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Systematic review of mechanical designs of rehabilitation exoskeletons for lower-extremity

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Exoskeletons of lower extremities are used mainly for gait treatment in physical rehabilitation. However, they are also capable of being involved in other types of exercises. Nevertheless, their structure needs to be adequately adjusted for such applications. To analyse approaches to that, this review paper investigates the mechanical designs of rehabilitation exoskeletons for lower extremities. The study seeks to identify best practices in designing and implementing these devices by analysing fifty-two articles. It covers aspects such as kinematic structures, materials used, types of drives, and the range of exercises. Standard design features include multiple degrees of freedom, primarily at the hip, knee, and ankle joints, and using lightweight materials to enhance mobility and reduce power consumption. The review also discusses the advantages of different driving systems. The findings provide valuable insights for developing effective and safe rehabilitation exoskeletons, contributing to improved patient outcomes in physiotherapy and rehabilitation settings.

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1. Introduction

The development of mechatronics led to the fusion of this field with others, including medicine. Thanks to these, many processes can be at least partially automatised [1]. Such enhancement of a single specialist's work partially solves problems of shortages in medical staff. As the robots are typically used for repetitive processes that require high precision and accuracy, they become popular in surgery, service of elderly patients and physiotherapy.

Physiotherapy is the process of recovering a maximum available physical performance of a patient with a certain level of impairment [2, 3]. The treatment with motion, kinesiotherapy, is used for patients with neurological and motor disorders. Kinesiotherapy can be performed either as active or passive [4]. In a human-conducted process, the participants' motion is supported or resisted by the professional. In the most severe cases, patients may not even be able to move at all voluntarily and require mobilising their joints to prevent stiffness.

The rehabilitation robots are used to either support patients' recovery process or substitute their missing motor functionality [5]. The use of such robots in kinesiotherapy aims at increasing the accuracy and repeatability of motions while reducing a physiotherapist's effort during exercises [4]. They are applicable for both, passive and active training, as can mimic typical motions of human-conducted exercises [3].

The recovery process can be realised with a task-oriented approach. For such, a patient is exercising while performing typical daily-life motions – often, the most necessary for themselves. These can include snacking, sipping, scratching and personal grooming [6] or other activities correlated with their work or hobbies [7, 8]. When it comes to the lower extremity, their main functionality is related to standing up or sitting, commuting, and sports. Therefore, most of the exercises are performed while walking or sitting. However, mobilisation of flaccid limbs to prevent joint stiffness is often performed while laying.

Rehabilitation robots used in kinesiotherapy of extremities use motors to support or oppose patients' motion, depending on their physical conditions. This requires sensing the intention of their motion and physically interacting with the extremity at the characteristic points. The rehabilitation robots are typically either end-effector open-chain type or exoskeletons. Within lower-extremity treatment, the latter are relatively more often used. These, compared to the end-effector structures, can mobilise every joint directly. However, they are also vulnerable to dimensional differences and misalignments relative to the user's extremities. As a result, they can cause harm to the patient if they are not accurately adjusted. The injuries or inaccurate exercising can appear as an effect of mistakes in designing or installing such devices [9].

Even though the exoskeletons of the lower limb are not lifted by the users' musculoskeletal system, their mechanical design strongly affects their functionality. The heavier structures, in general, require more bulky drives, which can limit the range of motion and make motion with the device more difficult. Moreover, these result in higher power consumption which is critical for battery-powered devices. Additionally, in line with telemedicine, rehabilitation robots easily transferable between institutions or even patients' houses are preferable compared to stationary large ones. For this reason, the selection of a kinematic chain, its mechanical implementation, and the physical components used are critical for the functionality of the constructed exoskeleton. These can indicate its real-life applicability.

The study is a literature review of the lower-limb rehabilitation exoskeletons' mechanical designs. It aims at analysing the structures currently constructed by the researchers and defining the best practices of such. However, multiple different reviews of wearable robots for lower extremities are available. Nevertheless, the majority of them focus on the control strategies of the robots [10]. Compared to other recent studies on exoskeletons of the lower extremity for physiotherapy, this one is limited mainly to deep analysis of mechanical designs [10, 11]. The discussion on additional technologies implemented within the research is added to correlate certain structures to their possible applications. Despite the trend of Bowden cable-based power transmission systems and soft exoskeletons[11, 12] the presented analysis is limited to direct drive-based rigid systems. The aim of such an approach is to focus on rehabilitation devices which can precisely control joint movements while reducing their mass and not resigning functionality. Also, the review is focused mostly on the devices enabling a wide range of exercises, rather than the ones targeted at gait recovery – as for some other reviews [11].

Intentionally, the presented paper should be a base for selecting the most appropriate kinematic structure and comparing critical parameters to the competition while designing own rehabilitation exoskeleton. Thanks to this, design errors can be detected in the early stages and corrected. Therefore, the risk of constructing too heavy and impractical rehabilitation devices will be omitted.

2. Methodology

The literature review was based on the *Scopus* database. The records included were selected from the result of the query: *TITLE-ABS-KEY("exoskeleton" AND ("rehabilitation" OR "physiotherap*") AND "lower" AND "limb" AND ("mechanical" OR "design")* AND NOT "software" AND NOT "soft"). Moreover, these were limited to articles and conference papers not older than five years, falling within the Engineering subject area and written in English. The review aimed to define the best practices for designing electrically-powered rigid rehabilitation exoskeletons for lower limbs. For this reason, the articles not mentioning mechanical design and/or not related to devices for lower extremities and/or not related to devices with electric drives were excluded from the systematic analysis. As a result, 52 original papers were included in the review. The schematic graph of the search process is presented in Fig. 1. The devices presented in the remaining papers were analysed in terms of kinematic structures, materials and manufacturing technologies used for their main parts, types and parameters of their drives, types of available exercises, and additional information and communications technologies (ICTs) used to enhance treatment.

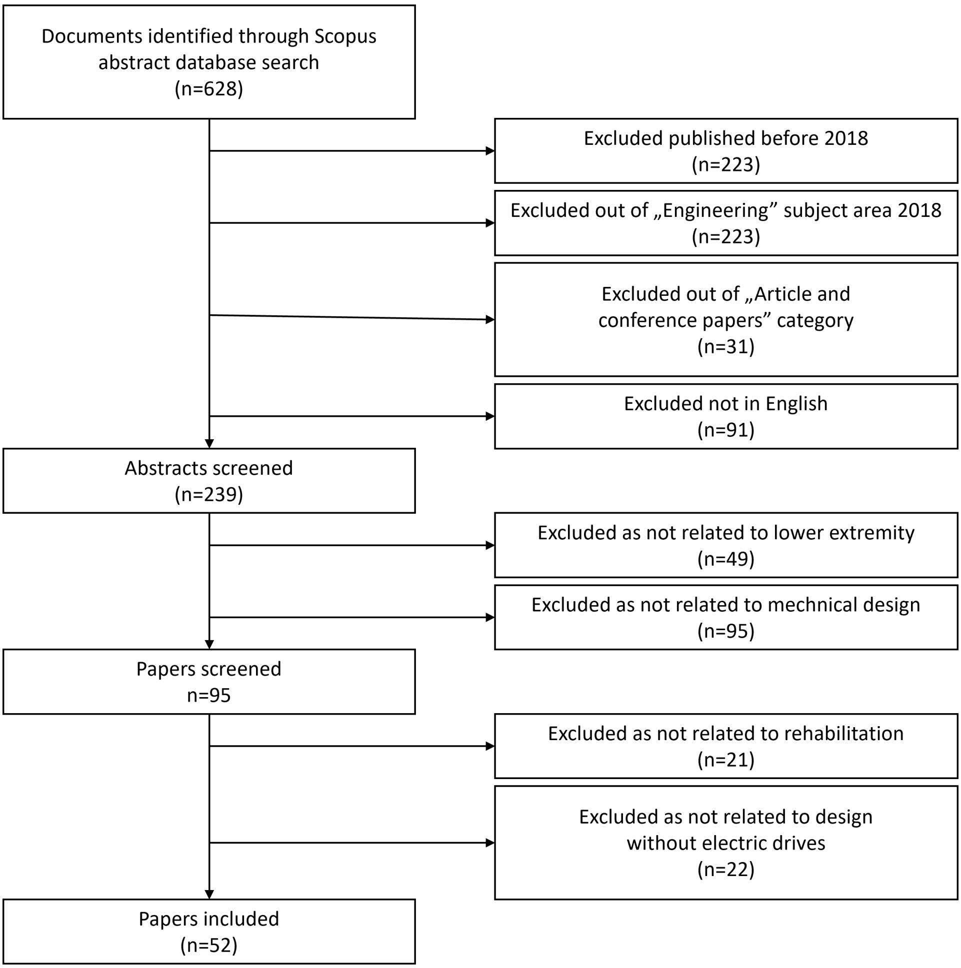

Fig. 1. Literature review search schematic process

3. Results and Discussion

The conclusions drawn from the review were based on 52 articles most closely associated with the subject. The distribution of publications indicates an increasing number of scientific papers in this field over the last five years. According to Scopus data, the year 2022 saw the highest number of articles published in this domain.

3.1. Mechanical Design

3.1.1. Kinematic structure

In the reviewed studies, constructions operating on all degrees of freedom in the lower limb were excessively rare. Among the considered papers, constructions most frequently described featured three degrees of freedom: in the hip, knee, and ankle (34.6% of the papers). Active degrees of freedom (joints) were predominantly located in the hip and knee, less frequently in the ankle [13, 14], where passive degrees of freedom were also applied [15, 16]. This mechanical configuration constituted the foundation for the majority of constructions discussed in other articles. However, such a configuration allows limb movement only in the sagittal plane. This can be used for gait training but is not applicable to exercising based on motions reflecting activities of daily living such as dressing up, wiping buttocks, grooming or picking up objects [17].

Increasing the number of degrees of freedom can result in bringing new exercises into treatment. Particularly, additional movements in hip joints than its flexion/extension enable task-oriented treatment not based on gait [18]. Such exercises include not only the ones in standing positions but also those lying and sitting. Moreover, the devices with the more complex mobility can be significantly beneficial for patients with muscle flaccidity who require full external mobilisation of joints for their recovery process [19].

Constructions with two degrees of freedom ranked second in quantity (25% of the papers). Systems with four degrees of freedom accounted for 13.5% of the considered papers [20, 21].

In a few cases, exoskeletons had over four degrees of freedom (13.5% of the papers), for instance, [22–24]. These stood out with additional degrees of freedom at the hip or ankle.

Publications addressing constructions with a single degree of freedom were the least common (5.8% of the papers) [25, 26].

In 7.7% of publications, data on the number of degrees of freedom of the exoskeleton design were not provided [27–30].

3.1.2. Kinematic Design

Most of the constructions reviewed operate as serial robots. Each subsequent segment is attached to the previous one, thus creating an open kinematic chain. Since these are exoskeletons, they are connected to the body in parallel. The designed constructions aim to achieve the greatest possible kinematic compatibility with the user's kinematic structure. Regulatory mechanisms are used to manipulate the distances between joints [31].

An important aspect from a constructional point of view is the type of contact the exoskeleton has with the environment. There are two possible scenarios: in one, the exoskeleton allows the user to have direct contact with the ground [20, 32, 33]; in the other, the exoskeleton is mounted to a frame [14, 34]. In some cases, the assisted limb does not contact the ground when performing exercises in a sitting or lying position.

In the construction described in [21], a two-degree-of-freedom exoskeleton is mounted parallel to the body. Its purpose is to assist hip movements during gait rehabilitation. No supporting frame mount is used.

The exoskeleton described in [35] does not allow the user to contact the ground. In addition to the exoskeleton segment, a mobile frame to which the entire construction is attached has been designed. The patient has the exoskeleton mounted parallel to the lower limbs, and foot plates support the whole weight.

Examples of the analysed designs are visualised in Fig. 2. Kinematic structure and other physical parameters of the described exoskeletons are presented in Table 1.

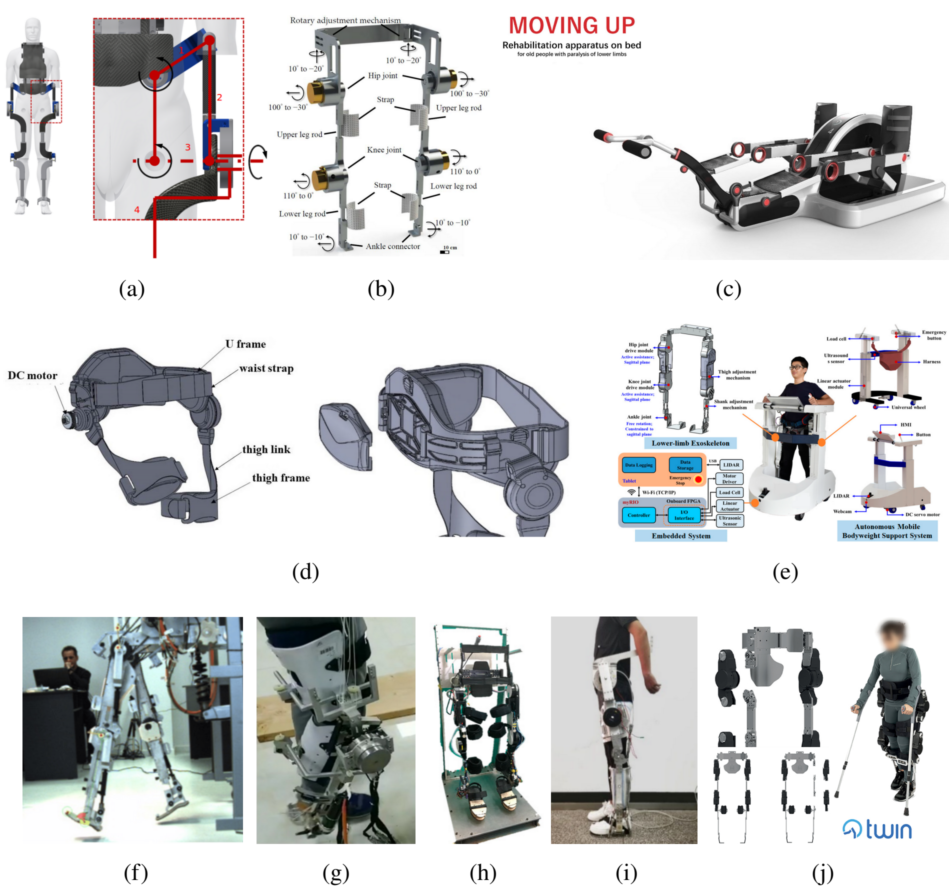

Fig. 2. Examples of the designs of the analysed exoskeletons (visuals in subfigures: a) [23], b) [31], c) [36], d) [21], e) [37], j) [20]; photos in subfigures: e) [37], f) [14], g) [38], h) [39], i) [40], j) [20])

Table 1. Parameters of mechanical constructions (abbreviations used for describing numbers of DOFs: HA – hip active, HP – hip passive, KA – knee active, KP – knee passive, AA – ankle active, AP – ankle passive, P – passive)

No.	DOFs	Construction Material	Mass	Drive Parameters	Ref
1	3 (1HA, 1KA, 1AP)	No data	No data	Hip: max. torque of 50 Nm, Knee: EC90 motor 90W, 56 Nm	[41]
2	4(3AA,1KA)	Aluminium	9.8 kg	Knee: DC gear motor	[42]
3	3(1HA,1AA,1KA)	No data	6.57 kg /2 legs	Each joint: EC 45 flat 70 watts	[13]
4	1 (KA)	Aluminium and iron	No data	BLDC EC45 flat 13,4Nm	[25]
5	2 (2AA)	Aluminium, steel, composite	No data	Motor 1, EC-4pole, 95,6 mNm Maxon Motor 2, 128 mNm	[33]
6	3 (1HA, 1KA, 1AP)	No data	14.4 kg	Hip: 64,2 Nm, Knee: 40,1 Nm	[43]
7	3 per limb (1HA,1KA,1AA)	No data	No data	Servomotors	[14]
8	2 per limb (1HA,1KA)	No data	No data	No data	[44]
9	4 per limb (1HA, 1HP, 1KA, 1AA)	No data	8 kg	Max torque for each joint 76 Nm	[45]
10	3 (1KA, 2P)	No data	No data	RE 40, 150 W, 27Nm	[46]
11	6 per limb (3HA,1KA,2AP)	Aluminium	No data	50 Nm/160 RPM MYACTUATOR RMD-X10 400W	[40]
12	2 (1HA, 1KA)	No data	No data	RE 40, graphite brushes, 150 W	[47]
13	2 (1HA, 1KA)	No data	No data	No data	[48]
14	3 (1HA, 1KA, 1AP)	No data	14.4 kg	DC motor, no data	[49]
15	3(1HA,1KA,1AA)	No data	No data	BLDC motor, no data	[50]
16	7 per leg (2HA 1HP, 1KA, 1AA 1AP, 1MP)	No data	No data	No data	[23]
17	2 per limb(1HA,1HP)	Aluminium alloy	2,4kg	BLDC EC60 Flat, PG 1:24	[21]
18	7 per limb(1HA,6P)	No data	8 kg	No data	[22]
19	3 (1HA, 1KA, 1AP)	Aluminium alloy	No data	EC90 Flat harmonic drive gear 1:160/1:100, 80Nm 30 RPM/ 50Nm 48RPM	[51]
20	3(1HA,1KA,1AA)	Magnesium aluminium alloy	No data	50 Nm (H), 50 Nm (K)	[52]
21	3(1KA,1AP,1HA)	Aluminium alloy 1100	7 kg	91.5Nm (K)	[53]
22	6 per limb(1KA,5P)	Aluminium and carbon fiber	No data	No data	[54]
23	2 (1KA,1HA)	Al7075 T6 and spandex	23 kg	74 Nm, EC90 flat, 100:1 gearbox, nominal voltage hip:36V knee:24V	[20]
24	3 (1HA,1KA,1AA)	No data	No data	No data	[37]

Table 1 – continuation

No.	DOFs	Construction Material	Mass	Drive Parameters	Ref
25	3 (1HA,1KA,1AA)	No data	No data	No data	[55]
26	3 (1HA,1KA,1AA)	7075 aluminium	8.4 kg	DJI M3508	[56]
27	2 (1KA,1HA)	304 stainless steel	No data	No data	[57]
28	4 (3HA, 1KA)	No data	No data	No data	[39]
29	2 (1HA,1KA)	No data	No data	No data	[58]
30	2 (1HA,1KA)	No data	No data	EC60 Flat, harmonic drive	[59]
31	2 (1KA. 1P)	No data	No data	No data	[60]
32	2 (1HA,1KA)	No data	No data	No data	[61]
33	3 (1HA,1KA,1AA)	Aluminium alloy	16 kg	25.72 Nm (H), 13.42 Nm (K), 4.11 Nm (A)	[35]
34	3AA	PLA	No data	No data	[62]
35	4 per limb (2HA, 1KA, 1AA)	Aluminium 6061	16 kg	Hip and knee motor: EC 90 Flat, 400 W, 1260 mNm	[31]
36	3 (1HA, 1KA, 1AP)	Aluminium	16 kg	52.055 Nm (H) 11.677 Nm (K)	[15]
37	3 per limb (1HA, 1KA, 1AA)	No data	No data	Stepper motors	[27]
38	4 active	Aluminium and plastic	3.2 kg	Up to 6 Nm	[63]
39	1 per limb (1KA)	No data	No data	Hip: 150W, 50Nm Knee: 180 W	[34]
40	2 (1HA,1KA)	No data	No data	No data	[64]
41	3 (1HA,1KA,1AP)	No data	No data	Hip joint torque: 32,66 Nm, Knee joint torque: 12 Nm	[16]
42	1 (1KA)	Nitrile butadiene rubber	No data	Knee motor: EC Flat 90	[38]
43	5 per limb (2HA,1KA,2AA)	No data	12.15 kg	No data	[24]
44	4 (1HA,1HP,1KA,1AP)	No data	4.55 kg	No data	[32]
45	4 (2HA,1KA.1AP)	No data	3 kg	No data	[65]
46	no data	No data	10 kg	No data	[28]
47	2 per limb(1HA,1KA)	No data	No data	No data	[36]
48	6 per limb (2HA,1HP, 1KA, 2AA)	No data	No data	No data	[66]
49	No data	840D double-sided fabric	No data	No data	[29]
50	3 (2HA, 1KA)	No data	No data	No data	[67]
51	5 per limb(1HA,1KA, 2AA,1AP)	No data	No data	No data	[68]
52	1KA	No data	No data	Servomotor - Yaskawa 100 W	[30]

3.1.3. Weight

The weight of individual constructions directly correlates with the number of degrees of freedom. Among structures with a maximum of three degrees of freedom, most of them did not exceed 15 kg, including actuators [35, 42, 45]. Notably, the most lightweight exoskeletons achieved a total mass below 5 kilograms [26, 65]. While reaching such low weight demands compromising strength and durability to some extent, the studies analysed included a comprehensive structural strength analysis, demonstrating a satisfactory safety margin [32].

For constructions with higher kinematic complexity, mass ranged between 16 and 20 kilograms [15, 35, 69]. A solitary article reported a design surpassing this range, reaching 23 kg [20].

Despite the majority of presented designs being dedicated to rehabilitation [22], [70] and providing force support for users, they remain relatively lightweight. Lower mass typically correlates with reduced manufacturing costs, power use (critical for battery-powered devices), and higher dynamics with lower torque requirements [21]. Contrariwise, heavier constructions are generally stiffer and, therefore, suitable for patients with limited neuromotor capabilities and greater motor assistance needs [27].

Regarding weight categories, the analysis indicates:

- Designs weighing 5 kg or less: 5 designs (representing 9.62%)
- Designs weighing over 5 kg up to 10 kg: 7 designs (representing 13.46%)
- Designs weighing over 10 kg up to 15 kg: 2 designs (representing 3.85%)
- Designs weighing over 15 kg: 5 designs (representing 9.62%)
- No data available for 33 designs (representing 63.46%)

3.1.4. Material

To minimise a device's weight, materials comprising low density and high strength must be selected. Moreover, the exoskeletons are often divided into supporting elements, carrying the main force loads, and other functional components, such as attachment elements, etc.

For the supportive elements, aluminium alloys [14, 21, 31, 40, 56, 59] are the most frequently selected materials (23% of the considered studies). Heavier materials such as stainless steel were rarely used in exoskeletons, mainly for main structural components [57]. This represents only 2% of all papers. 3D printing materials, such as PLA, as the primary material for exoskeleton construction, were used less often and mainly for single-DOF devices with lower loads acting upon them [62]. It is possible to further reduce the weight of construction by applying composite materials or titanium alloys. However, the materials themselves and the correlated manufacturing process can significantly increase the price of the devices. As the physiotherapy technology is intended to remain available for patients, the price for dedicated devices remains one of the key factors for their practical implementation.

Exact data regarding the material used for constructing the critical parts of the exoskeleton was rarely presented. In 64% of cases, this information was not available. Selected mechanical parameters for the mentioned materials used for the supportive components are presented in Table 2.

Table 2. Comparison of Physical Properties of Aluminium Alloys (YS – Yield Strength, UTS – Ultimate Tensile Strength)

Alloy	Density [g/cm^3]	Young's Modulus [GPa]	YS [MPa]	UTS [MPa]
6061	2.70	69	276	310
7075	2.81	71	503	572
1050	2.71	65	65	95

3.1.5. Body mounting

As the presented exoskeletons act parallel to the lower extremity, they must be attached to its characteristic point. Thanks to this, they prevent certain motions and support or resist others. Depending on the selected body mounts, different rigidity of connection is achieved. In the analysed research, velcro belts or bracket mountings were the most frequently chosen to achieve the most durable and user-friendly system. The application of Velcro belts has been shown here [20]. Velcro belts offer a practical and cost-effective solution for mounting the lower limb to an exoskeleton. They provide ease of use, customization, and comfort, although considerations such as durability and load-bearing capacity should be taken into account based on requirements. The usage of brackets was also presented in one of the research papers [54].

The primary function of brackets in an exoskeleton is to establish a secure and adaptable connection between the exoskeleton and the user's lower limb. Using brackets to secure the extremity to the exoskeleton brings an advantage in terms of substantial durability. Employing material straps reduces the risk of loose or damaged connections. Additionally, the simplicity of adjustment enables easy customization of stable connections to accommodate a variety of users. However, this method also entails certain drawbacks compared to other solutions. The replacement of worn-out components becomes considerably more complicated, especially without the appropriate tools. Additionally, there is a risk of reduced user comfort due to using metal or plastic clasps if preventive measures are not taken [45].

3.2. Driving system

In the field of engineering, various drive systems are used. In all analysed publications, motor functions were performed using electrically powered drives.

Nevertheless, many types of electric drives are available on the market, each with its own advantages and disadvantages, as observed in the discussed studies.

In most of the cases, brushless direct current (BLDC) motors were selected (utilized in 29% of analysed papers), due to high efficiency and rapid response to changes in current and torque. BLDC motors are characterized by a relatively low weight-to-torque ratio and offer a position or velocity control system [51]. These are often selected with the controllers enabling setting the individual motor positions. Regarding the manufacturers, *Maxon* is the most common choice in the recent designs. Outstandingly often, the motors of EC Flat series with the *EPOS* controllers are selected [21, 51].

The second most commonly chosen type of motors were brushed DC motors (6% of analysed publications). They are characterized by lower manufacturing costs and significantly easier control [47]. However, due to their lower lifespan compared to other types, such as BLDC, they are becoming increasingly less prevalent in the analysed field.

The least chosen types of drive systems were servo motors (2% of analysed publications) and stepper motors (2% of analysed publications). Servo motors operate on the feedback principle, where regulation is carried out to achieve and maintain the desired position. Stepper motors execute a specified number of steps per revolution; their movement is controlled by appropriate control pulses, causing precise rotational steps. Despite the advantages they offer, the quantity of such applications suggests the existence of more optimal solutions for lower limb exoskeletons.

An essential component of the motor systems appearing in the studies were pieces of apparatus to measure the angle in each joint, which served as a feedback signal for position control. The first solution utilized a rotary potentiometer, the measurement based on resistance change [13]. The other way of providing position data was using encoders. Such an implement is more accurate and allows precisely controlling each actuator's position [25]. They usually differed in the selected resolution per turn (counts per turn); for instance, encoder *Mile* with a resolution of 2048 counts per turn [21, 43].

It is generally more convenient to use an absolute encoder, but this is not always the case. For example, in research [68], both types of encoders were utilized to minimize possible position error. The work by [63] provides a detailed description of drive assemblies, which include absolute encoders (MA3, US Digital, WA, USA).

For instance, in [33], a typical incremental encoder is utilized. The level of complexity does not require any complicated solutions.

In the article [30], the type of encoder used is not specified. This situation is similar in many publications. Very often, there is a lack of information on the specific sensors used. In [38], the presence of an encoder is mentioned without describing any further details.

Pneumatic and hydraulic driving systems were not used for the analysed exoskeletons. However, air-based control is often used in soft exoskeletons based on the pneumatic muscles. They enable a better power-to-weight ratio without overheating. However, the power supply system is typically heavier and more bulky. Moreover, precise control of such requires more complicated tracking systems than rotational encoders [71].

3.3. Exercises

The described devices mainly appeared in the context of passive rehabilitation, where they could replace human involvement in simple therapies [25, 42]. However, it is possible to involve exoskeletons also in more advanced multijoint active treatment [72]. The motive of lower limb exoskeleton participation in treating stroke patients also emerged [50]. This is a response to speculations regarding an ageing society [73]. It should be noted that passive rehabilitation essentially involves performing repetitive exercises without significant structural loads; hence, lower torques of the drives are required. Moreover, it is worth noticing that the main purpose of rehabilitation robots is to repeat intensive, task-oriented exercises [74]. Therefore, the efficacy not necessarily is better with the same amount of treatment, but it is easier to receive therapy sessions of high intensity and accuracy of motion.

More advanced exercises for which exoskeletons were designed include sitting down and standing up [52] and even walking [67] – as a part of gait rehabilitation for individuals with walking difficulties and more. This approach remains in line with the task-oriented therapy [75]. In a rare instance, the exoskeleton was used to work on body balance [68]. The exoskeleton developed in this research combines features of sitting/lying and suspended weight-reducing robots to enable "Sit-Lie-Stand" multi-position rehabilitation training. It includes a leg abduction mechanism to adjust leg distance and shift the centre of gravity, increasing each leg's degrees of freedom to five for balance and ankle training. The construction consists of two modules: one for posture transformation and another for lower limb rehabilitation exercises.

An aspect to consider is whether the participation of physical therapists is included and whether physical assistance from a physical therapist is required when using the exoskeleton. In the study [44], the role of the physical therapist is described as controlling the start of each step and helping the patient get used to the device. Additionally, the physical therapist adjusted the exoskeleton to fit the participants' anthropometric characteristics and set the gait parameters.

In the study [50], the involvement of physical therapists was limited to conducting surveys during the design process to ensure the best possible adaptation of the exoskeleton to real-world requirements.

In most studies, due to their primarily mechanical focus, the involvement of physical therapists in operating the exoskeleton is not mentioned.

When utilized as an assistant, an exoskeleton in the hands of a physiotherapist can hold enormous significance for the future of rehabilitating patients with lower limb disabilities. The set of exercises which can be transferred into the exoskeleton-aided therapy with their kinematics and dynamics parameters are presented in the complementary research [17].

The exercises possible with the presented devices are described in Table 3.

Table 3. Functional parameters of exoskeletons

No.	Exercises	Additional Technologies	[Ref]
1	No data	Functional electrical stimulation (FES)	[41]
2	Rehabilitation exercise, passive assistance	No data	[42]
3	No data	No data	[13]
4	No data	A system that maintains the device's axis of rotation aligned with the knee's axis of rotation	[25]
5	No data	Series elastic actuators (SEA)	[33]
6	Assisting in lower limb during rehabilitation therapy	During rehabilitation therapy	[43]
7	No data	Transcutaneous Electrical Nerve Stimulation (TENS), CONTEMPLAS	[14]
8	No data	No data	[44]
9	Walking and gait rehabilitation	IMU, EMG and EEG-based neural interface shared control	[45]
10	No data	No data	[46]
11	Standing, leg lifting, gait training	No data	[40]
12	Functional support of the lower limbs, performing walking cycles	No data	[47]
13	Following the desired trajectories	Control methodologies: cooperative game theory, fuzzy set theory, probability theory	[48]
14	No data	Neural network	[49]
15	No data	No data	[50]
16	No data	Cable transmission system	[23]
17	Walking	EMG	[21]
18	Walking	Heel pressure data, fuzzy processing	[22]
19	No data	Compliant joint actuators	[51]
20	Sitting down and standing up	EMG	[52]

Table 3 – continuation

No.	Exercises	Additional Technologies	[Ref]
21	The subject stands from a sitting position at natural speed and sits down	ESP32	[53]
22	No data	No data	[54]
23	Walking	No data	[20]
24	No data	The LES can generate different cycles of gait training modes	[37]
25	No data	Dual-mode control, PID-fuzzy parallel control	[55]
26	Walking	Complex knee motion system	[56]
27	No data	No data	[57]
28	No data	Rpi as CCU, potentiometer to measure the ankle joint	[39]
29	No data	No data	[58]
30	No data	Air pressure actuator	[59]
31	No data	No data	[60]
32	No data	No data	[61]
33	Pediatric exoskeleton, assist gait rehabilitation	Kinect-LabVIEW	[35]
34	Repetitive leg recovery exercises	No data	[62]
35	Assisting people with walking disabilities	Self-tuning controller	[31]
36	Walking	No data	[15]
37	No data	No data	[27]
38	No data	No data	[63]
39	Sit-To-Stand (STS) process, walking training	No data	[34]
40	No data	No data	[64]
41	Supporting human body in walking, assist patients in rehabilitation	No data	[16]
42	Rehabilitation exercises	No data	[38]
43	No data	OpenSim simulation method	[24]

Table 3 – continuation

No.	Exercises	Additional Technologies	[Ref]
44	Assisting hemiplegic patients in lower-limb rehabilitation training	Motion capture technology	[32]
45	Aid in lower extremity paralysis recovery	EMG	[65]
46	No data	No data	[28]
47	Cycle racing exercises, flexion and extension exercises, leg lifting exercise	Adaptive Fuzzy Control (AFC)	[36]
48	Support during walking and rehabilitation training for children with cerebral palsy	No data	[66]
49	Walking	EMG	[29]
50	Walking	No data	[67]
51	Practice balance skills	Platform for user	[68]
52	Subjects were asked to slowly swing their knees while sitting with their calves fixed to the exoskeleton	EMG and a Hill-based muscle model for joint torque estimation	[30]

3.4. Additional Technologies

The exoskeleton-aided therapy is often supported by additional technologies (see Table 3). They can enhance the control capabilities of the system, visualisation for the patient or increase the therapy entertainment [24, 68].

So far, biosignal monitoring is one of the most common technologies accompanying robot-aided rehabilitation. They enable short-reaction-time monitoring of patient performance and can even be used for sensing individuals' intentions [30]. These include mainly electromyography (EMG, a measurement of muscle electric activity) and electroencephalography (EEG, a diagnostic method allowing the examination of the brain's bioelectrical activity). These signals can be used to analyse the treatment in almost real-time. However, the time of gathering and transferring data to the exoskeleton's control system can bring delays. Moreover, processing EEG data to obtain information on a patient's state can take even up to a few seconds [76].

In many cases, surface EMG was used to observe muscle activity to quantify muscle efforts during exercises in both situations: when wearing the exoskeleton and when not wearing it [21, 29, 52].

The EEG was used as an additional source of information while using the exoskeleton. As a result, observing the brain's reactions to the interaction with the exoskeleton becomes feasible [45]. It was utilized to establish a shared control neural interface based on EEG.

As patient safety is an important emerging topic, systems dedicated to these applications were developed. Only one of the analysed articles included a vision-based approach to such a challenge. In order to provide an accurate monitoring system to observe the operation of the exoskeleton and the patient, the Kinect sensor was used in collaboration with LabView National Instruments software [35]. Nevertheless, providing safety through minimally supervised treatment remains one of the main challenges in contemporary robot-aided physiotherapy [77, 78]. This is particularly significant for telerehabilitation applications, which currently struggle mostly with the stability of the remote connection between an operator and the device [79]. Apart from the mentioned system, is possible to add mechanical compensation mechanisms that reduce hazards coming from misalignments and dimensional inaccuracies of the devices [80].

The dynamics of the biomechanical systems, such as an extremity attached to the exoskeleton, are often difficult to determine [49]. A controller utilizing the RBFNN compensator is proposed to mitigate the impact of friction within the compliance tendon-sheath actuation system. In the design of the compensator, singular parameter exploration is conducted to substitute weight information within the neural network. Therefore, computations benefit significantly from using Feedforward Artificial Neural Network [59].

Furthermore, considering the rapid pace of artificial intelligence and machine learning advancements, the capabilities of neural networks within an exoskeleton as an autonomous personal rehabilitation device are becoming irreplaceable, particularly in detecting the intentions of a user and acting before certain events occur [81, 82]. Considering the needs of rehabilitation robotics, the systems would benefit from the control based on learning algorithms developing new exercising trajectories based on the user performance with the initially registered benchmark exercises and detecting hazards prior to their occurrence. This can be realised with the use of recurrent neural networks. Almost real-time operation can be obtained by teaching the models with the data shifted with the time required for computations of the pre-taught architecture [81]. Thanks to this, the exoskeleton can react to potential dangers to the patient and plan new therapeutic motions, implementing them between exercise cycles.

3.5. Future trends

Based on the analysed research papers, it can be expected that rigid exoskeletons of lower extremities will become lighter while keeping a high number of activated DOFs. This can be realised by performing mechanical optimisation to reduce the amount of materials used and maintain the strength of the construction or by implementing new materials with a higher strength-to-density ratio. The devices will be more portable and tailored to home-environment use. Thanks to this, patients will be able to exercise in nonmedical facilities, also while performing real-life activities.

Moreover, the kinematic structures of the exoskeletons will be adjusted to enable more complex motions. Compared to contemporary designs, it is highly possible that the devices will be mostly used for task-oriented treatment based on activities of daily living, not only walking.

When it comes to materials, many new designs will include main components made of lightweight composites or metastructures possible to manufacture with additive technologies. Electrically driven devices tend to use flat BLDC drives integrated with gearboxes of high ratios and dedicated controllers. However, due to this fact, the exoskeletons have low backdrivability and require additional methods of automatic safety supervision for spastic patients.

4. Conclusion

The presented review met its aim and revealed the most common practices for the design of rehabilitation exoskeletons. The critical criteria considered were the devices':

- mass of the device;
- kinematic chain;
- material of main components;
- body segments attachment method;
- driving system;
- exercises supported;
- accompanying ICT technologies.

Most of the analysed devices had no more than three active degrees of freedom. It was consistent with the most common intended use for gait treatment. However, the use of only flexion and extension in the parasagittal plane can lead to recalling incorrect motion patterns.

In general, the mass of the devices was correlated with their number of degrees of freedom and material. To keep them relatively lightweight, they were mainly manufactured from aluminium alloys and 3D-printable thermoplastic materials. However, mainly, the papers describing lighter designs had their mass included.

Based on the analysed sources, tracking the biomedical signal is the technology often used while supporting motion with exoskeletons. These, and the dynamics of the rehabilitated extremity, are also sometimes supported by predictive algorithms, including recurrent neural networks. Nevertheless, providing safe physiotherapy with minimal supervision of the specialist still remains a challenge.

Many of the presented designs can be implemented clinically in the future. However, rehabilitation robots typically suffer from low technological adaptation due to the high costs of the device required at one time compared with the low hour wage of a physiotherapist paid over a longer period [83], designing the devices for single exercises (e.g., gait treatment devices), and poor acceptance of the technology by physiotherapists and older patients [84].

The presented review is the basis for further work on constructing the exoskeleton for lower extremities for task-oriented exercises that are not limited to gait. Moreover, the project will consist of developing technologies for providing safe telerehabilitation over such devices and automation of treatment with minimal supervision. The former will be realised with a VR-based digital twin of the system, while the latter will be with EMG and EEG tracking to detect the discomfort of a patient and irregular, potentially dangerous muscular activations.

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References

[1] Paola Fantini, Marta Pinzone, and Marco Taisch. Placing the operator at the centre of industry 4.0 design: Modelling and assessing human activities within cyber-physical systems. *Computers & Industrial Engineering*, 139:105058, 2020. doi: 10.1016/j.cie.2018.01.025.

[2] Michael A Pagliarulo. *Introduction to Physical Therapy-E-Book*. Elsevier Health Sciences, 2021.

[3] Edwin Daniel Oña, Juan Miguel Garcia-Haro, Alberto Jardón, and Carlos Balaguer. Robotics in health care: Perspectives of robot-aided interventions in clinical practice for rehabilitation of upper limbs. *Applied Sciences*, 9(13):2586, 2019. doi: 10.3390/app9132586.

[4] Hassan M Qassim and WZ Wan Hasan. A review on upper limb rehabilitation robots. *Applied Sciences*, 10(19):6976, 2020. doi: 10.3390/app10196976.

[5] Leigang Zhang, Shuai Guo, and Qing Sun. An assist-as-needed controller for passive, assistant, active, and resistive robot-aided rehabilitation training of the upper extremity. *Applied Sciences*, 11(1):340, 2020. doi: 10.3390/app11010340.

[6] Mikkel Thøgersen, Muhammad Ahsan Gull, Frederik Victor Kobbelgaard, Mostafa Mohammadi, Stefan Hein Bengtson, and Lotte NS Andreasen Struijk. EXOTIC– a discreet user-based 5 DoF upper-limb exoskeleton for individuals with tetraplegia. In *2020 3rd International Conference on Mechatronics, Robotics and Automation (ICMRA)*, pages 79–83, Shanghai, China, 2020. IEEE. doi: 10.1109/ICMRA51221.2020.9398351.

[7] Jing Huang, Jia-Ri Ji, Chao Liang, Yan-Zhen Zhang, Heng-Cong Sun, Yuan-Hong Yan, and Xiao-Bei Xing. Effects of physical therapy-based rehabilitation on recovery of upper limb motor function after stroke in adults: a systematic review and meta-analysis of randomized controlled trials. *Annals of Palliative Medicine*, 11(2):521–531, 2022. doi: 10.21037/apm-21-3710.

[8] John Eraifej, William Clark, Benjamin France, Sebastian Desando, and David Moore. Effectiveness of upper limb functional electrical stimulation after stroke for the improvement of activities of daily living and motor function: a systematic review and meta-analysis. *Systematic Reviews*, 6:40, 2017. doi: 10.1186/s13643-017-0435-5.

[9] Nathanaël Jarrassé and Guillaume Morel. Connecting a human limb to an exoskeleton. *IEEE Transactions on Robotics*, 28(3):697–709, 2011. doi: 10.1109/TRO.2011.2178151.

[10] Gilbert Masengo, Xiaodong Zhang, Runlin Dong, Ahmad B Alhassan, Khaled Hamza, and Emmanuel Mudaheranwa. Lower limb exoskeleton robot and its cooperative control: A review, trends, and challenges for future research. *Frontiers in Neurorobotics*, 16:913748, 2023. doi: 10.3389/fnbot.2022.913748.

[11] Shuang Qiu, Zhongcai Pei, Chen Wang, and Zhiyong Tang. Systematic review on wearable lower extremity robotic exoskeletons for assisted locomotion. *Journal of Bionic Engineering*, 20(2):436–469, 2023. doi: 10.1007/s42235-022-00289-8.

[12] Leah Morris, Richard S Diteesawat, Nahian Rahman, Ailie Turton, Mary Cramp, and Jonathan Rossiter. The-state-of-the-art of soft robotics to assist mobility: a review of physiotherapist and patient identified limitations of current lower-limb exoskeletons and the potential soft-robotic solutions. *Journal of Neuroengineering and Rehabilitation*, 20(1):18, 2023. doi: 10.1186/s12984-022-01122-3.

[13] Rafhael M Andrade, Stefano Sapienza, and Paolo Bonato. Development of a "transparent operation mode" for a lower-limb exoskeleton designed for children with cerebral palsy. In *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, pages 512–517, Toronto, Canada, 2019. doi: 10.1109/ICORR.2019.8779432.

[14] Cristian Copilusi, Sorin Dumitru, Ionut Geonea, Leonard Gherghe Ciurezu, and Nicolae Dumitru. Design approaches of an exoskeleton for human neuromotor rehabilitation. *Applied Sciences*, 12(8):3952, 2022. doi: 10.3390/app12083952.

[15] R. Prashanna Rangan, C. Maheswari, S. Vaisali, K. Sriram, Albert Alexander Stonier, Geno Peter, and Vivekanada Ganji. Design, development and model analysis of lower extremity exo-skeleton. *Medical Engineering & Physics*, 106:103830, 2022. doi: 10.1016/j.medengphy.2022.103830.

[16] Bo Tang, Li Jiang, Xinxing Zhang, Rui Fu, and Shan Yang. Mobile platform type lower limb rehabilitation electromechanical system. In *2020 International Wireless Communications and Mobile Computing (IWCMC)*, pages 653–656, Limassol, Cyprus, 2020. doi: 10.1109/IWCMC48107.2020.9148126.

[17] Tomasz Osiak, Natalia Osiak, Piotr Falkowski, Mehmet Emin Aktan, Piotr Czerechowicz, and Vasfi Emre Ömürlü. Literature-based analysis of lower extremity kinematics and dynamics during task-oriented physiotherapy for rehabilitation robot design. *Lecture Notes in Networks and Systems*, 2024.

[18] Mohammadhadi Sarajchi and Konstantinos Sirlantzis. Pediatric robotic lower-limb exoskeleton: An innovative design and kinematic analysis. *IEEE Access*, 11:115219–115230, 2023. doi: 10.1109/ACCESS.2023.3325211.

[19] Karen O'Connor and Anne McCreesh. Principles of joint treatment. In Nicola J. Petty, editor, *Principles of Neuromusculoskeletal Treatment and Management, A Handbook for Therapists with PAGEBURST Access, 2: Principles of Neuromusculoskeletal Treatment and Management*, chapter 3. Churchill Livingstone, 2011.

[20] Matteo Laffranchi et al. User-centered design and development of the modular TWIN lower limb exoskeleton. *Frontiers in Neurorobotics*, 15:709731, 2021. doi: 10.3389/fnbot.2021.709731.

[21] Shi Heng Hsu, Chuan Changcheng, Heng Ju Lee, and Chun Ta Chen. Design and implementation of a robotic hip exoskeleton for gait rehabilitation. *Actuators*, 10(9):212, 2021. doi: 10.3390/act10090212.

[22] Bingshan Hu, Hongyang Yu, Hongrun Lu, and Yongjie Chang. Design of mechanism and control system for a lightweight lower limb exoskeleton. In *2018 3rd International Conference on Control, Robotics and Cybernetics (CRC)*, pages 83–88, Penang, Malaysia, 2018. doi: 10.1109/CRC.2018.00025.

[23] Tarcisio Antonio Hess-Coelho, Milton Cortez, Rafael Traldi Moura, and Arturo Forner-Cordero. Progressive improvement of the model of an exoskeleton for the lower limb by applying the modular modelling methodology. *Machines*, 10(4):248, 2022. doi: 10.3390/machines10040248.

[24] Yuexuan Wu, Aibin Zhu, Huang Shen, Zhitao Shen, Xiaodong Zhang, and Guangzhong Cao. Biomechanical simulation analysis of human lower limbs assisted by exoskeleton. In *2019 16th International Conference on Ubiquitous Robots (UR)*, pages 765–770, Jeju, Korea (South), 2019. doi: 10.1109/URAI.2019.8768685.

[25] Rafhael M. Andrade, Pedro H.F. Ulhoa, and Claysson B.S. Vimieiro. Designing a highly backdrivable and kinematic compatible magneto-rheological knee exoskeleton. In *2022 International Conference on Robotics and Automation (ICRA)*, pages 5724–5730, Philadelphia, USA, 2022. doi: 10.1109/ICRA46639.2022.9812308.

[26] Mohammadhadi Sarajchi, Mohamad Kenan Al-Hares, and Konstantinos Sirlantzis. Wearable lower-limb exoskeleton for children with cerebral palsy: A systematic review of mechanical design, actuation type, control strategy, and clinical evaluation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 29:2695–2720, 2021. doi: 10.1109/TNSRE.2021.3136088.

[27] Jyotindra Narayan and Santosha Kumar Dwivedy. Preliminary design and development of a low-cost lower-limb exoskeleton system for paediatric rehabilitation. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 235(5):530–545, 2021. doi: 10.1177/0954411921994940.

[28] Yong Yang, Lei Ma, Deqing Huang, and Na Qin. Output feedback repetitive learning control of an electrohydraulic actuator of a lower limb rehabilitation exoskeleton. *Computing in Science and Engineering*, 21(6):6–19, 2019. doi: 10.1109/MCSE.2018.110150902.

[29] Yanzhe Zhao, Yashi Zhang, and Shukai Tang. Multi-sensor-based lower limb rehabilitation assistant internet of things system. In *2022 IEEE 5th Eurasian Conference on Educational Innovation (ECEI)*, pages 55–58, Taipei, Taiwan, 2022. doi: 10.1109/ECEI53102.2022.9829473.

[30] Yanghui Zhu, Qingcong Wu, Bai Chen, Ziyue Zhao, and Conghui Liang. Physical human-robot interaction control of variable stiffness exoskeleton with semg-based torque estimation. *IEEE Transactions on Industrial Informatics*, 19(10):10601–10612, 2023. doi: 10.1109/TII.2023.3240749.

[31] Cheng Tang Pan, Ming Chan Lee, Jhih Syuan Huang, Chun Chieh Chang, Zheng Yu Hoe, and Kuan Ming Li. Active assistive design and multiaxis self-tuning control of a novel lower limb rehabilitation exoskeleton. *Machines*, 10(5):318, 2022. doi: 10.3390/machines10050318.

[32] Longhan Xie and Ledeng Huang. Wirerope-driven exoskeleton to assist lower-limb rehabilitation of hemiplegic patients by using motion capture. *Assembly Automation*, 40(1):48–54, 2020. doi: 10.1108/AA-11-2018-0221.

[33] Ozgur Baser and Hasbi Kizilhan. Mechanical design and preliminary tests of VS-AnkleExo. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 40:442, 2018. doi: 10.1007/s40430-018-1365-4.

[34] Zhibin Song, Wenjie Ju, Dechao Chen, Hexi Gong, Rongjie Kang, and Paolo Dario. A novel wheelchair-exoskeleton hybrid robot to assist movement and aid rehabilitation. In *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 11127–11133, Kyoto, Japan, 2022. doi: 10.1109/IROS47612.2022.9981240.

[35] Jyotindra Narayan, Mohamed Abbas, and Santosha K. Dwivedy. Robust adaptive backstepping control for a lower-limb exoskeleton system with model uncertainties and external disturbances. *Automatika*, 64(1):145–161, 2023. doi: 10.1080/00051144.2022.2119498.

[36] Xin Zhang, Jiehao Li, Salih Ertug Ovur, Ziyang Chen, Xiangnan Li, Zhenhuan Hu, and Yingbai Hu. Novel design and adaptive fuzzy control of a lower-limb elderly rehabilitation. *Electronics*, 9(2):343, 2020. doi: 10.3390/electronics9020343.

[37] Lian Wang Lee, I. Hsum Li, Liang Yu Lu, Yu Bin Hsu, Shean Juinn Chiou, and Te Jen Su. Hardware development and safety control strategy design for a mobile rehabilitation robot. *Applied Sciences*, 12(12):5979, 2022. doi: 10.3390/app12125979.

[38] Yapeng Wang, Wei Zhang, Di Shi, and Yunhai Geng. Design and control of an adaptive knee joint exoskeleton mechanism with buffering function. *Sensors*, 21(24):8390, 2021. doi: 10.3390/s21248390.

[39] Chiawei Liang and Tesheng Hsiao. Walking strategies and performance evaluation for human-exoskeleton systems under admittance control. *Sensors*, 20(15):4346, 2020. doi: 10.3390/s20154346.

[40] Moyao Gao, Zhanli Wang, Zaixiang Pang, Jianwei Sun, Jing Li, Shuang Li, and Hansi Zhang. Electrically driven lower limb exoskeleton rehabilitation robot based on anthropomorphic design. *Machines*, 10(4):266, 2022. doi: 10.3390/machines10040266.

[41] Naji A. Alibeji, Vahidreza Molazadeh, Frank Moore-Clingenpeel, and Nitin Sharma. A muscle synergy-inspired control design to coordinate functional electrical stimulation and a powered exoskeleton: Artificial generation of synergies to reduce input dimensionality. *IEEE Control Systems Magazine*, 38(6):35–60, 2018. doi: 10.1109/MCS.2018.2866603.

[42] Afshin Alipour, Mohammad J. Mahjoob, and Ara Nazarian. A new 4-DOF robot for rehabilitation of knee and ankle-foot complex: Simulation and experiment. *Journal of Robotics and Control (JRC)*, 3(4):483–495, 2022. doi: 10.18196/jrc.v3i4.14759.

[43] Lukas Bergmann, Oliver Luck, Daniel Voss, Philipp Buschermohle, Lin Liu, Steffen Leonhardt, and Chuong Ngo. Lower limb exoskeleton with compliant actuators: Design, modeling, and human torque estimation. *IEEE/ASME Transactions on Mechatronics*, 28(2):758–769, 2023. doi: 10.1109/TMECH.2022.3206530.

[44] Alice De Luca et al. Exoskeleton for gait rehabilitation: Effects of assistance, mechanical structure, and walking aids on muscle activations. *Applied Sciences*, 9(14):2868, 2019. doi: 10.3390/app9142868.

[45] David Eguren, Manuel Cestari, Trieu Phat Luu, Atilla Kilicarslan, Alexander Steele, and Jose L Contreras-Vidal. Design of a customizable, modular pediatric exoskeleton for rehabilitation and mobility. In *2019 IEEE International Conference on Systems, Man and Cybernetics (SMC)*, pages 2411–2416, Bari, Italy, 2019. doi: 10.1109/SMC.2019.8914629.

[46] Felix M. Escalante, Juan C. Pérez-Ibarra, Jonathan C. Jaimes, Adriano A.G. Siqueira, and Marco H. Terra. Robust Markovian impedance control applied to a modular knee-exoskeleton. *IFAC-PapersOnLine*, 53(2):10141–10147, 2020. doi: 10.1016/j.ifacol.2020.12.2740.

[47] Mohamed Ghezal, Mohamed Guiatni, Ismail Boussioud, and Cherif Sofiane Renane. Design and robust control of a 2 DOFs lower limb exoskeleton. In *2018 International Conference on Communications and Electrical Engineering (ICCEE)*, pages 1–6. El Oued, Algeria, 2018. doi: 10.1109/CCEE.2018.8634540.

[48] Jiang Han, Siyang Yang, Lian Xia, and Ye Hwa Chen. Deterministic adaptive robust control with a novel optimal gain design approach for a fuzzy 2-DOF lower limb exoskeleton robot system. *IEEE Transactions on Fuzzy Systems*, 29(8):2373–2387, 2021. doi: 10.1109/TFUZZ.2020.2999739.

[49] Haimin He, Ruru Xi, and Youping Gong. Performance analysis of a robust controller with neural network algorithm for compliance tendon–sheath actuation lower limb exoskeleton. *Machines*, 10(11):1064, 2022. doi: 10.3390/machines10111064.

[50] Vishnu Mani Hema et al. Upper and lower limb interchangeable exoskeleton-robot for post stroke rehabilitation. In *2021 9th RSI International Conference on Robotics and Mechatronics (ICRoM)*, pages 7–12, Tehran, Iran, 2021. doi: 10.1109/ICRoM54204.2021.9663510.

[51] Chao Huang, Weihai Chen, Jingmeng Liu, and Jianbin Zhang. Design of a compliant joint actuator for lower-limb exoskeleton robot. In *2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, pages 1522–1527. Siem Reap, Cambodia, 2017. doi: 10.1109/ICIEA.2017.8283080.

[52] Guo Shing Huang, Shao Chian Chang, Chung Liang Lai, and Chi Chun Chen. Development of a lower extremity exoskeleton as an individualized auxiliary tool for sit-to-stand-to-sit movements. *IEEE Access*, 9:48276–48285, 2021. doi: 10.1109/ACCESS.2021.3063253.

[53] Samina Jamil, Syed Wasi, Asif Mahmood, and Abdul Rehman. Design and fabrication of force augmenting exoskeleton using motion intention detection. In *2022 International Conference on Emerging Technologies in Electronics, Computing and Communication (ICETECC)*, pages 1–6, Jamshoro, Sindh, Pakistan, 2022. doi: 10.1109/ICETECC56662.2022.10069860.

[54] Mohamad Kardofaki, Nahla Tabti, Samer Alfayad, Fethi Ben Ouezdou, Yacine Chitour, and Eric Dychus. Mechanical development of a scalable structure for adolescent exoskeletons. In *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, pages 323–330, Toronto, Canada, 2019. doi: 10.1109/ICORR.2019.8779395.

[55] Chao Li, Xianzhi Jiang, and Xinchao Tian. Dual-mode control of rehabilitation mechanical leg based on kinematic modeling. In *2018 IEEE International Conference on Mechatronics and Automation (ICMA)*, pages 1106–1111. Changchun, China, 2018. doi: 10.1109/ICMA.2018.8484505.

[56] Pengbo Li, Wenhao Wei, Ruoyu Bao, Bailin He, Zhilong Su, Can Wang, and Xinyu Wu. A modular rehabilitation lower limb exoskeleton for stroke patients with hemiplegia. In *2021 IEEE International Conference on Real-Time Computing and Robotics, (RCAR)*, pages 656–661, Xining, China, 2021. doi: 10.1109/RCAR52367.2021.9517612.

[57] Yang Li, Weihai Chen, Jianhua Wang, Jianbin Zhang, and Xiantao Sun. Mechanical design and optimization on lower extremity rehabilitation robot. In *2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, pages 1612–1617, Kristiansand, Norway, 2020. doi: 10.1109/ICIEA48937.2020.9248432.

[58] Wenyuan Liang and Yong Yu. Manipulability inclusive principle for assistive result evaluation of assistive mechanism. *Journal of Healthcare Engineering*, 2018:2767129, 2018. doi: 10.1155/2018/2767129.

[59] Chih Jer Lin and Ting Yi Sie. Design and experimental characterization of artificial neural network controller for a lower limb robotic exoskeleton. *Actuators*, 12(2):55, 2023. doi: 10.3390/act12020055.

[60] Sergei V. Sarkisian, Marshall K. Ishmael, Grace R. Hunt, and Tommaso Lenzi. Design, development, and validation of a self-aligning mechanism for high-torque powered knee exoskeletons. *IEEE Transactions on Medical Robotics and Bionics*, 2(2):248–259, 2020. doi: 10.1109/TMRB.2020.2981951.

[61] Shaymaa M. Mahdi, Noor Q. Yousif, Ahmed A. Oglah, Musaab E. Sadiq, Amjad J. Humaidi, and Ahmad Taher Azar. Adaptive synergetic motion control for wearable knee-assistive system: A rehabilitation of disabled patients. *Actuators*, 11(7):176, 2022. doi: 10.3390/act11070176.

[62] Z. Nursultan, M. Ceccarelli, and G. Balbayev. Design of an exoskeleton for rehabilitation ankle joint. In *Proceedings of SYROM 2022 & ROBOTICS 2022*, pages 219–227, 2023. doi: 10.1007/978-3-031-25655-4_23.

[63] Fabrizio Patané, Stefano Rossi, Fausto Del Sette, Juri Taborri, and Paolo Cappa. WAKE-Up exoskeleton to assist children with cerebral palsy: Design and preliminary evaluation in level walking. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 25(7):906–916, 2017. doi: 10.1109/TNSRE.2017.2651404.

[64] Wei Sun, Jhih Wei Lin, Shun Feng Su, Ning Wang, and Meng Joo Er. Reduced adaptive fuzzy decoupling control for lower limb exoskeleton. *IEEE Transactions on Cybernetics*, 51(3):1099–1109, 2021. doi: 10.1109/TCYB.2020.2972582.

[65] Jiajun Xu, Youfu Li, Linsen Xu, Chen Peng, Shouqi Chen, Jinfu Liu, Chanchan Xu, Gaoxin Cheng, Hong Xu, Yang Liu, and Jian Chen. A multi-mode rehabilitation robot with magnetorheological actuators based on human motion intention estimation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 27(10):2216–2228, 2019. doi: 10.1109/TNSRE.2019.2937000.

[66] Yang Zhang, Sander De Groof, Larent Peyrodie, and Luc Labey. Mechanical design of an exoskeleton with joint-aligning mechanism for children with cerebral palsy. In *2020 8th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*, pages 106–111. New York, USA, 2020. doi: 10.1109/BioRob49111.2020.9224383.

[67] Libo Zhou, Weihai Chen, Jianhua Wang, Shaoping Bai, Haoyong Yu, and Yinping Zhang. A novel precision measuring parallel mechanism for the closed-loop control of a biologically inspired lower limb exoskeleton. *IEEE/ASME Transactions on Mechatronics*, 23(6):2693–2703, 2018. doi: 10.1109/TMECH.2018.2872011.

[68] Tong Zhou, Jianjun Yuan, Shugen Ma, Tieshi Zhao, Sheng Bao, Liang Du, Weiwei Wan, Zhongying Liu, and Ye Zhang. Integration mode of standing balance and trajectory training based on lower limb rehabilitation exoskeleton. In *2021 IEEE International Conference on Robotics and Biomimetics, (ROBIO)*, pages 1252–1257, Sanya, China, 2021. doi: 10.1109/ROBIO54168.2021.9739337.

[69] Alessia Sacchini, Federico Tessari, Christian Vassallo, Stefano Maludrottu, Elena De Momi, Matteo Laffranchi, and Lorenzo De Michieli. Sensorless impedance control for the TWIN lower limb exoskeleton: A preliminary study. In *2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob)*, pages 1–7, Seoul, Korea, 2022. doi: 10.1109/BioRob52689.2022.9925376.

[70] Rajan Prasad, Marwan El-Rich, Mohammad I. Awad, Irfan Hussain, H. F. Jelinek, Umer Huzaifa, and Kinda Khalaf. A framework for determining the performance and requirements of cable-driven mobile lower limb rehabilitation exoskeletons. *Frontiers in Bioengineering and Biotechnology*, 10:920462, 2022. doi: 10.3389/fbioe.2022.920462.

[71] Alan Francisco Perez Vidal, Jesse Yoe Rumbo Morales, Gerardo Ortiz Torres, Felipe de Jesus Sorcia Vazquez, Alan Cruz Rojas, Jorge Aurelio Brizuela Mendoza, and Julio Cesar Rodriguez Cerda. Soft exoskeletons: Development, requirements, and challenges of the last decade. *Actuators*, 10(7):166, 2021. doi: 10.3390/act10070166.

[72] Piotr Falkowski and Kajetan Jeznach. Simulation of a control method for active kinesiotherapy with an upper extremity rehabilitation exoskeleton without force sensor. *Journal of NeuroEngineering and Rehabilitation*, 21(1):22, 2024. doi: 10.1186/s12984-024-01316-x.

[73] David A Nicholls. Aged care as a bellwether of future physiotherapy. *Physiotherapy Theory and Practice*, 36(8):873–885, 2020. doi: 10.1080/09593985.2018.1513105.

[74] Dario Calafiore, Francesco Negrini, Nicola Tottoli, Francesco Ferraro, Ozden Ozyemisci-Taskiran, et al. Efficacy of robotic exoskeleton for gait rehabilitation in patients with subacute stroke: a systematic review. *European Journal of Physical and Rehabilitation Medicine*, 58(1):1–8, 2022. doi: 10.23736/S1973-9087.21.06846-5.

[75] Virgil Mathiowetz. Task-oriented approach to stroke rehabilitation. In Glen Gillen, editor, *Stroke Rehabilitation: A Function-Based Approach*, chapter 3, pages 59–74. Mosby, 2020. doi: 10.1016/B978-0-323-17281-3.00003-4.

[76] Piotr Falkowski, Jan Oleksiuk, Kajetan Jeznach, and Mehmet Emin Aktan. Method of automatic biomedical signals interpretation for safety supervision and optimisation of the exoskeleton-aided physiotherapy of lower extremity. In *Proceedings of the 2024 4th International Conference on Robotics and Control Engineering*, pages 57–63, 2024. doi: 10.1145/3674746.3674793.

[77] Julia Wilk and Piotr Falkowski. A concept of detecting patient hazards during exoskeleton-aided remote home motor rehabilitation. *Prace Naukowe Politechniki Warszawskiej. Elektronika*, pages 101–112, 2022.

[78] Julia Wilk, Piotr Falkowski, and Tomasz Osiak. The overview of challenges in detecting patients' hazards during robot-aided remote home motor rehabilitation. *Journal of Automation, Mobile Robotics and Intelligent Systems*, 17(4):17–27, 2023. doi: 10.14313/JAMRIS/4-2023/27.

[79] Piotr Falkowski, Tomasz Osiak, Julia Wilk, Norbert Prokopiuk, Bazyli Leczkowski, Zbigniew Pilat, and Cezary Rzymkowski. Study on the applicability of digital twins for home remote motor rehabilitation. *Sensors*, 23(2):911, 2023. doi: 10.3390/s23020911.

[80] Matthias B Näf, Karen Junius, Marco Rossini, Carlos Rodriguez-Guerrero, Bram Vanderborght, and Dirk Lefeber. Misalignment compensation for full human-exoskeleton kinematic compatibility: State of the art and evaluation. *Applied Mechanics Reviews*, 70(5):050802, 2018. doi: 10.1115/1.4042523.

[81] Piotr Falkowski. Predicting dynamics of a rehabilitation exoskeleton with free degrees of freedom. In Roman Szewczyk, Cezary Zieliński, and Małgorzata Kaliczyńska, editors, *Automation 2022: New Solutions and Technologies for Automation, Robotics and Measurement Techniques*, pages 223–232. Springer International Publishing, 2022. doi: 10.1007/978-3-031-03502-9_23.

[82] Piotr Falkowski. An optimisation problem for exoskeleton-aided functional rehabilitation of an upper extremity. In *IOP Conference Series: Materials Science and Engineering*, volume 1239, page 012012, 2022. doi: 10.1088/1757-899X/1239/1/012012.

[83] Cristina Fernandez-Garcia, Laura Ternent, Tara Marie Homer, et al. Economic evaluation of robot-assisted training versus an enhanced upper limb therapy programme or usual care for patients with moderate or severe upper limb functional limitation due to stroke: results from the RATULS randomised controlled trial. *BMJ Open*, 11(5):e042081, 2021. doi: 10.1136/bmjopen-2020-042081.

[84] Linda Shore, Valerie Power, Adam De Eyto, and Leonard W O'Sullivan. Technology acceptance and user-centred design of assistive exoskeletons for older adults: A commentary. *Robotics*, 7(1):3, 2018. doi: https://doi.org/10.3390/robotics7010003.