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Wajdi Sadik Aboud
Al-Nahrain University

Sallehuddin Mohamed Haris
Universiti Kebangsaan Malaysia

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A Review Study for Robotic Exoskeletons Rehabilitation Devices

Rafal Khalid Saleh [1*], Wajdi Sadik Aboud [2], Sallehuddin Mohamed Haris[3]

Authors affiliations:
1*) Prosthetics and Orthotics Engineering Department, College of Engineering , Al-Nahrain University, Baghdad, Iraq .
rafalkhalid295@gmail.com

2) Prosthetics and Orthotics Engineering Department, College of Engineering, Al-Nahrain University, Baghdad, Iraq.
wajdisadik@gmail.com

3) INDICES Research Group, Department of Mechanical & Manufacturing Engineering, Faculty of Engineering & the Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia.
sallehmh@ukm.edu.my

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Abstract

Nowadays, robotic exoskeletons demonstrated great abilities to replace traditional rehabilitation processes for activating neural abilities performed by physiotherapists. The main aim of this review study is to determine a state-of-the-art robotic exoskeleton that can be used for the rehabilitation of the lower limb of people who have mobile disabilities as a result of stroke and musculoskeletal conditions. The study presented the anatomy of the lower limb and the biomechanics of human gait to explain the mechanism of the limb, which helps in constructing a robotic exoskeleton. A state-of-the-art review of more than 100 articles related to robotic exoskeletons and their constructions, functionality, and rehabilitation capabilities are accurately implemented. Moreover, the study included a review of upper limb rehabilitation that has been studied locally and successfully applied to patients who exhibited significant improvements. Results of recent studies herald an abundant future for robotic exoskeletons used in the rehabilitation of the lower extremity. Significant improvement in the mechanism and design, as well as the quality, were observed. Also, impressive results were obtained from the performance when used by patients. This study concludes that working and improving the robotic devices continuously in accordance with the cases are necessary to be treated with the best results and the lowest cost.

Keywords: Lower Limb, Exoskeletons, Gait, Rehabilitation, Passive And Active.

دراسة مراجعة للهياكل الخارجية الروبوتية في اجهزة اعادة التأهيل

رفل خالد صالح ، وجدي صادق عبود , صلاح الدين محمد حارس

الخلاصة:

في الوقت الحاضر ، أظهرت الهياكل الخارجية الروبوتية قدرات كبيرة لاستبدال عمليات إعادة التأهيل التقليدية لتفعيل القدرات العصبية التي يقوم بها أخصائيو العلاج الطبيعي. الهدف الرئيسي من هذه الدراسة الاستعراضية هو تحديد الهيكل الخارجي الروبوتي الأكثر حداثة والذي يمكن استخدامه لإعادة تأهيل الأطراف السفلية للأشخاص الذين يعانون من إعاقات حركية نتيجة للسكتة الدماغية وأمراض الجهاز العضلي الهيكلي. تم عرض في هذه الدراسة تشريح الطرف السفلي والميكانيكا الحيوية للمشي البشري لشرح آلية الطرف للمساعدة في بناء الهيكل الخارجي الروبوتي. تم تنفيذ بدقة مراجعة لأكثر من ١٠٠ مقالة حديثة تتعلق بالهياكل الخارجية الروبوتية ، تصنيعها ، وظائفها، قدراتها في إعادة التأهيل. علاوة على ذلك ، تضمنت الدراسة مراجعة إعادة تأهيل الأطراف العلوية التي تمت دراستها محليًا وتم تطبيقها بنجاح على المرضى الذين أظهروا تحسننا كبيرا. تبشر نتائج الدراسات الحديثة بمستقبل وافر للهياكل الخارجية الروبوتية المستخدمة في إعادة تأهيل الأطراف السفلية. لوحظ تحسن كبير في الآلية والتصميم ، فضلا عن الجودة. كما تم الحصول على نتائج مبهرة من الأداء عند استخدامها من قبل المرضى. خلصت هذه الدراسة إلى أن العمل على تحسين الأجهزة الروبوتية بشكل مستمر وحسب الحالات ضرورية للمعالجة بأفضل النتائج وبأقل تكلفة.

1. Introduction

In Iraq, many people suffer from mobile disabilities due to stroke, musculoskeletal conditions, and previous wars. These individuals have a life with low-risk factors that allow them to live longer. Therefore, their treatment also needs to be improved by using modern rehabilitation techniques. One of these treatments is the use of robotic exoskeletons. Exoskeletons are developed as external devices fitted to the human body to enable their users to perform at a level they cannot execute on their own. The exoskeletons for lower limb rehabilitation, as well as some information about the exoskeletons for upper limb rehabilitation, are the main topics of this study. The study screened more than 100 papers in the area of these topics.

Stroke patients are the individuals that benefit most from these exoskeletons. Stroke is a fatal disease that has recently shown accelerated growth and high death and disability rates; 85% of stroke patients lose their ability to walk [1][2]. Also, the spinal cord injury (SCI) patients who suffer from paralysis can use these exoskeletons to enhance recovery.

Rehabilitation exercises are classified as either passive (P) or active (A). In passive, therapists or the robot actively assist the subjects in moving the affected parts, whereas in A exercises, the subjects must exert effort to move the affected parts without physical assistance [3].

The main goal of this study is to provide helpful information with the help of robotic exoskeletons to allow all workers in this field to know the fundamental principles and stages of using these robotic devices and how to improve them. This study contains comprehensive and very accurate sources on robotic exoskeleton. Also, the study aims to focus on the recent developments and challenges and restrictions that the researchers encountered in their works.

This study is structured as follows: Section 2 presents a brief information about the lower limb's anatomy. Section 3 discusses biomechanics in great detail. Section 4 presents the kinds of lower limb exoskeletons. Sections 5 and 6 discuss the definitions of A and P and the rehabilitation of the upper limb, respectively. The final section includes the main conclusion remarks.

2. Anatomy of the Lower Limb

Without a full understanding of the anatomy of the lower extremities, comprehending the mechanics, movements, and potential issues with each joint and the entire lower extremity may be difficult. The trunk extends down to the lower limbs(extremities), which are designed to support body weight and allow movement, locomotion, and balance maintenance [4-6]. To place a foot on the ground and move the body over these feet, the movements of all lower limb joints must be coordinated [7]. The pelvic girdle, thigh, leg, and foot are the bones that make up the lower limb. Fig. 1 shows the three primary joints: the hip, knee, and ankle. Each leg possesses seven degrees of freedom (DOF), with three DOF at the hip joint, one DOF at the knee joint, and three DOF in the ankle joint [9]. The DOFs of a leg are illustrated in Table 1.

Figure (1): Lower limb anatomy [11]

Table (1): Stage of the gait cycle

No	*Left leg*	*Right leg*
1	*Pre-swing*	*Heel strike*
2	*Toe off*	*Loading response*
3	*Mid swing*	*Mid stance*
4	*Terminal swing*	*Terminal stance*
5	*Heel strike*	*Pre-swing*
6	*Loading response*	*Toe off*
7	*Mid stance*	*Mid swing*
8	*Terminal stance*	*Terminal swing*

A. Hip the hip is a ball and socket joint, that is surrounded by highly powerful, well-balanced muscles. The hips not only transmit pressures from the bottom up, but they also convey forces from the trunk, head and neck, and upper extremities [10].

B. Thigh or femoral region This portion or region of the lower limb is found between the gluteal, abdominal, and perineal regions proximally and the knee region distally.

C. Knee The knee joint is one of the body's most complex joints that offer an extensive range of motion in the sagittal plane for flexion and extension, as well as the frontal plane for rotation in the varus and valgus positions because of its hinge joints. It also allows the knee to rotate laterally at the end of the knee extension and medially at the end of the knee flexion in the transverse plane. The knee maintains its stability throughout various forms of activities. It is composed of two bony articulations: the femur-tibia articulation carries the majority of the body's weight, whereas the patella-femur articulation transfers forces produced by the quadriceps femoris muscle contraction frictionless over the knee. The patellofemoral joint and the femorotibial joint, which make up the knee's two primary joints, allow the knee to move in three planes (e.g., sagittal, transverse, and frontal). A body part can move in six different ways, such as by flexion, extension (in the sagittal planes), internal and external rotation (in the transverse plane), and varus and valgus stress (in the frontal plane) [12].

D. Leg is the portion of the body between the knee and the malleoli, which are rounded prominences that flank the ankle joint.

E. Ankle The joint capsule, ligamentous support, and bony congruence all contribute to the stability of the ankle joint. Three primary supporting ligaments make up the syndesmosis that forms the inferior tibiofibular joint. The anterior inferior tibiofibular ligament comes first (AITFL). This flat, powerful ligament connects the lateral malleolus' anterior edge to the tibia's anterolateral tubercle. Superficial and deep sections make up the posterior inferior tibiofibular ligament. The superficial part works with the AITFL to keep the fibula firmly confined within the incisura of the tibia. The deep part extends from the tibia's posterior margin to the osteochondral junction on the distal fibula's posteromedial aspect [13].

F. Foot The anatomy of the foot is complex. It transfers force from the lower limb to the ground to allow stable walking and posture. The foot deforms to uneven surfaces during stride and serves as a flexible shock-absorber before going through a sequence of biomechanical modifications that enable it to behave as a rigid lever to produce force [14]. The anatomy and movements of the foot and ankle are shown in Fig. 2.

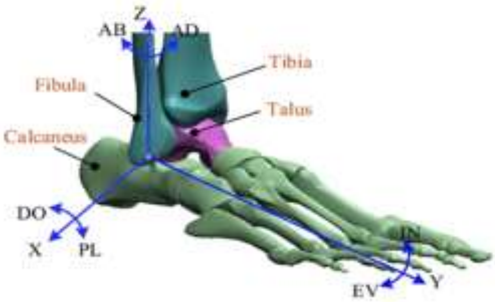

Figure (2): Anatomy of ankle joint and its rotational motions [14].

3. Biomechanics of Human Walking

When a person walks, it is known as a double support phase because at once, both feet are in touch with the ground [15-17]. Walking is an extremely complex biomechanical process because the human body has a significant DOF [18]. A complex synchronization of muscle forces, joint movements, and brain motor instructions [21] results in the synergistic movement of the skeleton around the joint, giving humans their characteristic walking motion [20]. Therefore, comprehending the biomechanics of human locomotion is crucial for the design of the lower extremity exoskeleton.

A. Reference planes:

The reference planes' descriptions of human movement are depicted in Fig.3.

1. The term “Sagittal plane” refers to any line that divides two bodily portions into their right and left halves [22] [23].
2. The body or any part of it is divided into anterior and posterior parts by the coronal plane, which is also referred to as the frontal plane [24].
3. The transverse plane separates the body’s superior and inferior portions [25].

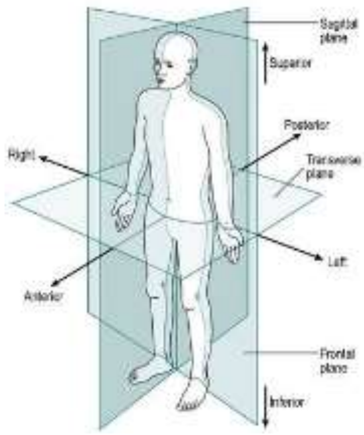

Figure (3): The anatomical position, with three reference planes and six basic directions [26].

B. Human gait cycle:

To form a clear picture of human walking movements, researchers and designers should study the human walking gait cycle before working in the exoskeleton field [27]. The term gait refers to the manner or style of walking [28]. Right heel contact signaled the start of the gait, and it ended in the same place. Table 1 details every step of the gait cycle. Fig. 4 and Fig.5 depict the gait cycle and normal gait steps of human walking stride respectively.

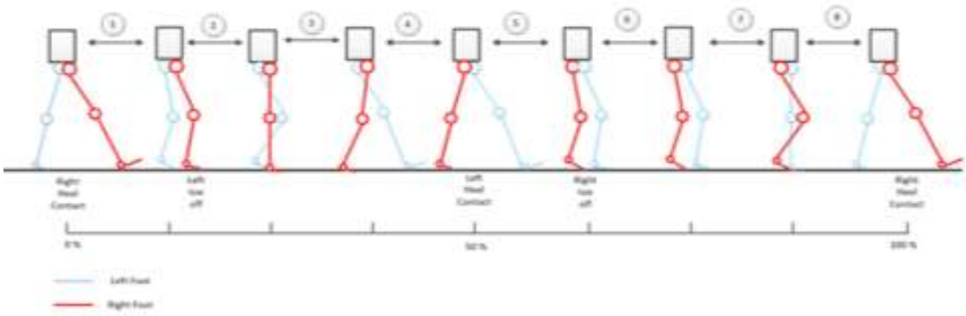

Figure (4): Gait cycle used by humans [29].

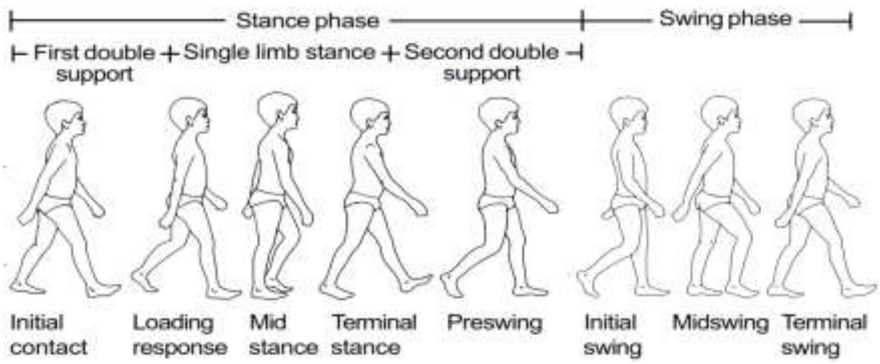

Figure (5): The normal gait cycle steps [30]

4. Lower Limb Exoskeletons

Since the 1960s, robots have been used for rehabilitation and gait assistance on a large scale [31] as a way to lessen the efforts of therapists and assist in the healthcare field for patients with neurological disorders, sports injuries, and any lower limb disorder that required a long-term and intensive rehabilitation intervention, as well as age-related disorders, and to reduce the clinical costs [32], [33]. Exoskeletons, often referred to as wearable robots, refer to the solid, protective, and preventive coverings that people wear [36]. These robots have a wide range of uses across numerous industries, and they can be used to carry heavy objects [37] or increase worker strength during long voyages [38]. It is utilized in the medical industry to support patients who cannot walk because of various lower limb disorders [39]. Exoskeletons come in various forms, including neuro-rehabilitation robots [40], power-increasing orthoses [41], prosthetics, and orthoses for rehabilitation [42]. All forms of rehabilitation equipment will be described in this document. The ankle joint is the subject of our investigation, and some types will be focused exclusively on the ankle joint, whereas others will be joint-specific. Additionally, to the different varieties of treadmills, there will be A and P rehabilitation devices.

A. Treadmill Training Exoskeleton.

High-complexity devices, such as products from Biodex [43][44], Lokomat [45][46], LokoHelp, ALEX, LOPES, KAFO, AAFO, and NEUROBike [47],[48], are used for the entire lower limb. The treadmill is used for stroke patients. The annual incidence of stroke is approximately 180 per 100,000 people in the industrialized world [49]. After a stroke, a third of the survivors are still wheelchair-dependent, and the gait speed and endurance in approximately 80% of the ambulatory patients are reduced significantly [50]. A specific repetitive training seems promising to restore and improve walking functions and to increase the number of steps during the training sessions with partial body support [51-53]. Some treadmills are used for the repetitive practice of floor walking and up-and-down stair climbing on stroke patients [54]. Also, published research about treadmill are abundant: [55-65].

B. Orthosis System for Lower Limb Rehabilitation

In this section, various types of lower limb exoskeletons would be discussed. Exoskeletons are classified according to the location of the power source, which is represented by actuators that are typically placed on human joints, such as the hip, knee, and ankle. Exoskeletons are beneficial to move the joints of the subjects [67]. The types of lower limb orthosis are reviewed in the next subsections:

I. Hip Exoskeletons

According to **Lenzi et al. [68],** hip exoskeletons improved hip and ankle muscle activity.

Honda created Honda Walking Assist exoskeleton [69]. A direct current (DC) motor is found on each hip of the device. The forces that come from the motor are passed through the thigh of the subject via the straps, thereby providing assistance during walking.

The actuator of the exoskeleton in **Giovacchini et al. [70]** was situated close to the hip joint and was supplied with a P actuator that provided the subject with more comfortable movement in adduction and abduction (Fig. 6a). This hip orthosis aids in moving the subjects' hips in the flexion and extension directions.

Figure (6): Different hip exoskeletons types [70-78]

Hibso (hip ball screw orthosis) [71] A ball screw is used in each leg of the HiBSO to convey the force from the DC motor, and straps at the tip of the ball screw are used to transmit actuation movements to the thigh. This tool permits the rotation of the thigh while permitting hip flexion, extension, and adduction and abduction (Fig. 6b).

Asbeck et al. [72] A geared motor carried on the subjects back is used to link the straps for the exoskeleton, which are then connected to the subjects' thighs. During heel strike until terminal stance, the straps are contracting and expanding on the legs (Fig. 6c).

Miyoshi et al. [73] developed a robotic gait trainer in the water (RGTW), a McKibben actuator for pneumatic hip, knee, and ankle orthosis for underwater gait training. This hydrotherapy was used to increase the effectiveness of treatment for patients with hip joint dysfunction. This study sought to establish consistent physiological gait patterns to treat movement disorders (Fig. 6d). Also, other types of hip orthosis are available [74-76].

Tudor et al. [74] invented a high-performance device for P rehabilitation training for post-traumatic disability subjects, known as continuous P motion (CPM), using pneumatic muscle (PM) actuation system. This device extends by using pressured air to fill a pneumatic bladder in an approximation of human muscles. This type of actuator is used because of its light weight and its ability to deliver power with a weight ratio that is as high as 400:1 as compared with other actuators that can deliver only 16 times of their weight, and it also provides inexpensive system for rehabilitation [74]. This device employs air as an energy source, and the lower section is fixed while the patient is receiving therapy while lying flat. This device allows the shocks to be completely absorbed, thereby enabling the hip and knee joints to undertake healing activities (Fig. 6e) [75].

II. Knee Joints Exoskeleton

For simplification, most knee exoskeleton devices have been molded in only one DOF to move the knee in flexion/extension actions.

Sawicki et al. [79] created knee, ankle, and foot orthoses with pneumatic propulsion (KAFO). It was put out through research on kinetic energy, gait rehabilitation, and human locomotor adaptation. This system employs a physiologically inspired control unit that measures the timing and magnitude of artificial muscle stimuli using electromyography to identify the patient's muscle data. For basic science and clinical applications, the KAFO exoskeleton are so promising because they have successfully helped the SCI subjects during locomotor training, metabolic energy consumption, and neural adaptation for neurologically intact human walkers (Fig. 7a).

Sridar et al. [80] employed a smooth, detachable cushion as an actuator in his exoskeleton, and the actuator was mounted behind the subject's knee. The exoskeleton is inflated and deflated using a pneumatic system. Fig. 7b shows that during the walking gaits swing phase, the exoskeleton is inflated, and it deflates during the other phases.

Witte et al. [81] used two DC motors to move two Bowden cables in an exoskeleton. As seen in Fig. 7c, one cable is fastened to a belt behind the lower leg, and another cable is fastened to a belt in front of the upper thigh.

Wang et al. [82] created a knee exoskeleton that had a motor for actuation and a double pulley for transmission on the subject's knee. This set-up facilitates the user's ability to kneel and walk. The design of this exoskeleton is shown in Fig. 7d.

Additionally, a lot of exoskeletons for treating knee joints are available [83]and[84].

Figure(7): Knee exoskeletons types [79-82]

III. **Ankle joint exoskeleton**

Due to neurological impairment, accidents, sports injuries, and other dysfunctions relating to the ankle joint, the number of injured subjects with ankle dysfunction has increased in the recent decades. As a result of the robot-assisted ankle joint rehabilitation for neurological impairment, such as stroke, rehabilitation engineers became quite interested in it [85–91]. Although parallel ankle rehabilitation robots (PARRs) are employed for participants in seated positions, orthosis [85], [92] [93], which is used for treadmill and over ground training, may also be used. The application of parallel robots in ankle rehabilitation is practical because of their high rigidity and increased precision over a narrow range of movements.

The Rutgers Ankle, developed by [94] M. Girone et al. [94] and pneumatically actuated with six DOF, is a well-known robot. It is intended to assist stroke victims in training in their homes. To make therapy more enjoyable and efficient, Rutgers will develop a library of virtual reality rehabilitation exercises. Further research focuses on this restriction, which is depicted in Fig. 8a, because Rutgers' DOF is not aligned with the ankle DOF.

Figure (8): PARRs with different mechanism configurations [94-105]

In 2004**, J.Yoon and J. Ryu [95]** proposed 4-DOF parallel mechanisms (1T- 3R AND 2T-2R) with two platforms as illustrate in Fig. 8b. Also, many PARRs have a very wide range of advantages, such as high rigidity, compactness, greater portability, and larger payload capacity [96-105]. All the aforementioned PARRs are pneumatically actuated and driven by PMAs, as illustrated in Figs. 8 (c-l).

Other PARRs are electrically driven to help the subjects to regain their ROM, some of them found in [106-114].as illustrated in Fig. 9.

In 2021, the main objective of the ankle rehabilitation robot proposed by **Ismail et al. [115]** is to aid injured people who have had a motor impairment in the lower body by supporting the lower body, particularly the ankle. The mechanical layout of the robot used for ankle rehabilitation is based on a realistic model of the human ankle.

In 2022, Zoa et al. [116] proposed a 3-RRS PARR, which could carry out simple and complex ankle rehabilitation activities in accordance with the configuration, the ankle joints bone structure, and motion mechanism. PARR has two modes of operation: single-DOF compound rehabilitation training, which combines two or more types of exercise at the same time; and multi-DOF compound rehabilitation training.

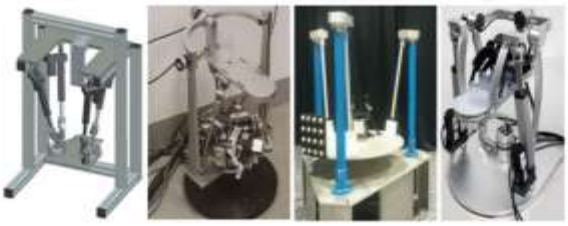

Figure (9): Electrically driven PARRs [106-114]

5. Active and Passive Exoskeleton

The type of actuator P or A can be used to identify the motion source of the device. The actuators of an A exoskeleton are powered by a supply of pressurized air. Although this actuator has the advantages of being lightweight and flexible, similar to human muscles, it also has the disadvantages of having limited power and being challenging to regulate [117]. Despite their tremendous power and stability, hydraulic actuators are very expensive [118]. Because of their ability to be controlled, electrical actuators are frequently used to track the precise movements of the exoskeleton. The P exoskeleton has no power source and benefits from the kinematic forces that use springs and dampers [119]. The type of actuator and the DOF of some PARRs are shown in Table 2.

The opposite motions of dorsiflexion, inversion, and adduction are plantarflexion, eversion, and abduction, respectively.

Table (2): The types of actuators and the DOF of some PARRs

Group/device	DOFS	ROM	Exercise mode
Girone et al. Rutgers Ankle	6	DF/PF◦ IN/EV◦ ADD/ABD◦	P and A
Yoon et al. Recon – figurable parallel ankle robot	4	DF/PF◦ IN/EV◦	P
Dai et al. 3−SPS/PS mechanism	4	-	-
Liu et al. “3−RSS/S” mechanism	3	DF/PF IN/EV ADD/ABD	Passive; assistant; resistive
Saglia et al. ARBOT	2	-	P and A Active (Isometric Isotonic)
Malosio et al. PK Ankle	3	-	P and A
Ayas et al. 2-DOFs parallel ankle robot	2	-	P and A
Hamid et al. 9-DOFs hybrid PARR	9	DF/PF IN/EV ADD/ABD	P
Ai et al. 2-DOFs ankle rehabilitation robot	2	-	P
Jamwal et al. Reconfgurable PARR	3	DF/PF IN/EV ADD/ABD	P
Jamwal et al. intrinsically compliant ankle rehabilitation robot	3	-	P and A
Zhang et al. CARR	3	Varying workspace	P and A
Tsoi et al. Redundantly actuated PARR	3	DF/PF IN/EV ADD/ABD	P and A
Wang et al. 3 −RUS/RRR	3	DF/PF IN/EV ADD/ABD	P
Cazalilla et al. 3−PRS	3	DF/PF IN/EV	P, Active (assistive; Resistive)
Li et al. 2-UPS/RRR PARR	3	DF/PF IN/EV ADD/ABD	P and A

6. Exoskeletons for Upper Limb Rehabilitation

Similar to exoskeletons for lower limb rehabilitation, many types of devices for upper limb rehabilitation are used to relive stroke patients. The most common consequence of a stroke is arm and wrist impairment [120]. The range of devices available for upper extremity rehabilitation is wide [121-123].

To return the activities of daily living for patients suffering from different conditions, such as stroke and SCI, in 2022, 126. N. Sabri and W. S. Aboud created a smart robotic exoskeleton: a 3-DOF for the rehabilitation of wrist forearm [124-126]. The use of EMG signal and gyroscope sensors is crucial for assessing the rehabilitation process and exoskeleton control methods. P exercises did not use EMG or gyroscope sensors. The rehabilitation method was converted into A exercises as the patient attained or demonstrated muscle activation and ROMs progressed. Finding suggests that the use of exoskeleton as a rehabilitation tool improved the EMG signal and ROMs for 3-DOF.

According to these studies, these exoskeletons are used effectively for patients of stroke or any diseases that cause paralysis of any parts of the human body. Exoskeletons are sometimes used as an orthosis with joints or with actuators. Also, exoskeletons may be P or A. As a result, these devices are crucial in all fields of rehabilitation. Robotic exoskeletons have lessened the therapist's fatigue and time. Moreover, it increased the sessions for the patients to improve the efficiency of the physical therapy. The results show a promising future in relying on the use of robotic exoskeleton devices in the treatment of patients who suffer from an inability to move in the lower extremities as a result of stroke through their incorporation in physical therapy. Also, the possibility of weight reduction, less cost, and simplicity are considered when designing and constructing such devices.

7. Conclusion

In this study the anatomy of the lower limb and the biomechanics of human walking are presented, and the limb movement mechanism is explained. The most recent article about lower limbs rehabilitated by robotic exoskeletons is reviewed.

Also, local studies concerning upper limbs that are rehabilitated robotically are discussed. This study showed abundant future for robotic exoskeletons used in the rehabilitation of the lower extremity. In addition, the following conclusions are made:

i. The continuous development of robotic exoskeleton rehabilitation can possibly compensate for traditional methods.
ii. Modern materials and techniques can be used in the manufacturing of robotic devices.
iii. The designing and manufacturing of robotic exoskeleton rehabilitation devices are simple and economical.

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