based on natural human movements. A lot of researchers have developed natural trajectories based on the data collected from healthy subjects (Jezernik *et al*., 2003; Neuhaus *et al*., 2011; Kwa *et al*., 2009; Farris *et al*., 2013).

Robot-Assisted Training Methods

The effectiveness of the physical therapy depends on delivering the right form of exercise to the patient, at the right stage of recovery. It depends entirely on the competence of the caregiver. Currently, based on the patient's health condition and recovery stage, the therapist selects the proper form of physiotherapy. The primary role of the robot is to follow the therapist's command and perform a task repetitively. It is expected that in the near future with the help of artificial intelligence and natural language processing, the robot will be able to select the appropriate exercise(s) based on the patient's symptoms.

The conventional physical therapy-based recovery process consists of three stages: Primary, intermediate and advanced stage. During the primary stage, the therapist moves the limb along a specific trajectory to improve the joint's range of motion, blood circulation and reduce disuse atrophy. In the robotic rehabilitation system, the robot does the same thing. This mode of therapy is also referred to as passive form of physical therapy. During the intermediate stage of physiotherapy, the subject is also engaged in the exercise. During conventional physical therapy, the patient is asked to move a limb voluntarily. But in the robot-based physical therapy called the active form of physical therapy, the robot moves the limb along a trajectory based on the user's intentions. In the active assist form of physical therapy, the subject is asked to move voluntarily. If the subject fails to complete the task based on specific criteria, the robot will assist in completing the task. The final stage of physical therapy is active resist form of exercise. Some resistive force is applied to the limb and the patient needs to work against the resistive force. The active resist form of exercise helps to increase muscle strength. Most of the time, viscous friction is applied to the joint to create specific resistive forces. During robot assistive physiotherapy, a physiotherapist may be present in person or may use haptic technology. Table 3 summarizes different forms of robot assistive exercises, their expected outcome along with representative research works.

Review of Existing Human Lower Extremity Exoskeleton Robots

During the last two decades, significant advances have been made in establishing robot-assisted physical therapies. The major advantage of robot-based physical therapy is that the robot can efficiently provide passive or active forms of physical therapy without the downside of provider fatigue. The patients can receive therapeutic exercises based on their schedule. The performance evaluation is easier and accurate compared to conventional forms of physical therapy.

Based on our literature search, 25 rehabilitation robots were identified that are used to assist patients with lower extremity disorders. Some robots are specific to gait pattern rehabilitation whereas some are more focused on active or passive forms of robot-assisted physical exercises. In this study, the focus is on the sensing and actuation mechanism used for existing robots. Table 4 enumerates existing rehabilitation robots along with their DoF, actuator type, mechanical power transmission, feedback sensing method and control algorithms.

The existing HLE rehabilitation robots can be classified in many ways based on purpose of the device, actuation system, control scheme used, type of exercise provided by the robot, the sensing method used, etc. Figure 9 illustrates the classification criteria for existing human lower extremity rehabilitation robots.

The next section discusses the actuators and drive system principles along with representative works.

Actuators and Drive System

Actuator selection and placement plays a vital role in the robotic system. Based on the working principle, an actuator can be active or passive. The actuator is selected based on the peak torque and power requirements during dynamic simulation which in turn depends on the input trajectory, the robot's shape, size and payload considered during the simulation. Based on the application requirements, an actuator can be electric, hydraulic, pneumatic, or hybrid type. The robot's mechanical structure also has a strong influence on the actuator's shape and size. The power requirement of the actuator is proportional to the robot's bandwidth (maximum range of operating frequency). Higher bandwidth robots require more powerful actuators. The efficiency and total power consumption of a robot largely depends on the actuator's characteristics. In the case of robots with electric actuators, the power transmission wire gauge depends on the actuator's specifications. For a specific power, the higher the actuator's operating voltage, the lower are the current requirements, with a corresponding influence on the wire gauge. A proper selection of actuators increases the power-weight ratio.

Table 3: Different forms of physical therapy, their expected outcome and representative work

Control modes	Description	Expected outcomes	Representative works
Passive mode	Robot helps the patient by performing passive exercises repeatedly along the predefined trajectories	Helps in motor function recovery, reduce muscle disuse atrophy by repetitive exercises	Veneman *et al*. (2007a; Colombo *et al*., 2001; Zeilig *et al*., 2012; Esquenazi *et al*., 2012)
Active mode	Robot helps patients for the voluntary movement. Mainly move the joints based on the user intentions	Helps in motor learning, engage patient into the exercise process	Kawamoto *et al*. (2009; Kawamoto and Sankai, 2004; Veneman *et al*., 2007a; Suzuki *et al*., 2005; Wang *et al*., 2013)
Active assist mode	Robot helps patient's voluntary movement; if the user fails to meet specific criteria, the robot helps to complete it	Helps in motor learning, improving confidence via guided process	Veneman *et al*., (2007a)
Active resist mode	It is similar to active mode. The robot provides resistive force as a challenge to the patient.	Helps to strengths muscles, suitable for the final recovery phases	Lam *et al*. (2011; Kawamoto *et al*., 2010)

Table 4: List of existing rehabilitation robot along with their DoF, actuator type, mechanical power transmission, feedback sensing method and control algorithms

#	Device name	Degrees of freedom	Actuator type	Mechanical power transmission method	Feedback/ intention sensing method	Control algorithm	Ref.
1.	EXPOS and SUBAR	Hip: F-E (A) Knee: F-E (A) Ankle: (U) Double legs	DC motor	Mechanical Gearbox, Cable pulley system	Force sensors	Fuzzy logic control, Impedance control	Kong and Jeon (2006)
2.	Lokomoat	Pelvis: VM (U) Hip: F-E (A) Knee: F-E (A) Ankle: F-E (U) Double legs	DC motor	Ball screw mechanism	Goniometer, force sensor	Hybrid force-position control	Colombo *et al*. (2000; Bernhardt *et al*., 2005)
3.	Lopes	Hip: F-E A-A (A) Knee: F-E (A) Double legs	SEA	Bowden-cable based	Spring-based passive force sensor	Impedance control	Veneman *et al*., (2007a; 2005)
4.	ALEX	Trunk: 4 DOF Hip: F-E (A), A-A Knee: F-E (A) Ankle: F-E Single leg	Linear Actuator, Spring as a passive actuator	Mechanical linkage	Force and torque sensor	Force, impedance control	Banala *et al*. (2007; Agrawal *et al*., 2007; Kim *et al*., 2010; Stegall *et al*., 2012)
5.	HAL	Hip: F-E Knee: F-E Ankle: F-E (U) 1 leg	DC Servo motor	Harmonic drives	sEMG signals	Proportional myoelectric control	Kawamoto and Sankai (2004; Suzuki *et al*., 2005; Kawamoto *et al*., 2009)
6.	REWALK	Hip: F-E(A) Knee: F-E(A) Foot: F-E(U) 2 legs	DC motor	-	Motion sensor, tilt sensor	Proportional myoelectric control	Zeilig *et al*. (2012; Esquenazi *et al*., 2012)
7.	ELEGS	Hip: A-A (U) F-E (A) Knee: F-E (A) Ankle: F-E (U)	Hydraulic actuator	-	Switching system	Finite state machine	Strickland (2019)
8.	Vanderbilt exoskeleton	Hip: F-E (A) Knee: F-E (A) 2 legs	Electric motor	-	Using user vocal commands, Center of Pressure triggered	Proportional myoelectric control	Farris *et al*. (2013)
9.	ATLAS	Hip: F-E (A) Knee: F-E (A) Ankle: F-E(U)	Brushless DC motor	Mechanical linkage	Switching via the user interface	Finite state machine/PD control	Sanz-Merodio *et al*. (2012)
10.	MINA	Hip: F-E (A) Knee: F-E (A) Ankle: F-E(U) 2 legs	Brushless DC motor	Mechanical linkage	Switching via the user interface	PD control	Neuhaus *et al*. (2011)
11.	Mind walker	Hip: A-A (A) F-E(A) Knee: F-E(A) Ankle: F-E (U) 2 legs	SEA Compliant actuator, Springs	Mechanical linkage	Switching via the user interface	Model predictive control-based gait pattern generation	Wang *et al*. (2013)
12.	AssistON-Gait	Pelvis-Hip: 6DOF	SEA Compliant actuator	Cable pulley system	Switching via the user interface	Manual start/stop and speed varying operation	Munawar *et al*. (2015)
13.	Ortholeg and Ortholeg 2.0	Hip: F-E (A) A-A (U) Knee: F-E (A) Ankle: F-E(U)	DC motor	Mechanical linkage	Electrooculography and switches	Brain wave control	Araujo *et al*. (2015; Gloger *et al*., 2015)
14.	Walking Assistance lower limb exoskeleton	Hip: F-E (A) A-A (U) Knee: F-E (A) Ankle: U	DC Brushless motor	Harmonic drives	Inclinometer and force sensor	Center of Pressure Control	Kim *et al*., (2013)
15.	IHMC mobility assist exoskeleton	Hip: F-E (A), A-A (A), R-R (U) Knee: F-E (A) Ankle: F-E (U)	Rotary series elastic actuator	Harmonic drives	Optical encoder works as a passive force sensor	Position, force/ torque control	Kwa *et al*. (2009)
16.	Lower-limb power assist exoskeleton	Hip: F-E Knee: F-E Ankle: U	BLDC motor based series elastic actuator	Two stages reduction gear mechanism	Torque sensor	PI velocity control loop nested in a torque control loop	Tagliamonte *et al*. (2013)
17.	Wearable Power-Assist Locomotor (WPAL)	Hip: F-E (A) Knee: F-E(A) Ankle: F-E(U)	DC servo motor	Harmonic drives	Encoder and force sensor	Swing phase step trajectory control	Jianfeng *et al*. (2013)
18.	ABLE	Hip: F-E Knee: F-E Ankle: F-E	DC motor	Ball screw mechanism, Worm gear,	Inclinometer, mechanical and touch switch, measurement wheel, load cell, potentiometer	PD control	Mori *et al*. (2006)

Table 4: Continue

19. Body Extender	12 DoF for both legs	PM DC motor	Ball screw mechanism, lever mechanism, tendon pulley mechanism	Force sensor, Accelerometer	-	Marcheschi *et al.* (2011)
20. Nurse robot suit	Supports shoulder, waist, legs	Micro air pump for rotating .pneumatic actuators	Pneumatic rotatory actuator	Pressure sensor, Muscle hardness sensor	PID control	Yoshimitsu and Yamamoto (2004; Yamamoto *et al*., 2004)
21. XoR	Hip: F-E(A) A-A(U) RR(U) Knee: F-E(A) Ankle: F-E(A)PS(U)	Hybrid pneumatic and electric	-	EMG signal,	-	Hyon *et al*. (2011; Morimoto *et al*., 2012)
22. Soft Exosuit	Flexible strap with infinite DoF	Direct drive actuator	Bowden cable	Customized silicon-based feedback sensor, Load cell, mechanical switch	Trajectory based position control	Asbeck *et al*. (2013)
23. Barkeley Exoskeleton System	Hip: F-E (A), A-A (A), R (U) Knee: F-E (A) Ankle:A-A(U), F-E(A) R, Toe: F-E	Hydraulic piston cylinder	Mechanical linkage	Force sensor, encoder	Force position hybrid controller	Zoss *et al*. (2006; Kazerooni *et al*., 2006)
24. AAFO	Ankle: F-E(A)	BLDC motor, MACCEPA	Ball screw, Mechanical lever	Optical encoder, Absolute magnetic encoder	-	Moltedo *et al*. (2016)
25. CUHK-Exo	Hip: F-E (A), R Knee: F-E (A) Ankle: F-E(P)	DC motor	Planetary gearbox, Bevel gearbox	Encoder, potentiometer, Inertia measurement unit, Force-sensitive resistor, mechanical switch	PD controller	Chen *et al*. (2017; 2019)

F-E → Flexion-Extension, A-A → Abduction-Adduction, R-R → Internal – External Rotation (A) → actuated, (U) → un-actuated, (P) →Pronation, (S) → Supination

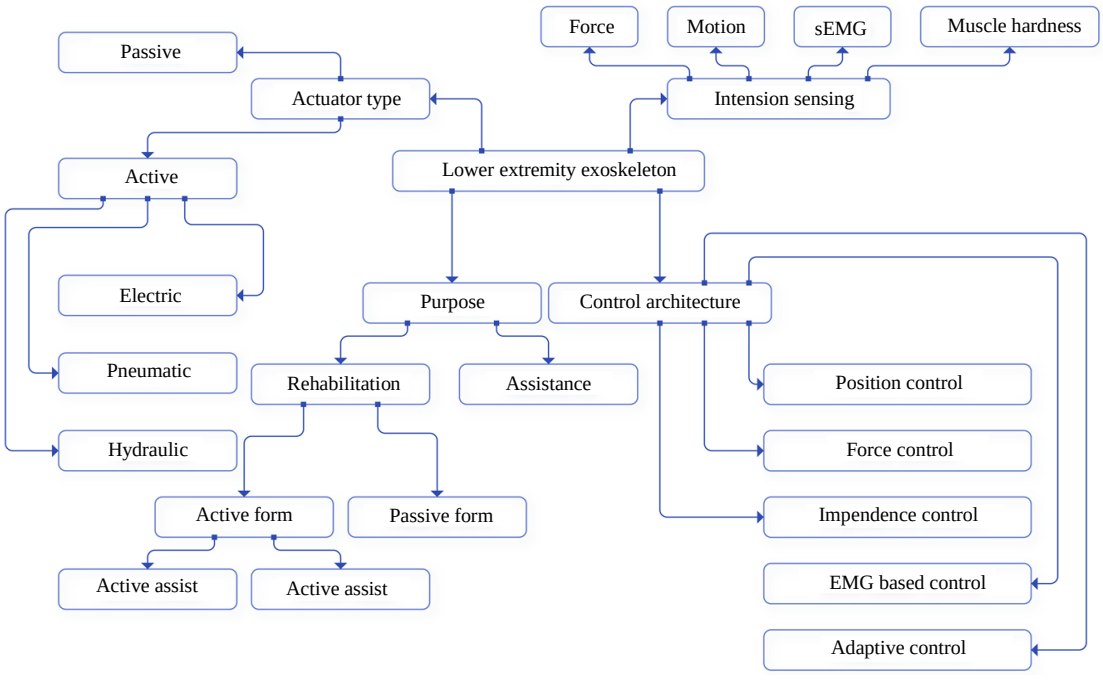


Fig. 9: Classification of lower extremity exoskeleton based on different criteria

In the next couple of subsections, different types of actuators commonly used for exoskeleton robots are discussed along with their selection criteria and control strategies.

Passive Actuators

Passive actuators don't require any power to operate. Based on the application requirement(s), a passive actuator is used individually or in combination

with an active actuator. Passive actuators play a vital role in the design and development of energy-efficient robots. Springs are commonly used as the standard form of passive actuators in robotics applications (McGeer, 1990). Collins *et al*. (2001) presented applications of passive actuators in bipedal walkin. Some existing robots which have used spring as a passive actuator are discussed in (Wang *et al*., 2013; Banala *et al*., 2007; Strickland, 2019).

Active Actuators

A majority of the actuators used in robotics applications are active actuators. Active actuators need a power supply to function. They are comparatively expensive and need a sophisticated control system to operate. The major types of active actuators include the electric actuator, the hydraulic actuator and the pneumatic actuator. Every actuator type has its advantages and disadvantages. A proper selection of actuators plays a vital role in robot design and development. Presented next is a brief description of the working principles of different types of actuators, their applications, along with representative works that employ these actuators.

Electric Actuator

The most common type of actuator used in robotics applications is the electric actuator. High peak torque, the flexibility of motion control, low operating and maintenance costs, reliability, workability in a high bandwidth system, compact shape and size have made electric actuators very popular for robotics applications. There are different types of electric actuators available (Krishnan, 2001). Based on the application requirements, a suitable electric actuator is selected. Presented next is a brief description of different types of electric actuators.

DC Motor

A DC motor is one of the most common types of actuators used in robotics applications. Based on the electrical configuration between the stator and rotor magnetic field coil, the DC motor can be classified as a series-wound, shunt-wound, or compound wound motor. In the case of Permanent Magnet (PM) DC motor, the stator field coil is replaced by a set of permanent magnets. Each type of motor is characterized by its torque-speed relation curve, which expresses the operating characteristics at different loading conditions. Figure 10 shows the characteristics curves of different types of DC motors. In the case of PM DC motor, since the motor speed decreases proportionally with the load, such motors are not suitable for constant speed applications. A shunt-wound DC motor is less sensitive to the load around the rated motor capacity but at loads exceeding two times the rated load, the speed falls very sharply. From the motor characteristic curve, it can be seen that the series-wound DC motor is capable of providing a high starting torque (as high as eight times of the rated torque). The speed of a series-wound DC motor is more sensitive to the load. They are good for the applications that require variable speed and higher starting torques. In compound wound motors, the field coils are connected in both series and parallel combination with the rotor coils. They exhibit characteristics between the shunt and series-wound motors.

The DC motor speed is controlled by varying motor torque as the torque is proportional to the current through the motor windings. Electronic driver circuits control the current to control the torque. A use of DC motors as the major actuator in the robots can be found in (Zeilig *et al*., 2012; Esquenazi *et al*., 2012; Kong and Jeon, 2006; Colombo *et al*., 2000; Bernhardt *et al*., 2005; Araujo *et al*., 2015; Gloger *et al*., 2015; Mori *et al*., 2006; Marcheschi *et al*., 2011; Chen *et al*., 2017; 2019).

AC Motor

AC motors are less expensive compared to the DC motor. AC motors can have different torque-speed characteristics curves, which makes them an excellent choice for various applications. If AC power is supplied directly from the AC supply line, then these motors are limited to a few different speeds because the motor speed has a direct relationship with the supply voltage frequency. The running speed can be varied by using an inverter. Another option is to use a mechanical gearbox to change speeds and available torque. AC motors can be subdivided as a synchronous motor and asynchronous motor. Synchronous motor speed has a relation with the AC line frequency ($n_s = \frac{120 f}{p}$, where n_s is the synchronous speed, f is line frequency and p is the number of motor poles), whereas asynchronous motor has a small amount of slip (typically 3 to 10%).

Brush Less DC Motor (BLDC)

BLDC motor is also known as Electronically Commuted motor (EC) or synchronous DC motor. The BLDC motor is popular for robotics applications because of its higher efficiency, low acoustic noise and longer operating life. In a BLDC motor, the rotor consists of a set of permanent magnets and the stator is based on the electric-magnetic field. The stator magnetic field rotates continuously driven by the electronic switching circuit. The rotor always tries to synchronize with the stator's rotating magnetic field and as a result, it rotates. Like the permanent magnet DC motor, no electric medium required for carrying current to the rotor. Many of the existing lower extremity rehabilitation robots use a BLDC motor. A list of representative works include (Neuhaus *et al*., 2011; Sanz-Merodio *et al*., 2012; Kim *et al*., 2013; Tagliamonte *et al*., 2013; Moltedo *et al*., 2016).

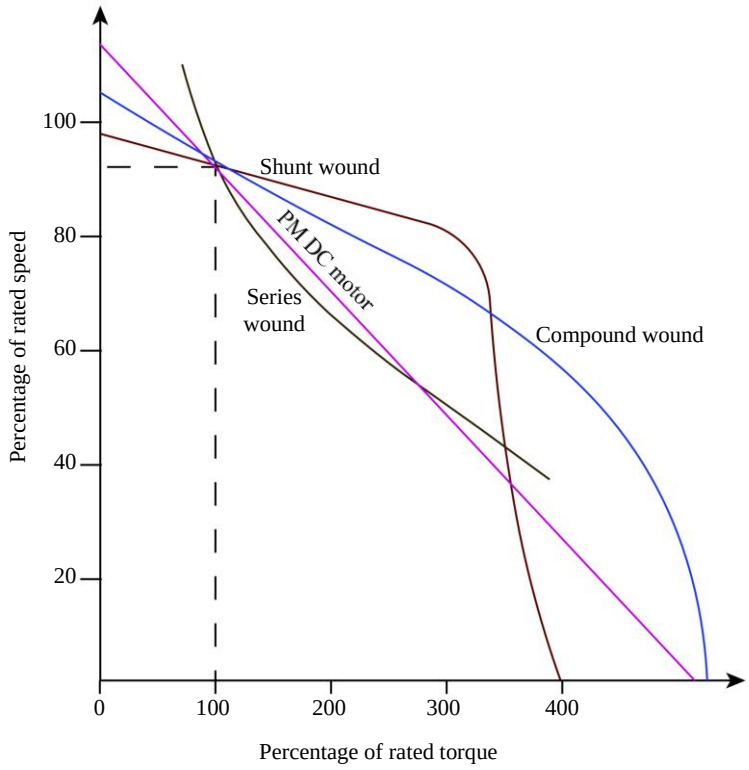


Fig. 10: DC motor characteristics curves

Stepper Motor

The working principle of the stepper motor is similar to the BLDC motor. Typically, it runs based on open-loop control architecture. As no feedback system exists in an open-loop control system, the rotor position can be out of phase at any instant. To deal with this problem, often, little extra power is added with the calculated power of the motor. The main advantage of a stepper motor is that they can sit energized for an extended period (although the temperature rises as high as 150°F). The number of magnetic strips arranged around the circumference of the rotor determines the resolution of the motor (typically 200 steps/rev). With the help of a micro-stepping stepper motor driver, the resolution can be increased as high as 2000 steps/rev. The main difference between the BLDC motor and stepper motor is that the BLDC motor runs more smoothly than the stepper motor, while the stepper motor is very good at providing holding torque.

Servomotor

Servo motor refers to a complete actuation system that includes the motor (based on the application requirements AC/DC motor can be used), driver, motor position/velocity sensor (encoder/tachometer) that runs based on some close loop control algorithms. AC motor based servo systems are more popular because they can be run at a wide variety of speeds by varying the supply voltage frequency. AC synchronous motor speed becomes fixed at a specific value based on the AC line frequency, which is called the synchronous speed of the motor. A servo motor is capable of providing a programmed function of position, velocity, acceleration and torque. A servo system is popular because of its fast response, high efficiency and high torque to inertia ratio. The following references used servo motors as the major actuator for their robots (Kawamoto and Sankai, 2004; Suzuki *et al*., 2005; Kawamoto *et al*., 2009; Jianfeng *et al*., 2013).

Series Elastic Actuator

The Series Elastic Actuator (SEA) is a relatively new concept introduced by (Williamson and Robinson, 1995). In the conventional robotic system, the actuator is rigidly attached to the load. A force or a torque sensor is placed in between them to measure the flow of force or torque to feedback to the control system. In some cases, the motor current is measured to estimate the motor torque. But in the case of a series elastic actuator, instead of using a force, torque, or current sensor, the spring's displacement is used to measure force/torque passively. The spring allows the load to move freely. Figure 11 shows a common configuration of a series elastic actuator. A pair of springs is attached in antagonist configuration. With the help of two encoders, the change of spring length is measured.

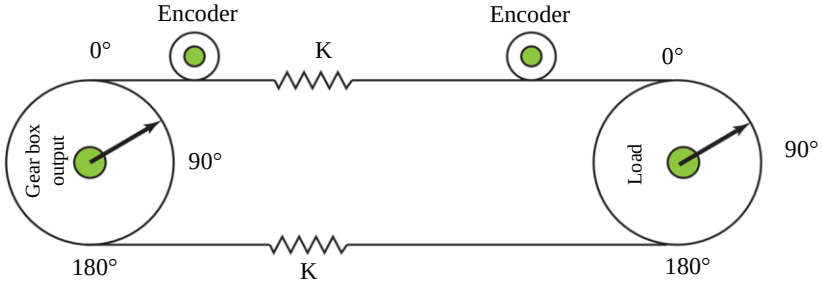


Fig. 11: Series elastic actuator

The Hooke's law defines the relationship between the force (F) and displacement of the spring (X) as:

$$F = KX \tag{22}$$

In the Equation (22), F is the force, K is the spring stiffness (constant for a specific spring) and X is the displacement. In the above equation, the force can be measured with the help of displacement. A similar principle is applicable for torsional spring. Nowadays, SEA is widely used in rehabilitation robotics. The following references use series elastic actuators (Kwa *et al*., 2009; Veneman *et al*., 2007a; 2007b Wang *et al*., 2013; Veneman *et al*., 2005; Munawar *et al*., 2015; Tagliamonte *et al*., 2013;). Krishnan has discussed the modeling, analysis and control techniques of all the above mentioned electric actuators in-depth (Krishnan, 2001).

Hydraulic Actuation System

The hydraulic actuation system is more suitable for high power-weight ratio applications. Both linear and rotary hydraulic actuators are available. The efficiency of the hydraulic system is less than that of an electric system. The hydraulic system does not require reduction gears. It can work for a wide range of bandwidths. The hydraulic system requires a pump, reservoir, motor and hoses. Operating temperature affects the system performance (since fluid viscosity varies with temperature). The following references discuss some robots actuated using hydraulic actuation system (Strickland, 2019; Zoss *et al*., 2006; Kazerooni *et al*., 2006; Lee *et al*., 2020; Scheidl *et al*., 2018).

Pneumatic Actuation System

The pneumatic system runs using compressed air. Pneumatic systems are comparatively inexpensive and have been used in many exoskeleton robots. Position control applications are challenging in the pneumatic system than other types of actuation mechanisms. The main drawbacks of the pneumatic systems are that they are noisy and very difficult to control. The pneumatic system deforms under constant loading conditions. It provides the lowest power-weight ratio. The McKibben type of artificial muscle is one of the best examples of a pneumatic actuator.

McKibben Artificial Muscle

The McKibben artificial muscle was introduced in the 1950s (Gavrilović and Marić, 1969). It is one of the best examples of a pneumatic actuators for an exoskeleton robot (Kobayashi and Hiramatsu, 2004; Noritsugu *et al*., 2007). Currently, most of the Pneumatic Artificial Muscles (PAM) is based on McKibben artificial muscles. It consists of an internal bladder plaited by a flexible, but non-extensible mesh. The ends of the bladder are firmly attached to both ends of the mesh. When the inner bladder pressurized, the bladder expands to maximize the volume. Due to the action of non-extensile mesh, the whole system expands radially and shortens axially. McKibben artificial muscle possesses the following mechanical properties: Spring with variable stiffness, nonlinear passive elasticity, flexible and very lightweight (Hannaford and Winters, 1990).

Chou and Hannaford (1996) developed a linear model of the McKibben pneumatic artificial muscles. Wickramatunge and Leephakpreeda (2010) studied different properties of pneumatic artificial muscles, including the relation between pressure, force, length, stiffness, elastic force. The relationship between the activation level and length, velocity, tension varies with the physical construction of the artificial muscle and needs to be modeled for the individual prototype. McKibben artificial muscle is used in pairs and antagonistic configuration to increase the joint stiffness. Teng *et al*. (2016) characterized the activation, displacement and velocity in the case of the opposing pair configuration. Zhang *et al*. (2008) presented the modeling and control of pneumatic muscle actuator for the elbow exoskeleton. They developed a fuzzy logic controller for controlling a pair of antagonistic pneumatic artificial muscles for the elbow exoskeleton.

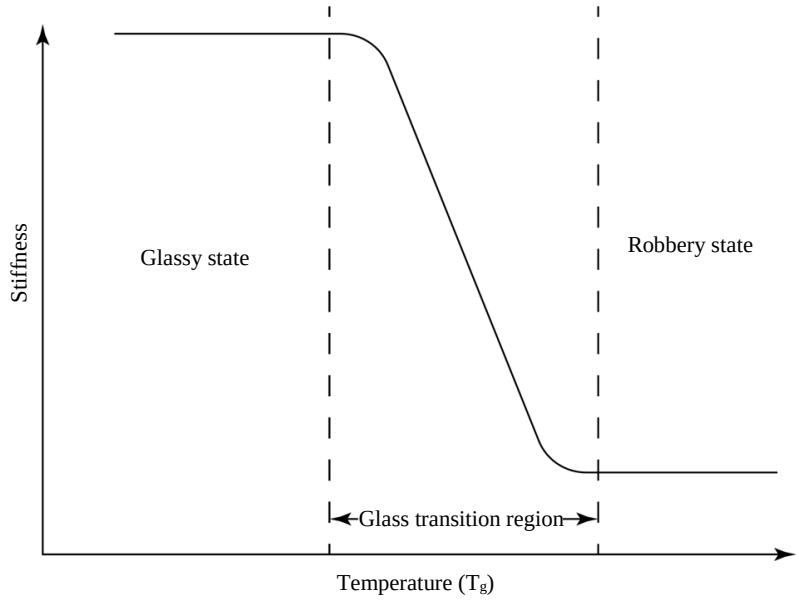


Fig. 12: Temperature Stiffness relationship of the shape memory polymer

McKibben Artificial Muscle Using Shape Memory Polymer

The main drawback of McKibben Artificial Muscle is that it needs continuous control for position tracking, which makes it challenging for real-life applications. Using a shape memory polymer can solve this problem (Sokolowski *et al*., 1999; Tobushi *et al*., 2001; 2003; Ishizawa *et al*., 2003; Behl and Lendlein, 2007; Huang *et al*., 2005; Baer *et al*., 2007; Lendlein and Langer, 2002; Lan *et al*., 2009; Xie, 2010). Shape memory polymer consists of two phases, the hard phase and the soft phase. At any temperature lower than the glass transition temperature (T_g) temperature, it has higher stiffness and is considered a hard phase or "glassy" phase. At temperatures above the glass transition temperature, it exhibits a lower stiffness. This is called the soft phase or "rubbery" phase. Figure 12 shows the temperature stiffness relationship of the shape memory polymer.

Takashima *et al*. (2010) developed McKibben artificial muscle using shape-memory polymer and showed its effectiveness in robotic applications.

Mechanical Power Transmission System

A majority of the robots are actuated by electric actuators. Most of the electric motors run at high speed and deliver a small amount of torque. But for the robotics application, low speeds and high torques are required. To fulfill these requirements, mechanical power transmission is used. Mechanical power transmission can be done in several ways such as using gears of different types/sizes, belt drives, chain drives, sun planet gearbox, strain wave gearing, synchronous belt and timing pulley, etc.

Each type of transmission mechanism has its pros and cons. The selection of suitable mechanical power transmission depends on many factors such as the robot end-effector accuracy and precision requirements, overall cost, shape and size factors, mechanical power loss, cost of the actuator, environment, total power consumption, direction of power flow, mechanical noise and vibrations, etc. A brief description of different types of mechanical power transmission options along with their pros and cons are given below.

Gear Drive

The gear drive is the most common type of mechanical power transmission system with applications ranging from small precision settings to large applications. Gear drives can be used for controlling speed, torque and rotational direction. The most common type of gear is the spur gear. The gear teeth are parallel to the shaft on which the gear is mounted. Spur gears transmit power between two parallel axes. The main drawback of a spur gear based power transmission system is that it provides a significant amount of backlash. As robotics applications require high precision, an antibacklash mechanism is widely used to compensate for mechanical backlash.

A helical gear is very similar to spur gear. The main difference between the spur gear and helical gear's teeth is that helical gear teeth are not parallel to the power transmission axes. Helical gears also have

reduced backlash compared to spur gears. They make less noise and induce lesser vibrations. The bevel gear is used for power transmission between two nonparallel/intersecting shafts. It affords a compact arrangement. There four types of bevel gears: Straight bevel gear, spiral bevel gear, zero bevel gear and hypoid bevel gears. The worm gear is used for power transmission between two nonparallel nonintersecting shafts. Figure 13 presents different types of gears widely used for mechanical power transmission. An application of bevel gears in the robot power transmission system can be found in (Kong and Jeon, 2006; Mori *et al*., 2006; Chen *et al*., 2017; 2019).

Belt Drive

The belt drive is used to transmit power between two shafts. There are three types of belts: Flat belt, V-belt and the toothed belt. Flat belt and V-belt are based on friction between the belt and the pulley; as a result, belt slippage can cause problems. The synchronous belt (toothed belt) eliminates the risk of slippage. Such belts are widely used for robotics applications.

Sun Planet Drive

The sun planet gear system, also known as the epicyclic gear train, is a compact way to provide a higher gear ratio (higher torque and lower speed). The epicyclic gear system has three main parts, sun, planet and the outer ring gear. Based on the internal architecture of the epicyclic gear train, it is two degrees of freedom system, i.e., the user can control the output, including torque, speed, the direction of rotation by controlling two input variables. In the case of robotics application, only one degree of freedom is used as the ring gear is kept stationary. Many times, a multistage epicyclic gear train is used to get a more compact gearing system. Some representative works on the use of epicyclic gear train for robotic applications include (Tagliamonte *et al*., 2013; Chen *et al*., 2017; 2019). Figure 14 and 15 show the internal architecture and a multistage sun planet gear system.

Strain Wave Drive

Strain wave gearing is also known as a harmonic drive. It is widely used for robotics applications and possesses many excellent qualities such as: (i) Almost zero backlash, (ii) compact design, (iii) lightweight, (iv) high gear ratio, (v) good resolution, (vi) excellent repeatability, (vii) high torque capability, (viii) coaxial input-output shaft and (ix) very high gear ratio in a single stage (typically 30:1 to 320:1).

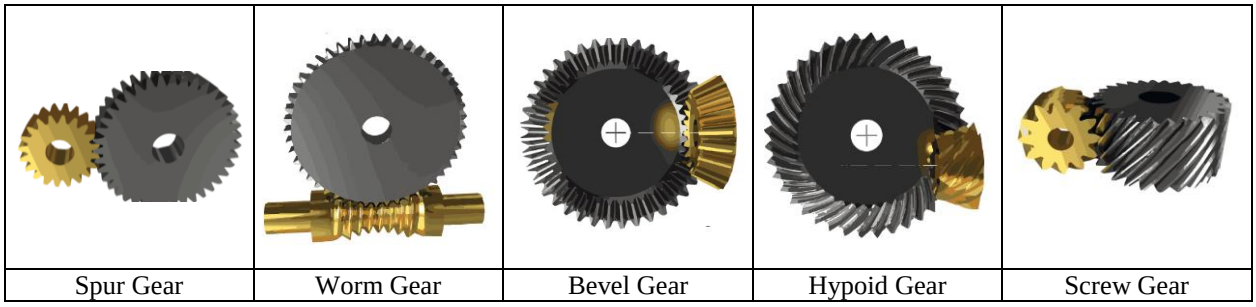


Fig. 13: Spur gear, Worm gear, Bevel gear, Hypoid gear, Screw gear

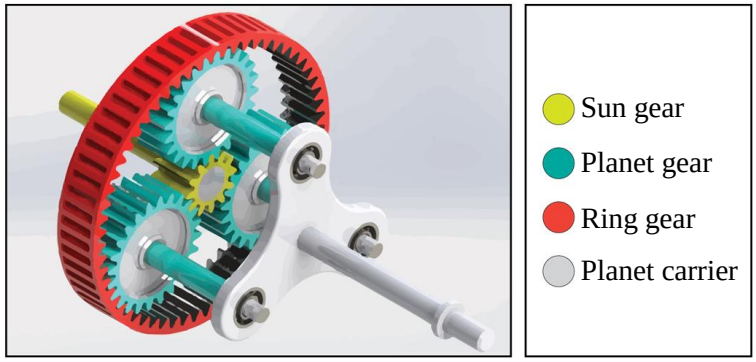


Fig. 14: Sun planet gear system

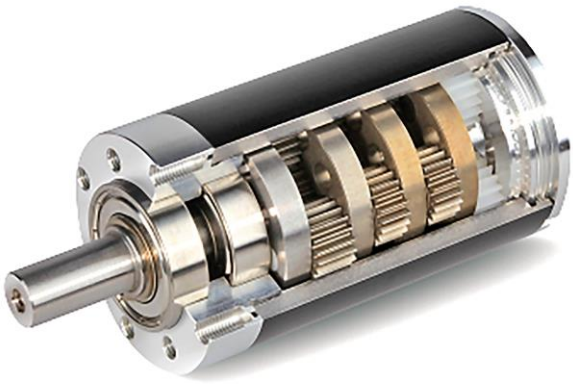


Fig. 15: Multistage sun planet gear system

Fig. 16: Strain wave generator

The strain wave drive is built based on the elastic/flexible properties of the metal. It has three major components: A wave generator, flexible-spline and a circular spline (Fig. 16). The source is connected to the wave generator and the output is connected to the flex spline. A wave generator is an epicyclic disk covered by ball bearings. The outer cage of the ball bearings is made of flexible metal that allows changing of the shape during rotation. The wave generator is inserted into the flexible spline (a flexible shallow metallic cap with a finite number of teeth on the outer side). The flexible spline is made of flexible material and due to the action of the inside epicyclic disk, the flex spline continuously changes its shape. The major axis of the flex spline rotates with the wave generator and the flex spline meshes with the circular spline only at a few teeth. For every rotation of the wave generator, the flex spline advances a very small amount. Some references that have used strain wave generator based gear reduction system include (Kwa *et al*., 2009; Kawamoto *et al*., 2009; Kawamoto and Sankai, 2004; Suzuki *et al*., 2005; Kim *et al*., 2013; Jianfeng *et al*., 2013).

Bowden Cable

In the conventional power transmission system, the motor and the gearbox stay close to the joint. The main drawbacks of the conventional power transmission system are: They make the exoskeleton robot heavy and large. The robot consumes extra power for carrying the motor and the gearbox and requires a strengthening of mechanical structures. All these problems can be solved with the help of the Bowden cable-based power transmission system. In the Bowden cable-based power transmission system, the actuators are located at a distant place. Mechanical power is transmitted to the joints via cables. The main drawback of the Bowden

tube-based transmission system is that it introduces a significant amount of backlash. If the gearbox is attached to the motor at a distant location, then the system gives more backlash, whereas if the gearbox is located at the joint and the motor is at a distant location, the backlash gets divided by the gear ratio and becomes small. There are many robotic rehabilitation system where the Bowden cable-based power transmission system is used such as (Kong and Jeon, 2006; Veneman *et al*., 2005; Munawar *et al*., 2015; Marcheschi *et al*., 2011; Asbeck *et al*., 2013; Veneman *et al*., 2007b; Ekkelenkamp *et al*., 2005).

Ball Screw

The ball screw is a linear actuator that converts rotatory motion into linear motion. The basic components of a ball screw mechanism are a screw with helical grooves on its body, balls and a nut. The ball stays between the screw and the nut. The balls are routed in a continuous path. The following specifications characterize the ball screw mechanism: Lead accuracy, axial play, preload and life/load relationship. The ball screw is a popular mechanism in robotic applications as it provides high accuracy and efficiency. A use ball screw based power transmission in robots can be found in (Colombo *et al*., 2000; Bernhardt *et al*., 2005; Mori *et al*., 2006; Marcheschi *et al*., 2011; Moltedo *et al*., 2016).

Intention Sensing System

The user's intention sensing, measurement and proper interpretation are vital for selecting active, active assist or active resist forms of physical therapy. For the active form of robotic neurorehabilitation, the exoskeleton robot's assistance or degree of involvement depends on the user's intention. There are many ways to sense and interpret user's intentions, such as sensing force or torque, sensing different forms of motion, or by analyzing biological signals from a particular or a group of muscles, including surface electromyography (sEMG), mechanomyography (MMG), pressure pattern (Force myography), etc. In the following subsections, different types of intention sensing methods are discussed that can be used for exoskeleton assisted rehabilitation applications.

Force Sensing

The force/torque sensing method is frequently used for determining the user's motion intention. Often force/torque sensors are attached between the exoskeleton robot's mechanical structures and the lower extremity to measure the force/torque exerted by the user. In many cases, force sensors are also attached at the shoe sole or the bottom of the crutches to determine the state of walking. The torque sensor is placed between the motor and the output links to feedback the output torque to the controller or to measure torque assistance provided by the robot. Depending on the output of the force/torque sensor, the robot controller makes maneuvering decisions. In the case of series elastic actuators, force/torque is measured passively with the help of displacements. The following references used force or torque sensors for interacting with the users (Veneman *et al*., 2007a; 2007b; Kong and Jeon, 2006; Colombo *et al*., 2000; Bernhardt *et al*., 2005; Veneman *et al*., 2005; Banala *et al*., 2007; Agrawal *et al*., 2007; Kim *et al*., 2010; Stegall *et al*., 2012; Kim *et al*., 2013; Tagliamonte *et al*., 2013; Jianfeng *et al*., 2013; Mori *et al*., 2006; Marcheschi *et al*., 2011; Yoshimitsu and Yamamoto, 2004; Asbeck *et al*., 2013; Zoss *et al*., 2006; Kazerooni *et al*., 2006; Chen *et al*., 2017; 2019).

Motion Sensing

Another popular way to sense the user's intention is to measure the motion of a specific point on the limb. The motion can be in the form of linear or rotational displacement, velocity, or acceleration. Rotatory encoders, accelerometer, inertial measurement unit, gyroscope and inclinometer sensor can be used for sensing motion. A rotatory encoder converts angular motion (angular position and velocity) into equivalent analog voltage or digital signals. The modern accelerometers are microelectromechanical devices, tiny in size, widely used for measuring acceleration forces or inclination angles. A gyroscope measures the angular velocity. Inertial Measuring Unit (IMU) is a combination of 3 axis accelerometer, a three-axis gyroscope and a magnetometer and is capable of providing absolute orientation. IMU can be used for measuring the absolute orientation of a moving body in the space. An inclinometer also can be used for measuring the absolute angles. A use of these devices can be found in (Kwa *et al*., 2009; Zeilig *et al*., 2012; Esquenazi *et al*., 2012; Colombo *et al*., 2000; Bernhardt *et al*., 2005; Kim *et al*., 2013; Jianfeng *et al*., 2013; Mori *et al*., 2006; Marcheschi *et al*., 2011; Zoss *et al*., 2006; Kazerooni *et al*., 2006; Moltedo *et al*., 2016; Chen *et al*., 2017; 2019).

Different Forms of the Switch

Mechanical switches can be used as sensors. Often single pole single throw switches are used as limit switches. For the user's intention sensing, different types of switches can be used, including reed switch, pillow switch, mercury switches. Pillow switch is handy for detecting the interaction between the user and the exoskeleton robot as discussed in (Neuhaus *et al*., 2011; Wang *et al*., 2013; Strickland, 2019; Sanz-Merodio *et al*., 2012; Munawar *et al*., 2015; Araujo *et al*., 2015; Gloger *et al*., 2015; Asbeck *et al*., 2013).

Surface Electromyography

Electromyography (EMG) is an effective way to evaluate and record electrical activity produced by skeletal muscle during movements. Surface ElectroMyoGraphy (SEMG) is a non-invasive form of EMG. Instead of using needle, surface electromyography uses surface electrodes for picking up muscles' electrical activities. Typically, the amplitude of the signal varies from 0 to 10 mV (peak-to-peak). The frequency of the signal varies between 0 to 500 Hz, with the dominant energy being in the 50 to 150 Hz range. SEMG signals can be used for estimating the force/torque developed by an individual or group of muscles. There are different types of SEMG instruments are available in the market. Sometimes they come with additional functionalities such as real-time acceleration measurements. Modern SEMG systems use Bluetooth wireless communications, which provide more accessibility to users. SEMG applications for intention sensing is discussed in (Kawamoto *et al*., 2009; Kawamoto and Sankai, 2004; Suzuki *et al*., 2005; Wang *et al*., 2013; Hyon *et al*., 2011; Morimoto *et al*., 2012).

Pressure Pattern (Force Myography)

In force myography, a cuff with arrays of pressure sensors surrounding thigh, shank, or foot is used for determining different muscle activation levels. The user's movement intention can be classified based on the pattern of the force myography as explained in (Yoshimitsu and Yamamoto, 2004; Yamamoto *et al*., 2004).

Digital Camera and Depth Sensor

By using modern digital image processing and machine vision technologies, the individual joint angles can be measured with great precision. Microsoft Kinect combines both the digital camera and image depth sensors and includes an Application Program Interface (API) to get the readily available human upper and lower extremity joints angle (Lun and Zhao, 2015). Kinect was developed for gaming purposes, but it can be used for rehabilitation purposes. The primary application of Microsoft Kinect in rehabilitation robotics is to determine the user's intentions and to measure joint angles at any instant. Even without using Microsoft Kinect, by combining data from two sensors and by using custom algorithms, the same objective can be accomplished.

Discussion

A comprehensive review of the state-of-the-art for HLE exoskeleton robots is presented that includes detailed discussions on lower extremity anatomy, possible causes of HLE disability, rehabilitation protocols, and basic safety and ergonomic design requirements that need to be considered during design/selection of an exoskeleton robot. Both electrical and mechanical sensing and actuation technologies are discussed in depth to familiarize the reader with current technologies. A lack of commercial names and/or model information of previously used sensors and actuators should not be considered as a limitation of this paper. Instead of focusing on a specific brand, the sensor family's working principles are discussed. Attempting to explain all the previously used sensors and actuators requires a considerable amount of information which presents challenges in keeping this article of reasonable length. A comprehensive coverage of all relevant anatomical, actuation and sensing aspects of lower extremity exoskeleton robots will help a designer come up with the best possible solution for a specific application.

Conclusion

The goal of this paper was to extract and analyze information from existing lower extremity exoskeleton robots, identify the gaps and utilize them for further improvement(s) in the design of exoskeleton rehabilitation robots.

To achieve this goal, 25 existing human lower extremity exoskeleton robots were examined carefully based on published articles and relevant review papers. It was noticed information pertaining to human lower extremity anatomy was missing from exoskeleton robot design and development. The gap has been filled herein by explaining human lower extremity bones, joints, nervous system, muscles, anthropomorphic DoF, RoM and anthropometric parameters. Knowledge of human lower extremity anatomy is vital to understanding the causes of human lower extremity disability. For design, development and performance evaluation of human lower extremity exoskeleton robot, anatomical features play a crucial role.

It was also noticed that in the existing literature, there is insufficient explanation of the causes of human lower extremity disabilities. An explanation of the probable causes of human lower extremity disability is provided herein along with an explanation of how they are related to the nervous system and the muscular system.

Safety and ergonomic design are two critical aspects that need to be addressed during the design and development of human lower extremity exoskeleton robots. Safety is the first requirement for any device that deals with humans. As the lower extremity exoskeleton robot firmly attaches to the human lower extremity, the designer needs to consider safety issues seriously. Different ways to improve safety aspects from multiple dimensions were explained. Ergonomic design features help improve the user's comfort thereby helping users to exercise for a prolonged period. Techniques for incorporating ergonomic features in the exoskeleton robot were discussed.

Different phases of neurorehabilitation and the associated physical exercises, including passive, active, active assist and active resist forms of physical therapies, were also explained.

After reviewing the existing literature, it was also noticed that no review article has addressed in depth the sensing and actuation system used for human lower extremity exoskeleton robots. The actuators act like muscles of the robot whereas the sensors help to interact with user and control of the robot. A detailed description of different types of sensors and actuators used in existing exoskeleton robots, their working principle, along with representative works, is presented.

It is hoped that a comprehensive treatment of all aspects that need to be considered while designing a lower extremity exoskeleton robot will help designers develop a good understanding of human anatomy which in turn, will facilitate the design of safe and ergonomic robots. Knowledge of disability causes will help in the selection of the best form of exercise for the patient. Comprehensive knowledge about all the sensors and actuators that are used for existing lower extremity exoskeleton robots will help the designer choose the best sensor or actuator for a specific application.

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Author's Contributions

Sk. Khairul Hasan: Literature search, paper organization and writing.

Anoop Dhingra: Paper organization, proof-reading and editing the manuscript.

Ethics

This article is original and contains unpublished material. Authors declare that are no ethical issues and no conflict of interest may arise after the publication of this manuscript.

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