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DESIGN DEVELOPMENT OF ROBOTIC EXOSKELETONS IN REHABILITATION

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ABSTRACT

Robotic exoskeletons have garnered significant attention and continue to be commonly used as a rehabilitative intervention for diverse physical disabilities. These devices offer aid and support in order to enhance the functional capabilities of patients and facilitate their treatment. This article offers a concise overview of the evolutionary trajectory of robotic exoskeletons, tracing their inception in historical contexts to the latest advancements in this domain. The field of robotic exoskeletons has undergone extensive research, resulting in the advancement of three generations of exoskeleton technology. These advancements aim to enhance the efficacy of exoskeletons in the context of rehabilitation, with the ultimate goal of improving the well-being of individuals afflicted by severe or degenerative disabilities, as well as those suffering cognitive-motor difficulties. This review provides a summary of the medical demands, historical development, classification, applications, and treatment modalities of robotic exoskeletons along with the design implementation in a clear and informative manner.

1. INTRODUCTION

Robotic exoskeletons are a crucial and rapidly growing research domain within the field of medical mechatronics. As to the World Health Organization, about 2.4 billion individuals are experiencing disabilities as a result of sickness, accidents, or old age, and this figure is on the rise. This represents a substantial segment of the global population, consisting of individuals aged 15 and above, who have functional difficulties and often need medical intervention as a result of their disabilities [1].

Disability refers to any bodily disability that limits participation and imposes constraints on activities. Particularly those varieties that impact an individual's motor abilities and can lead to a significant decrease in their quality of life. Research has revealed that individuals with disabilities have a higher likelihood of unemployment and tend to earn much less while labor. Consequently, they experience more financial hardship compared to those who lack disabilities and often rely more heavily on assistance from others to do everyday chores. This underscores the adverse impacts on individuals with disabilities and society as a whole [2]. Medical conditions such as stroke, tumors, brain or spinal cord injuries, autoimmune disorders, cerebral palsy, and hereditary diseases can lead to disability. These various medical disorders can lead to a range of limitations that impact individuals across all age groups. Alternatively, older individuals are more susceptible to acquiring impairment as a result of prolonged health disorders such as diabetes, cardiovascular disease, and/or mental illness [3].

Disabilities can be categorized based on the affected body portion, including upper limb disabilities and lower limb disabilities. Upper limb disabilities are a prevalent form of disability, with most cases resulting from injuries to the hand or forearm. Spinal cord injuries often impact the functioning of the wrist and hand. Moreover, approximately 85% of stroke patients experience a decrease in the functioning of one side of their upper and lower limbs within the first three to six months after the stroke. Even after completing a rehabilitation program, the affected limb's function is not adequately restored in 50-80% of patients, thereby restricting their ability to perform daily activities. Restoring the human capacity to do everyday tasks is a very intricate issue. Physiotherapy and physical activity regimens based on rehabilitation protocols facilitate motor recovery and subsequent restoration of function. In addition to the early intervention, task-oriented training, practice frequency and timing, and involvement level are considered to be the primary factors influencing motor recovery [4], [5].

The use of modern Exoskeletons is significantly enhancing the realm of rehabilitation by substituting the laborious and time-consuming one-to-one therapy approach. The use of robotic devices in rehabilitation is in high demand due to their equivalent or even superior influence on rehabilitation progress compared to traditional techniques. Research indicates that the utilization of robotic rehabilitation devices offers benefits in terms of cost reduction and minimizing physical strain on therapists. These devices are designed to be customized, allowing for high-intensity, repeatable, and task-oriented interactive exercises. Furthermore, they enable an objective and dependable monitoring of the patient's progress. Conversely, robotic systems have the capability to modify the intensity of exercise based on the patient's capacities through precise and systematic regulation of applied force, gradually adjusting the level of aid or resistance. These traits have a favorable impact on excessive muscular tone or spasticity and pain, in addition to positively impacting the patient's recovery, regardless of the level of rehabilitation [6].

This paper aims to emphasize the significance of mechatronic and robotic devices in rehabilitation. A comprehensive examination of robotic exoskeletons (REs) will ensue, beginning with their historical development and medical necessity and progressing through their classification, applications, and treatment modalities, as well as the technologies underlying their design and implementation.

2. Anatomical Overview of the Upper and Lower Limbs

The human upper limb segment comprises the shoulder, elbow, wrist, and fingers, represented in Figure (1). The shoulder joint has three bones (clavicle, scapula, and humerus) and four articulations (glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic), with the thorax providing a secure foundation. The glenohumeral joint, commonly referred to as the shoulder joint, is referred to as both a ball and socket joint. The primary movements of the shoulder joint are shoulder flexion and extension, shoulder abduction and adduction, and shoulder internal-external rotation. The elbow set comprises the elbow joint and the radioulnar joints. An elbow joint is characterized as a hinge joint that allows for flexion-extension and supination-pronation movements. The wrist joint serves as the connection point between the hand and the forearm. It consists of eight carpal bones and allows for a variety of movements, including flexion-extension and ulnar-radial deviation. The compound joint is composed of two separate joints, namely the humeroradial and humeroulnar articulations.

The human lower limb comprises the hip joint, knee joint, and ankle joint. The hip joint is created by the articulation between the femoral head and the pelvic bone. The pelvic bone serves as the anatomical link between the trunk and lower leg. The range of motion of the hip joint encompasses sagittal flexion and extension, frontal abduction and adduction, and transverse external and internal rotation. The knee joint is an intricate structure that links the tibiofemoral and patellofemoral joints. The motion capabilities of this object encompass sagittal flexion/extension and transverse internal/external rotation. The knees play essential roles in the process of walking. During the swing phase, the knees undergo flexion to reduce the length of the leg, whereas during the stance phase, they remain flexed to absorb impact and transfer forces along the legs. The ankle joint functions as a shock absorber and primarily moves through the talocrural and subtalar joints. The talocrural joint, a hinge joint, is situated between the talus, distal tibia, and fibula. Its primary function is to enable plantar/dorsiflexion. The subtalar joint, situated between the talus and the calcaneus, facilitates eversion and inversion, as well as internal and external rotation.

Paralysis refers to the impairment of motor function and is characterized by the inability to perform voluntary motions. This can have an impact on particular bodily regions or perhaps the entirety of the body. Paralysis is a physiological condition that arises when the transmission of nerve signals to muscles is interrupted. Disability or paralysis can be categorized into two forms, localized and generalized, depending on the specific area of the impairment. Localized paralysis specifically impacts a limited region of the body, such as the face, hands, feet, or vocal cords. On the other hand, generalized paralysis affects a greater area and is categorized by healthcare professionals as hemiplegia, monoplegia, paraplegia, or quadriplegia. Hemiplegia is a form of paralysis that specifically impacts one side of the body, affecting both the arm and leg on that side. In contrast, monoplegia refers to the inability to move a single limb, either the arm or the leg. Paraplegia refers to the state of having both legs paralyzed, while quadriplegia denotes a total paralysis of both limbs. Individuals diagnosed with quadriplegia may experience limited or complete absence of mobility from the cervical spine downwards. Paralysis can be attributed to various factors, with the most prevalent being stroke, traumatic brain or spinal cord injury, brachial plexus injury, cerebral palsy, and autoimmune disorders like multiple sclerosis. Any other reasons can be categorized as less common. Rehabilitation can effectively mitigate, control, or avert consequences linked to various health disorders. It serves as a crucial supplement to medical and surgical interventions in order to get the most best outcome feasible [8].

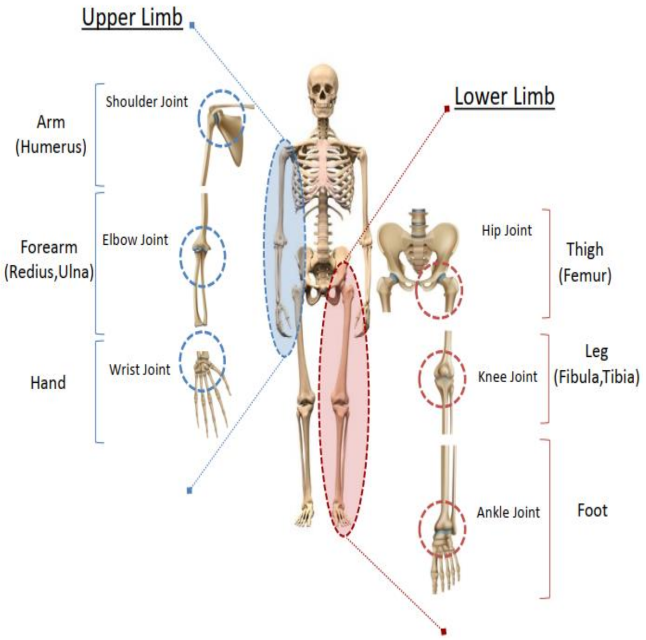

Figure 1: Human Body Exoskeleton: Anatomical Perspective of the Upper and Lower Extremities.

3. Historical Development of Robotic Exoskeletons

The concept of creating and constructing robots that may be affixed to the human body to assist with specific duties is not novel. Assistive robots have evolved through three generations since their inception. However, the development of assistive robots for therapeutic and rehabilitation purposes represents the latest advancement in medical and academic research.

In the early 1800s, initial efforts were made to create a wearable robot designed to enhance the physical strength of the human body and assist with activities such as sprinting and jumping. The invention of the first full-body exoskeleton in the sixteenth to nineteenth century marked the inception of the second generation of assistive robot development. This exoskeleton was specifically designed for military applications, to enhance human physical capabilities. In the early 1980s, the first upper-limb orthoses using robotics technology were developed. Subsequently, several iterations of assistive robotics were introduced to address and alleviate health issues resulting from the war that prevailed during the twentieth century.

From then, the notion of using these robots for medical, therapeutic, and rehabilitation purposes with commercialized products originated, to support and facilitate an easier life for the old and disabled by the start of the twenty-first century. Studies and genuine attempts to construct these robots have continued over the course of three generations, and each study served as the foundation for the creation of a new generation of these robots. With reference to [9- 18] in Figure (2), this displays the most well-known studies ever carried out and documented in this field of study.

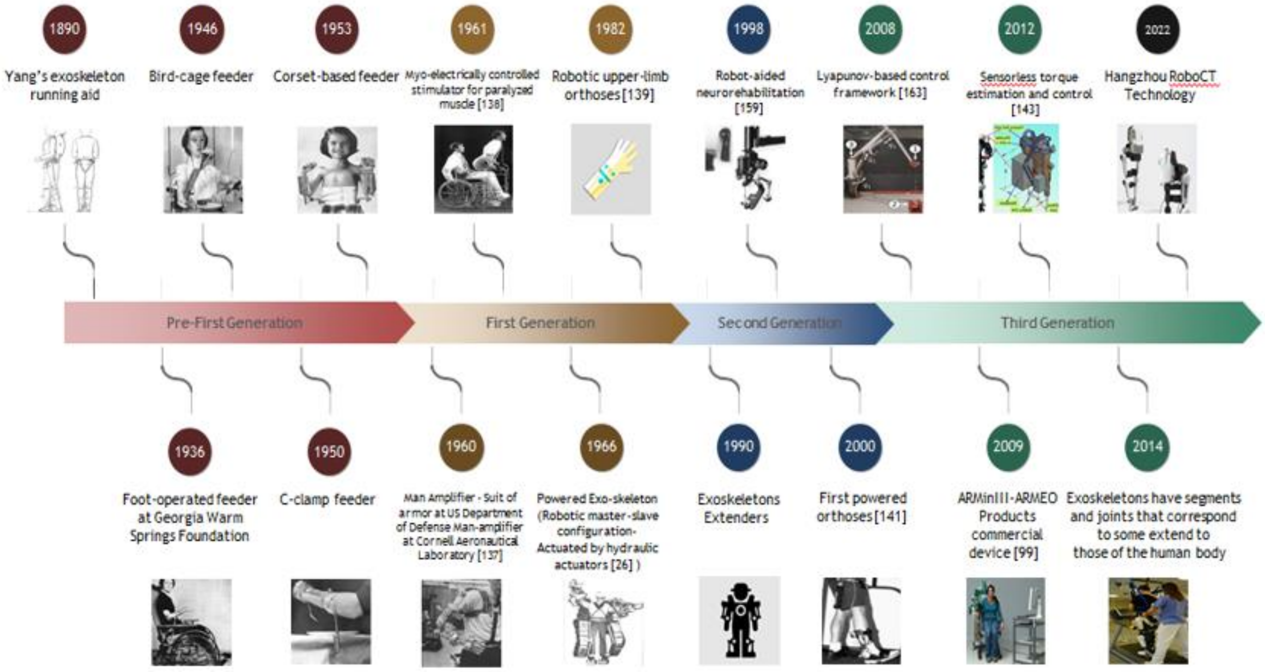

Figure 2: The historical development of exoskeleton assistive robots, with the most recognized research documented over three generations.

4. Robotic Exoskeletons

Robotic exoskeletons (REs) are designed to assist in healthcare, specifically for rehabilitation objectives related to the activities of daily life (ADL). Assistive technologies can be categorized into both upper-limb devices and lower-limb devices. These categories can be further divided into two types: prostheses and orthoses, as illustrated in Figure (3) [7]. Prostheses are artificial replacements that can be worn to compensate for a missing limb, whereas orthoses are orthopedic devices intended to support and treat physical abnormalities or enhance the functionality of movable body parts. Additionally, orthoses can be categorized into two types: those that are specifically created to align the end effector with the user, and exoskeleton robots that are engineered to align the joints of the device with the joints of the user. Exoskeleton Robots (ERs) are a distinct category of assistive robots designed to assist users in performing certain tasks or movements, hence improving the quality of life for individuals who require external assistance for their daily activities.

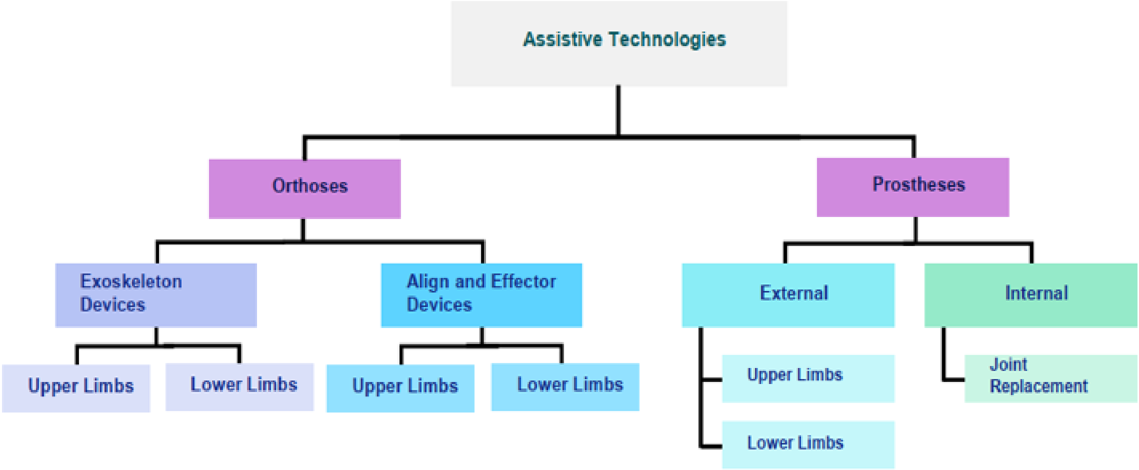

Figure 3: The classification of Assistive Technologies in the fields of Medical Robotics.

The significance of robotic exoskeletons in facilitating and assisting those with disabilities has been heightened due to the worldwide increase in the aging population. An "exoskeleton" is the rigid outer covering found in certain animals, which functions to safeguard and provide structural support to their body [19]. Humans possess internal endoskeleton, which means that current robotic devices have been built to be attached to the back, palm, or side of the human body. Furthermore, it is essential to consider specific criteria while designing REs, regardless of whether they are intended for assistive, rehabilitative, augmentative, or haptic purposes [2].

4.1 Classification

The classification of exoskeleton robots can be based on five main standards: the application scope, the Exo-structure design, the implemented technology for design, the robot interaction, and the body part involved (such as lower limbs or upper limbs), as illustrated in Figure (4).

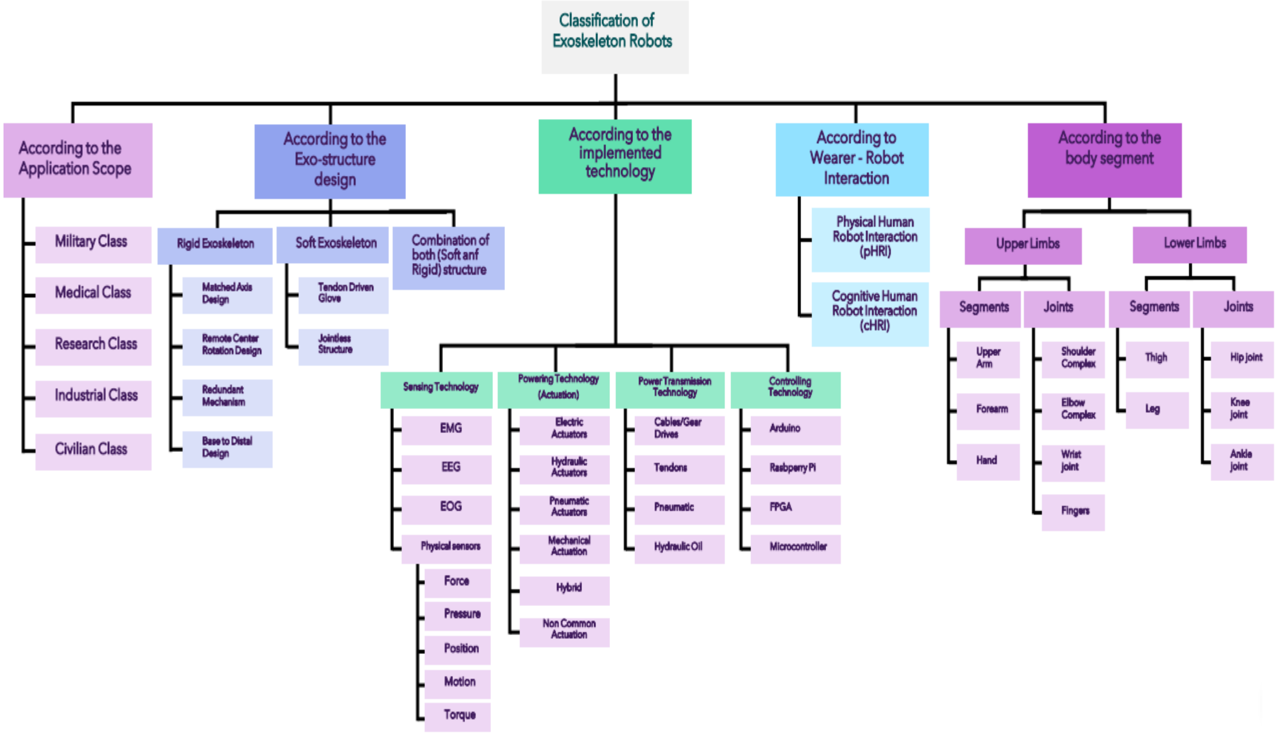

Figure 4: Comprehensive classification of Exoskeleton Robots.

4.1.1 Classification of Robotic Exoskeleton devices according to the Application Scope: Exoskeleton robots are categorized into five primary groups by their intended purpose. The REs can be categorized based on their evolutionary as follows: military class, medical class, civilian class, industrial class, and research class. An exoskeleton utilized in any military-related activity, including those carried out by the army, navy, air force, or any other armed forces falling under the military classification. The medical class consists of exoskeletons that are utilized in clinical activities, including operations, performance assistance, and rehabilitation. Another assisting category is the civilian category, specifically intended for utilization by individuals in their residences or public spaces to aid them in jobs that they are unable to effectively accomplish independently without support. Furthermore, the industrial class, as indicated by its name, consists of exoskeletons that are specially built for industrial purposes and can also be used for military applications. Ultimately, the research class includes exoskeleton robots that are now in the developmental phase, as well as any other types not addressed by the aforementioned classifications [20].

4.1.2 Classification of Robotic Exoskeleton devices according to the Exo-structure design: The classification of exoskeletons can be effectively based on the exo-structure design, which is determined by the materials employed, whether it's rigid, soft, or a combination of both. A rigid exoskeleton is an exoskeleton composed of inflexible construction materials, such as metal, plastic, or carbon fiber, that provide a solid and unyielding structure. The alignment of exoskeleton joints with the wearer's joints is crucial, and the design process usually takes into account the reduction of device size and the enhancement of joint movement flexibility. On the other hand, a soft exoskeleton, also known as Exosuits, is constructed using textiles. This design allows for greater flexibility in joint alignment and results in a smaller, lighter, and more energy-efficient device compared to rigid exoskeletons. Soft exoskeletons eliminate the hard frames found in standard exoskeletons, which is a significant disadvantage of the latter. Certain components, like as battery packs and controllers, need to maintain a rigid structure yet are typically stored in a backpack positioned behind the user. Power is exclusively delivered through flexible materials, such as Bowden cables or air muscles [2].

4.1.3 Classification of Robotic Exoskeleton devices according to the implemented technology: The implemented technology involves actuating technologies, power transmission, sensing technologies, and controlling technologies. The powering technologies are categorized into four primary classes, with one dedicated to hybrid technology and another for any other non-conventional power technology; consist of electric, hydraulic, pneumatic actuators for active motion, and mechanical systems for passive motion. The electric actuators encompass many types of electric motors that initiate the movements of the exoskeleton. Alongside advancements in powering technologies, power transmission techniques will incorporate the utilization of various methods such as gear drive, cable drive, linkage mechanism, belt drive, ball screw drive, or a hybrid combination of two or more methods [21]. The utilization of sensing technology, such as Electromyography (EMG) for muscle activity information or electroencephalography (EEG) for brain activity information, plays a crucial role in enhancing the device's efficiency to a higher level of intelligence and accuracy. In addition, controllers play a crucial role in the operation of devices, working alongside powering and sensing technologies. There are several options available for usage as controllers, including Arduino, Raspberry Pi, FPGA, and controllers equipped with Internet of things, or IoT, technology for tele-applications [2].

4.1.4 Classification of Robotic Exoskeleton devices according to Human-Robot Interaction: The category of Human-Robot Interaction (HRI) runs concurrently with the technologies of sensing and controlling. Human robot interaction is a crucial element in the design of exoskeletons, and it may be categorized into two types: cognitive human robot interaction (cHRI) and physical human robot interaction (pHRI). The pHRI plays a crucial role in ensuring comfort and safety for the wearer during manipulation with the exoskeleton robot. It encompasses various factors including actuation, power transmission, degree of freedom (DOF), and proficiency [22]. The suitability of an exoskeleton system can be assessed through the use of pHRI (physical human-robot interaction) techniques, which involve gathering kinematic and kinetic data using various sensing technologies such as potentiometers, encoders, electro-goniometers, accelerometers, gyroscopes, IMU (inertial measurement unit) strain gauges, piezoresistive sensors, and force/torque sensors. When designing exoskeletons, it is crucial to consider the measurement of the interaction forces between the device and the user's limbs. pHRI can be utilized to evaluate the user's proficiency in carrying out an activity, such as measuring the extent of exertion exerted by a patient in accomplishing a therapy [23].

In addition, cHRI evaluates the cognitive capabilities of the device's control system. The sense module collects data from both the human operator and device sensors, including bioelectric signals such as electromyogram (EMG) for muscle activity, electroencephalogram (EEG) for brain waves, and electrooculogram (EOG) for eye movements. Electrooculography can be employed to gather data from the human operator for the purpose of cHRI. The decision module analyzes the sensory data and coordinates the operations within the entire system. The execution module is accountable for the activation and provision of mechanical power [24].

4.1.5 Classification of Robotic Exoskeleton devices according to the human body segment: The design requirements of rehabilitation exoskeletons are greatly influenced by their unique application and the limb segment to which they are fitted. Hence, exoskeleton robots can be categorized into two distinct groups depending on the specific body part they aim to rehabilitate: the upper limb Rehabilitation Exoskeletons (ULREs) and the lower limb Rehabilitation Exoskeletons (LLREs).

- **ULREs:** The ULREs, are worn external devices designed to enhance the functionality of the human body by supplying the necessary force to mobilize crippled upper limbs. ULREs can be categorized as hand exoskeletons, forearm exoskeletons, whole upper-limb exoskeletons, or combination segment exoskeleton robots within the application segment category. The design process of these robots is intricate because they primarily depend on the upper limb segment for which they are intended, in addition to the intricate nature of human upper-limb anatomy [21]. The upper limbs exhibit a wide range of motion, encompassing various movements that vary in magnitude depending on the specific body part involved, such as the shoulders, forearm, arm, wrist, hand, and fingers.

One of the major issues in ULREs design along with the upper limbs movement wide range is the probability of joint axis misalignment between the body's joints and the device. This misalignment can result in significant interaction forces, increased motion torque, and contact pressure at the connecting points. This, in turn, causes discomfort for the user. It is important to note that any deviation from the recommended range of motion can have severe consequences, such as muscle tears or even damage to the joint [21].

Several studies have focused on addressing the issue of misalignment between the human body and the robot interaction. However, the wide range of movements in the upper limb and the unique specifications of each joint have posed challenges in finding a unified solution that encompasses all types of movements for all upper extremity joints. Referring to reference [25], the researchers proposed employing a unique linking mechanism for the shoulder joint and a compliant actuation system called NEUROExos. This approach aims to address joint misalignment and eliminate the external force exerted on the elbow joint. When it comes to wrist joint movements, many studies assume that robotic exoskeletons are designed with two axes of movement. However, the wrist joint requires four axes to achieve comprehensive movement, including wrist flexion, wrist extension, wrist radial deviation, and wrist ulnar deviation. This is necessary to generate wrist motions that are biomechanically similar to natural movements [26], [27].

Complex mechanisms are suggested in many cases to overcome the joint axes misalignment effect, and such methods are realistically infeasible in portable designs. Robot mechanical singularity shouldn't happen in the range of movements, or it should be in a good spot for anthropometry due direct human robot interaction which make safety a crucial condition is very. However some designs, though, can take this uniqueness into account [28], [29].

- LLREs: LLREs are wearable robots that aid with lower limb movement disorders. Gait impairment, which affects the quality of daily activities and can result from a wide range of neurotrophic disorders, is weakness or inability to move the lower extremities.

Utilizing lower limb robotic exoskeletons (LLREs) enables individuals to engage in repetitive walking exercises, which effectively improve motor function by promoting muscle group repair and strengthening [30]. Traditional gait rehabilitation involves performing treadmill exercises while receiving partial body weight support (BWS) and manual help from physiotherapists. An inherent drawback of this treatment is the demanding physical effort required from the patient, necessitating cautious manipulation of the weakened limb and supervision of the patient's core motions by the physiotherapists [31]. Consequently, there grew the need to create more advanced rehabilitation robots to surpass the constraints of traditional therapy.

Advanced LLREs systems have the potential to enhance user autonomy, enhance bowel and bladder function, alleviate chronic pain, decrease spasticity, increase bone density [32], and reduce the energy required by the user to move joints such as the knee, hip, and ankle, as the exoskeleton bears this load. Furthermore, offering physiotherapy sessions that are characterized by repetition, extended duration, and high intensity, all while minimizing the workload for therapists and decreasing healthcare expenses. In order to accurately assess patient improvement, many kinematic and dynamic parameters of limb movement, such as range of motion, velocity, and smoothness, are measured [33- 35].

From a design standpoint, again the wearability is a crucial characteristic for the development these robots in order to ensure compatibility between the human body (wearer) and the robot. Consequently, a thorough comprehension of lower limb anatomy and human gait analysis is necessary to support the design and control process. Gait is accomplished through the coordination of the pelvis, hip, knee, and ankle, which is regulated by the range of motion (RoM) to enable a diverse array of movements with varying extents. The movements of the pelvis joint include superior/inferior, lateral, anterior/posterior, obliquity, tilt, and vertical rotation. The hip joint allows for flexion/extension, adduction/abduction, and internal/external rotation. The knee joint primarily allows for flexion/extension. The ankle joint permits dorsiflexion/plantarflexion, adduction/abduction, and internal/external rotation [36]. The movement and structural parameters exert a substantial influence on the characteristics of human gait, such as step length, width, and speed, which are directly correlated with the range of motion (RoM). The earlier research have taken into account the main structural characteristics, such as joint angles, body height, and body mass index (BMI), in order to provide a foundation for controlling lower limb rehabilitation exoskeleton robots [35].

The LLREs are categorized into two groups based on the type of gait training: the fixed stationary system and the movable overground walking system. The fixed exoskeleton systems are designed to mechanize traditional therapies, such as those that involve treadmills or programmed foot end-effectors. Treadmill-based systems utilize a robotic exoskeleton or orthotic that is connected to the patient's lower limbs. These systems unload a portion of the patient's weight during the stance phase of their walking pattern [33]. Mobile exoskeleton systems have been developed to assist with human motion and rehabilitation for patients who have lost all mobility in their lower limbs. These systems apply external torque to the joints in the lower limbs to compensate for the patients' impaired motor function, allowing them to perform everyday movements [37]. In contrast to stationary systems, powered mobile systems are smaller, lighter, and easier to move, making them suitable for future residential use [35].

4.2 Applications

Investigating the robotic exoskeleton applications, it was found that they are mainly emerging in the medical field, including therapeutic, rehabilitative, assistive, haptic, and augmentative exoskeleton robots. Some of these applications intersect and converge with each other within the overarching and essential category of rehabilitative exoskeleton robots. Rehabilitation-assistive exoskeleton robots, as well as rehabilitative haptic exoskeleton robots, can be found. Exoskeleton robots, regardless of their application, must meet specific criteria, including safety, comfort, affordability, adaptability, and most importantly, wearability, due to their direct interaction with the human body. To meet these requirements, all programs mentioned below must possess certain essential attributes to guarantee enhanced efficiency and user safety.

4.2.1 Therapeutic Exoskeletons: The utilization of therapeutic exoskeletons provides substantial advantages for individuals with mobility problems. Robotic exoskeletons can assist in both injuries and postoperative rehabilitation. Exoskeletons are employed therapeutically to provide joint or muscular support, allowing individuals to accomplish otherwise unattainable actions, such as grasping objects, consuming food and beverages, transitioning from sitting to standing, and walking independently. The primary purpose of this gadget is to facilitate the restoration of an individual's capacity to move autonomously by assisting at vital points.

4.2.2 Rehabilitation Exoskeletons: Rehabilitative exoskeletons designed to aid individuals in their recovery process following an injury or surgical procedure. These devices enhance strength, mobility, and endurance by facilitating continuous passive motion therapy. They achieve this by enabling the limbs to move within their typical range of motion using upper limb braces and lower limb gait trainers. These exoskeletons are specifically created to aid in the rehabilitation of individuals with disabilities and motion impairments. They assist therapists by performing repetitive actions and motions, such as flexing and extending the limbs, to imitate activities of daily living (ADL). As per the physiotherapy training regimen and rehabilitation practitioners, these devices apply substantial force on the patient's limbs to reduce joint and tendon stiffness. The user's text is "[38]."

4.2.3 Assistive Exoskeletons: Assistive robots are specifically engineered devices that aid individuals with limited mobility in accomplishing their everyday activities with greater self-reliance than they would typically be capable of. These robots achieve this by reinstating the ability to move and enhancing physical activity levels long after an injury has occurred [39]. These devices can enhance quality of life by reducing sedentary behavior, increasing time spent standing and walking, and facilitating social interactions through the provision of mobility aids such as wheelchairs and ramps. Moreover, the software applications enable individuals with restricted motor abilities to interact with the robot via methods such as voice commands, head gestures, eye tracking (e.g., eye glances), or brain signals.

4.2.4 Haptic Exoskeletons: Robotic haptic devices are a type of hybrid robotic exoskeletons utilized in rehabilitation. They range in design from basic gloves to comprehensive exoskeletons capable of accommodating all of a human's limbs. Typically, these gadgets incorporate feedback sensors that offer therapists immediate data for monitoring the patient's advancement and assessing the extent of the damage. Integrating the hand exoskeleton rehabilitation system with fingertip haptic stimulation is a beneficial addition to improve the outcomes of the rehabilitation process. This is achieved by coordinating the fingertip haptic stimulation with the movement of the hand exoskeleton, as well as incorporating virtual interaction with objects in certain applications.

Engaging in rehabilitation training actively leads to improved treatment results, as it allows for the collection of data on regular hand movements to assess the progress of the restored limb. Haptic robotic rehabilitation devices facilitate the assessment of several aspects of everyday tasks, such as precise manipulation, retrieval, and placement of objects. Furthermore, the haptic robotic rehabilitation devices incorporate virtual access exercises that can be tailored to the patient's unique requirements. These devices also have the capability to adjust to the patient's range of motion, making them beneficial tools for both the patient and therapist. Additionally, they offer the potential to improve activities of daily living on mobile devices. Ultimately, including this method into rehabilitation programs has the potential to captivate patients and enhance therapy outcomes [40].

4.3 Treatment Modalities

Choosing a suitable treatment module is a critical option for rehabilitation therapists. This choice signifies the commencement of executing an efficacious treatment regimen for the patient. The rehabilitation treatment modules consist of three types: active treatment, passive treatment, and mirror treatment. Every therapy module is specifically tailored to target specific concerns based on the patient's ability to effectively use the training technique. The therapist aims to determine the most efficient method for treating the damaged limbs, taking into account the individual conditions of the case.

4.3.1 Active Treatment: This type of treatment is recommended for patients who can move their impaired limb to a certain extent. The term "active" refers to the ability to move the impaired limb, although inefficiently. Active treatment is divided into two types: active assistive treatment and active resistive treatment.

- Active Assistive Treatment entails the utilization of a robot to apply an external force, aiding the patient in accomplishing a designated job, such as enhancing the range of motion. In reference to the case study [41], a patient with compromised shoulder and elbow function had active-assistive therapy. During this therapy, the patient was instructed to reach a designated objective, while a robot attached to them provided assistance in accomplishing the job. When the patient's performance of the activity was incomplete and ineffective, the accompanying robot intervened [42]. Empirical evidence has demonstrated that this therapeutic approach has substantially enhanced the mobility of affected limbs [43].
- Active Resistive Treatment is a method that uses a robotic device to apply a force in the opposite direction to the affected limbs [44]. The gradual increase of the opposing force results in a progressive enhancement of patients' performances. This enhancement can be expedited by employing an algorithm

that computes the suitable counteracting force based on the patient's specific capability [45]. The primary objective of this treatment is to improve the arm's sustained muscular strength over an extended period of time [38].

4.3.2Passive Treatment: Passive therapy is a treatment method that does not need any effort from the patient. It is commonly employed in the initial phases of post-stroke symptoms, particularly when the affected limb does not respond or to evaluate the range of motion of the limb [46]. Hemiplegia patients with unilateral paralysis are commonly recommended passive treatment. The process involves repetitively moving the injured limb along a predetermined path, using stretching and contracting techniques, during each session [47]. The rehabilitation robot often performs this treatment by employing repetitive motions that are based on the range of motion (RoM) of the afflicted limb [42]. Given that the movement's trajectory is carefully orchestrated to prevent any injury to the patient. Multiple studies have verified that passive therapy is highly successful in reducing spasms and stiffness in damaged limbs [38].

4.3.3 Mirror Treatment: The rehabilitation technique of mirroring treatment is commonly known as bilateral therapy or bimanual training. Mirroring treatment is a rehabilitation approach that relies on the inherent synchronization between limbs. Training post-stroke patients with tasks that require the use of both hands enhances the effectiveness of grasping actions on the damaged side. This is followed with alterations in brain mappings on the affected hemisphere [48]. When the damaged limb imitates the motion of the functional limb, the user possesses full command over the affected limb [49]. The Mirror Image Movement Enabler (MIME) and a small number of other exoskeletons utilize mirroring treatment [50]. In accordance with reference [51], a total of fourteen individuals took part in the study and underwent professional training utilizing an exoskeleton robot equipped with mirroring treatment mode. The study was carried out during the initial six months following a stroke, and the findings demonstrated a notable improvement in both the affected hemisphere and motor abilities [43].

5. Design Implementation

Exoskeleton robot design consists of two parts: hardware and software. The hardware part includes all of the hardware requirements such as the controller, sensors, and actuators, while the software part includes the code that is embedded inside the controller as well as the therapists' treatment definition. The hardware and software designs will differ depending on the dominant applications and functions. Exoskeleton devices can be used for a variety of purposes, including rehabilitation, assistance, and haptics.

5.1 Hardware: The Robotic exoskeletons' system architecture is depicted in the block diagram shown in Figure (5). It is made up of three major components: a sensor circuit, a controller, and an actuator. The sensors will make contact with the human body to obtain a direct signal, which will then be sent to the controller, who will read the signal from the sensor, analyze it, and send the instruction to the motor controller, which will directly control the part of the body for which the rehabilitation device is designed. The sensor, actuator, and controller requirements will vary depending on the application and the targeted limp. In this section, the device requirements for various researchers will be investigated based on the types of sensors, controllers, and actuators.

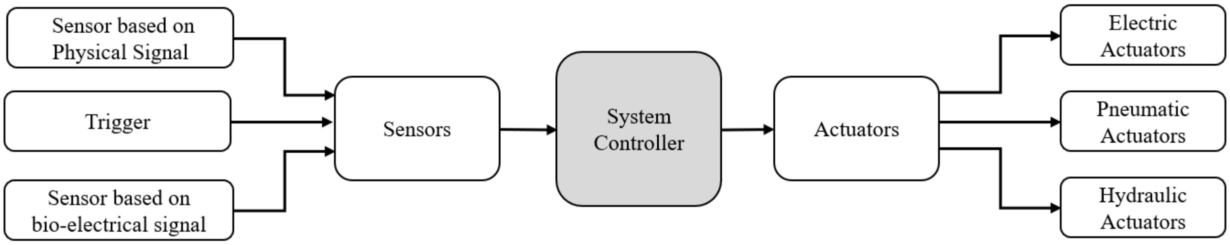

Figure 5: System architecture of the Robotics exoskeleton

5.1.1 Sensors: Monitoring the interaction force and motion between the patient and the robot is a critical component of rehabilitation robotic system control. This is typically a difficult process that necessitates the use of precise sensors, raising the cost and complexity of the robotic equipment. The sensor detects human data and sends feedback or control signals to humans or robots. Rehabilitation robot devices can use a variety of signals, including physical signals, triggers, and bioelectrical signals [48], [53].

- Sensors based Physical Signal: The sensors that detect physical signals, including position (motion) and force, are the most numerous in the hand rehabilitation robot system. The purpose of the force or position signal is to furnish data regarding the tangible condition of a specific hand segment, as illustrated in Figure (6). This data may include the bending angle of the finger or the applied force of motion. In a study conducted by [53], a virtual sensor was developed to serve as a substitute for the physical force and motion sensors utilized in the Universal Haptic Pantograph (UHP) rehabilitation robot, which is designed to train upper limbs. These virtual sensors evaluate force and motion at the point of contact between the patient and the robot by employing a mathematical model of the robotic device and data obtained from low-cost position sensors. A sophisticated position/force controller for the UHP rehabilitation robot was equipped with the proposed virtual sensors so that their performance could be experimentally evaluated. As demonstrated by the experimental findings, the controller's performance when virtual sensors are utilized is equivalent to that when direct measurement is utilized (less than 0.005 m and 1.5 N difference in mean error). Therefore, actual precise yet frequently costly sensors, which are essential components for sophisticated control of rehabilitative robotic systems, can be substituted with the proposed virtual sensors for estimating contact force and motion.
- Trigger: The trigger is an electrical switch that can control the output or switch between several actions. The primary benefit of the switch is that it provides a basic control framework and is reliable, whereas the disadvantage of this type of trigger is that the switches must be turned on and off by another hand or person, which can be difficult with some rehabilitation devices [2].
- Sensors based Bioelectrical Signal: Bioelectric sensors, which detect bioelectrical signals such as EEG, EMG, or EOG signals and are used in hand rehabilitation, are another important type of sensor. The bioelectrical signal's purpose is to reflect the human's intended motion, which can then be used as robot control signals. Other possible but inconvenient signals include magnetic resonance imaging (MRI), EEG, and EMG signals, which are the most representative signals received from the brain and muscle.

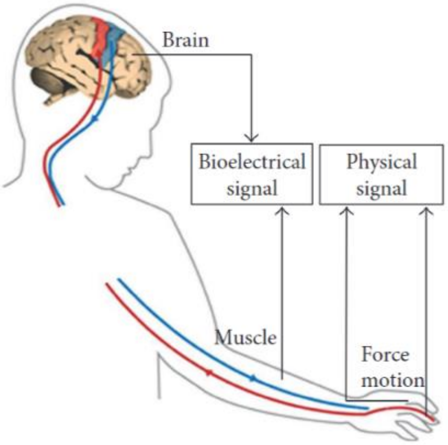

Figure 6: Source of two kinds of signals, bioelectrical and physical [54].

Electromyograph (EMG): EMG is a technique for measuring and recording the electrical activity of skeletal muscles. The electrical potential generated by muscle cells in response to electrical or neurological stimulation is measured by an EMG. Medical problems, activation level, recruitment order, and human body movement biomechanics can all be determined using the signals.

An electric potential is generated by a single muscular membrane. The EMG potential ranges between 50 V and 30 mV, depending on the type of muscle and the conditions present during the observation. EMG signals are used in a variety of clinical and biological applications, including identifying neuromuscular diseases, measuring low-back pain, kinesiology, and motor control issues. Control signals for prosthetic equipment, such as prosthetic hands, arms, and lower limbs, are frequently generated. New low-noise technologies can detect even isometric muscular activity, which produces no movement, which has significant implications for neurological and neuromuscular disorders [55].

An electromyograph (EMG) signal must be efficiently retrieved for use in rehabilitation robots. The EMG signal can be obtained in two ways: invasive (which produces intramuscular electromyography (iEMG)) and noninvasive (which produces surface electromyography) (sEMG). The intrusive technique involves inserting electrodes into the muscle's motor units, whereas the noninvasive technique involves inserting electrodes into the muscle's belly, which provides maximum contraction. Despite the fact that iEMGs produce reliable EMG signals, sEMGs are frequently used because they are patient-acceptable and do not require any intrusive treatment. The circuit consists of three electrodes: one for the reference electrode, one for the active electrode, and one for the ground electrode [48]. The difference signal between the reference and active electrodes is processed by the AD620 Operation Amplifier to reduce noise in the system. The design of the electrodes attracts unwanted signals from the surrounding environment. As a result, the electrode signals must be routed through wires to the AD620 instrumentation amplifier. As a result, the noise in both inputs will be illuminated while the action potential (the EMG signals) will be preserved [133]. Using the EMG signal as a control input for robots entails several steps, starting with selecting the appropriate muscle to collect the EMG and then amplifying the extracted EMG to be processed and categorized by a PC [38].

Electroencephalography (EEG) sensor: EEG sensors measure voltage changes caused by ionic current flows within the brain's neurons and capture electrical activity along the scalp. The brain's electrical charge is maintained by billions of neurons. Membrane transport proteins that push ions across neuronal membranes electrically charge them [57]. EEG is the most studied prospective used in brain-computer interface (BCI), and it is extensively studied for motor rehabilitation [58]. One of the preferred and effective methods is to use the attention threshold measured by an electroencephalography (EEG) sensor as a brain-controlled switch for exoskeleton robots [40]. Because of its fine temporal resolution, portability, ease of use, and low set-up cost, but also because of the technology's noise susceptibility [59], this method is characterized as a non-invasive interface.

Electrooculography (EOG) sensor: The active cornea-retina standing potential between the back and front of the human eye is measured by the EOG signal. This signal is typically used in conjunction with EEG signals to carry out specific tasks [2].

Physical and bioelectrical sensors are used with the upper and lower limbs depending on the application, as shown in Figure (7). Furthermore, EMG-driven rehabilitation robots outperformed passive rehabilitation robots, as demonstrated by [38] in a discussion of the most commonly used rehabilitation robots and their efficacy in clinical studies. More clinical research is needed to determine the effectiveness of rehabilitation robots based on their control mechanisms.

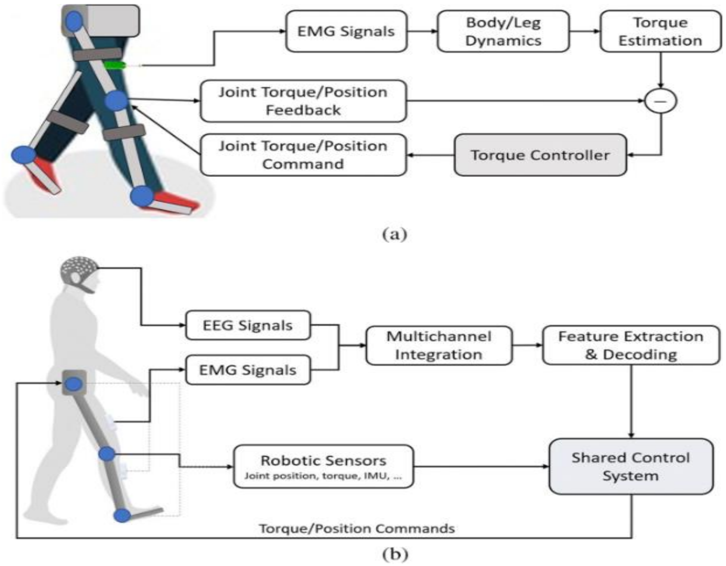

Figure 7: The control scheme of the lower limb exoskeleton [60].

5.1.2 Actuators: A device that converts energy into physical motion to provide mechanical power for exoskeletons is known as an actuator, and most actuators produce rotational or linear motion. The three basic types of actuators are hydraulic, pneumatic, and electric, and the best one to use depends on the type of robotic structure being built [23]. Hydraulic actuators generate motion by using pressured oil. They are most commonly found in large machinery and can generate tremendous force. Pneumatic actuators are similar to hydraulic actuators in many ways. To generate motion, compressed air is used instead of compressed oil. Magnets and electric current are used in electric actuators.

- Hydraulic Actuators: In mechanical systems, hydraulic actuators—like fluid chambers—are frequently used. An essential component of these systems is actuator efficiency, which is lowered by the energy needed to overcome friction force. Wearable rehabilitation robots are among the applications for hydraulic actuators [56], [61].
- Pneumatic Actuators: FREA, inflatable chambers, and pneumatic artificial muscles are all varieties of pneumatic actuators. Pneumatic actuators provide a multitude of degrees of freedom, facilitate the support of structural forms, and are versatile and lightweight as fundamental benefits. Nonetheless, pneumatic actuators are not without their limitations [62], [63], including the requirement for compressed air and a reservoir, incorrect forces, leak issues, and restricted mobility.
- Electric Actuators: Muscle wires, tendon-driven actuators, and shape memory alloys comprise the three classifications of electric actuators. This actuator is the most frequently mentioned component in the literature regarding powered exoskeletons due to its ability to be controlled with high precision, its

cable paths minimizing friction, its provision of continuous forces, its capacity for energy storage, and its commercial availability. The power-to-weight ratio is low, and the operational hours of operation are restricted; these are the only drawbacks of electrical actuators [23]. Additionally, the transmission is complicated.

- Hybrid Actuators: Hybrid actuators are used in exoskeletons that use a combination of two or more primary classes from the hybrid class. The most common hybrids use electrical actuators and mechanical systems, but they are not the only ones. SEA (series elastic actuators), which are electric actuator-mechanical system combinations, are also among the most widely used hybrids [64].

All actuators can be classified as passive or active; mechanical systems provide passive action in the four major classes, while electric, hydraulic, and pneumatic actuators provide active action. Electric actuators include any electric motor that drives the exoskeleton's movements.

Pistons and soft actuators are used in both hydraulic and pneumatic actuators. They have a good power to-weight ratio, but their nonlinear behavior makes accurate positional control difficult. Mechanical systems are defined as any system that stores or transmits mechanical energy (for example, springs and dampers) [64]. PAMs, also known as McKibben-type actuators, are a type of pneumatic actuator that is widely used in exoskeletons [65]. In such actuators, an internal bladder is surrounded by a braided mesh shell with flexible but nonextensile threads. When the bladder is pressed, the actuator expands and contracts in proportion to its volume, resulting in tension at the actuator's ends.

The correct positioning of actuators for an exoskeleton robot requires prior determination. Thus, proximity between the actuators and the actuated joints was possible. To optimize power transmission, this configuration employs direct drives on joints. Nevertheless, as the distal segment of the exoskeleton gains mass, the overall system becomes more difficult to control due to inertia. However, the weight and inertia of the distal portion are diminished when the actuators are positioned in the portion that remains constrained. However, a system of mechanical power transmission is required. This complicates the mechanical design and may impede control as a result of friction [35].

5.1.3 Power Transmission: Power transmission is responsible for conveying the actuator's motion in the correct direction so that the joint can move. Mechanical, electrical, and pneumatic power transmission systems are all viable alternatives, along with tendon drive, Bowden cable, gear drive, linkage mechanism, cable drive, and hydraulic drives.

- Mechanical Power Transmission Systems: are primarily utilized in the engineering industry to transfer mechanical energy from one machine component to another, including shaft couplings, chain drives, and gear drives. The mechanical power transmission system, such as Bowden cables, is utilized by rehabilitation robots to transmit force and torque from the motor to the exoskeleton joint.
- Linkages: are widely utilized alternatives in hand rehabilitation robot systems, similar to the traditional mechanical design. The linkages are portable, lightweight, and easy to manipulate in accordance with a pre-established path.
- Cables: The pulley cable and Bowden cable, for example, are frequently used as transmission in hand rehabilitation robots. The use is limited by the pulley's requirement for constant tension in order to maintain traction on the pulleys. The Bowden cable, on the other hand, is superior because it is flexible and includes a cable conduit. The curve's variable and high-friction force is a disadvantage [54].

5.1.4 Degree of Freedom: In mechanics, degrees of freedom (DOF) refer to the number of independent variables that specify the potential positions or motions of a mechanical system in space. DOF measurements assume that the mechanism is rigid and unrestrained, regardless of whether it is operating in two-dimensional or three-dimensional space. The degree of freedom (DOF) of a robotic arm is a separate joint that allows the manipulator to freely move in both rotational and translational (linear) directions; one actuator is required for each degree of freedom.

The number of degrees of freedom required for the upper/lower limb exoskeleton depends on the number of active joints in that limb, such as 1 DOF, 2 DOF, 3 DOF, and so on. For example, to build a hand robot, five DOF are required, one for the thumb and one for each finger [48].

5.1.5 Controller: Microcontrollers are essential components in automated products. Recent improvements have significantly lowered the available size and price. The microcontroller is connected to the sensors and actuators in a robotic rehabilitation device, the signal obtained from the sensor is an input to the controller and the actuator action is the output. The microcontroller will read the signal from the sensor, which could be a physical signal, an electrical signal, or a bioelectrical signal, depending on the type of sensor used, analyze it internally, and send it as an output to the actuators. Figure (5) depicts a schematic diagram of the robotic rehabilitation system, which consists of three primary units: a sensor, controller, and actuators. Depending on the functions required, several controllers like Arduino, Raspberry Pi, and FPGA can be utilized. Because Arduino microcontrollers are open source, they are significantly less expensive in most projects. On the other hand, the Raspberry Pi, as a microcomputer, offers more functionalities, most notably internet connectivity and a desktop interface, but lacks the analogue-to-digital converter (ADC) found in Arduino boards.

Several researchers have completed projects based on both the Raspberry Pi and the Arduino. One approach for connecting the Arduino and Raspberry Pi is to use an RF24L01 and a wireless transmitter, which allows wireless data transmission between two or more devices [64]. However, some studies have shown that using a Real-time control system based on Field Programmable Gate Array (FPGA) can implement many computational operations under deterministic constraints. Furthermore, the advantage of the real-time system, which deploys FPGA, is that it can perform with a high clock rate (over 20MHz). This helps in the data acquisition process and data output with high resolution. Some researchers used FPGA as a main controller [52], [67], [68].

While a digital signal processor can be used as an embedded circuits system as shown in [56], the authors used a microprocessor with Harvard architecture to read the signal from the sensor, process it then control the motor which is used to power the body-hand.

5.2 Software

The design of the exoskeleton robots consists of two main phases, hardware, and software phase. The hardware part includes the sensors, controller, and actuators implementation, as described above. While the software part is about choosing the software that matches the controller then write the code and upload it into the controller. Different types of software can be used with ERs depending on the controller types, such as MATLAB, Arduino IDE, Raspberry Pi OS, and Quartus II. The software part usually consists of three stages, collecting data from the sensors, processing the data, and then sending the signal to control the actuators.

6. Results and Discussion

By sequentially applying a descriptive analysis method and consulting secondary databases containing information from a number of significant studies conducted in this field, a comprehensive picture has been constructed that examines the necessity and significance of exoskeleton robots through the chronology of their development. By summarizing the findings obtained from secondary databases, it became feasible to offer a broad overview of the information necessary to properly understand the significance of these robots and the critical applications they serve.

Robotic exoskeletons are a subset derived from assistive technologies that vastly enhance the quality of life in various manners. Exoskeleton robots encompass a diverse range of applications, serving in several sectors including laboratories, manufacturing, augmentation, agriculture, urban development, and military operations. Simultaneously, these robots play a significant role within the medical domain, serving as auxiliary, supportive, and potentially therapeutic devices.

This study aims to assess the efficacy of robotic exoskeletons in the medical domain, with a particular focus on their application in the field of rehabilitation. Gaining knowledge about the anatomical structure of the human body, particularly the upper and lower extremities, while considering the degree of freedom and motion ratio, is crucial in determining the requirements for designing and implementing the device. This understanding is essential for making the correct decisions regarding the system architecture, the relationship between the input signal received from the sensors and the resulting output motion produced by the actuators is determined by the system control. This connection ensures that the system achieves a precise degree of freedom, as previously mentioned. The systematic architecture design of the robotic exoskeleton's must be determined based on the therapy modality that the device will provide, considering whether it will employ an active, passive, or mirror treatment strategy, as well as the targeted area of the human body.

7. Conclusion

In this review, a comprehensive investigation of the development of robotic exoskeletons covers their categorization, utilization, and therapeutic approaches. The examination of the evolution of REs encompasses an analysis of their historical origins, following progression from the early stages state to the current advanced iterations across three generations. The first generation of robotic exoskeletons has evolved from full exoskeletons to wearable robots designed to enhance human physical capabilities for industrial and army purposes. The second generation saw the development of robotic upper-limb orthoses and assistive robots for health-related issues. In the third generation, robots became a commercialized products used for medical, therapeutic, and rehabilitative applications, to improve the quality of life for older individuals and those with disabilities.

The first part of this article discussed the REs classification, their applications, and the treatment modalities utilized within this scope. The REs classification section state that the robotic exoskeletons can be categorized based on their application scope, Exo-structure design, implemented technology, human-robot interaction HRI, and the human body segment that the robot is applied to, whether it is used for the upper or lower extremities. In the REs applications section, therapeutic, rehabilitative, assistive, and haptic applications were discussed. Finally, the treatment modalities section addressed one of the most crucial and delicate issues, which is the selection of the correct treatment method for the correct patient case including active, passive, and mirror treatment.

On the other hand, the design implementation discussed in deep taking in consideration both the hardware and software aspects. The hardware section included sensors, actuators, power transmission, degree of freedom and controllers. There are many types of sensors can be used for REs design in order to monitor the interaction force and motion between the patient and the robot including sensors based physical signal, trigger and sensors based bioelectrical signal such as electromyography (EMG), electroencephalography (EEG) and electrooculography (EOG) sensors. In addition, providing mechanical power to the robot actuation is required, there are different types of actuators including hydraulic, pneumatic, electric and hybrid actuators. Power transmission important to transmit the motion of the actuator in the right direction, includes mechanical power transmission systems, linkages, and cables.

Conflicts of Interest

The author(s) declare(s) that there are no conflicts of interest in the context of the publication of this manuscript.

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