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Design and control of soft rehabilitation robots actuated by pneumatic muscles: State of the art☆

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ABSTRACT

Robot-assisted rehabilitation has become a new mainstream trend for the treatment of stroke patients with movement disability. Pneumatic muscle (PM) is one of the most promising actuators for rehabilitation robots, due to its inherent compliance and safety features. In this paper, we conduct a systematic review on the soft rehabilitation robots driven by pneumatic muscles. This review discusses up to date mechanical structures and control strategies for PMs-actuated rehabilitation robots. A variety of state-of-the-art soft rehabilitation robots are classified and reviewed according to the actuation configurations. Special attentions are paid to control strategies under different mechanical designs, with advanced control approaches to overcome PM's highly nonlinear and time-varying behaviors and to enhance the adaptability to different patients. Finally, we analyze and highlight the current research gaps and the future directions in this field, which is potential for providing a reliable guidance on the development of advanced soft rehabilitation robots.

1. Introduction

In recent years, the number of stroke patients has increased rapidly and stroke has become the second leading causes of disability [1]. There are about 0.795 million people with stroke in the United States, among them 0.61 million are first or new strokes [2]. In developing countries, the incidence of stroke is even higher. For example, there are 1.3 million new stroke patients every year and three-quarters of them live with motion disability in China. In Latin America, the Middle East, and sub-Saran Africa, there will be a tripling in stroke mortality for the next two decades, one of the major disabled survivors [1]. As a result, the growth of hospitalization rates and prolonged treatment causes a steep increase in the requirement of health care resources. Rehabilitation robotics, which is able to provide robotic assistance for rehabilitation clinics and release the shortage of professional labor-force, has attracted increasing attention in both industrial and academic fields. The rehabilitation robot can assist patients during rehabilitation to restore some of the lost functions. Two kinds of robotic devices are currently available for rehabilitation: end effector robots and exoskeleton robots. Among these studies, PMs become a promising choice in actuators for wearable and compliant rehabilitation devices, due to its high power-to-weight ratios, inherent compliance, and similar behavior with human muscles. In recent years, there have been several well-known PMs-actuated rehabilitation robots, such as the series of upper limb exoskeleton RUPERT [3–5] and lower limb orthosis KAFO [6,7]. Compared with widely-adopted rigid actuator-type rehabilitation robots, like Lokomat [8,9] and ArmeoPower [10,11], there exists no mature PMs-actuated products in the market up to now. Further, the PM's high-nonlinear and time-varying behavior arise the control difficulties for the PMs-actuated robots. "McKibben" muscle is a typical PM, with a cylinder elastic tube and a double helical braid wrapped around the outside, which has been widely utilized in recent soft rehabilitation robots [12]. However, "McKibben" muscle's reticular fiber structure exactly limits its contraction ratio and output force. Hence, some researchers designed straight-fiber-type pneumatic muscles to increase its output force and reduce the friction. Saikawa et al. applied high-intensity longitudinal reinforced Kevlar fibers outside the silicone tube to relieve the pneumatic muscle's friction and hysteresis, but it is easy to crack [13]. Likewise, Hirano et al. proposed a similar straight- fiber-type artificial muscle [14,15]. In addition, Beyl et al. designed a kind of novel pleated pneumatic artificial muscle (PPM) to drive a powered knee exoskeleton (KNEXO) [16,17]. Compared with "McKibben" muscle, PPM has a higher threshold pressure and substantial hysteresis [18,19]. This paper aims to review the remarkable mechanical designs and control strategies

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of the PMs-actuated rehabilitation robots, targeting to provide valuable information for relevant researcher's further studies.

In the past decade, the application of PMs in rehabilitation robotics has experienced rapid evolution, however, only a few review articles focus on PMs-actuated rehabilitation robots. Andrikopoulos et al. summarized the key enabling applications of PMs in various fields, such as biorobotic, medical, industrial and aerospace fields [18]. This review covered most application scenarios of PM, but little details of dynamic models and control strategies are presented. Chou et al. classified and discussed PM actuators and high-level control strategies for lower limb wearable robots [19]. But this paper lacks detailed discussion on PM-actuated rehabilitation robots. Additionally, study [20] provides a review on actuating technologies and applications towards wearable robotic orthosis, including electric/hydraulic/pneumatic actuators, and other promising actuating technologies. Tondu reviewed the modeling methods of "McKibben" muscle [21]. Meng et al. discussed mechanisms and control strategies of some PM-driven lower limb rehabilitation robots [22]. Dzahir et al. clarified existing applications and control strategies of PMs-actuated lower-limb leg orthoses, but only focusing on the PM antagonistic configurations [23]. As the aspect of control, Andrea et al. conducted the survey on the compliant control approaches for stiff and fixed-compliance robots, especially to promote human–robot interaction [24]. And Young et al. provided a complete and informative introduction about the recent development and future direction of the lower limb robotic exoskeleton [25]. Peng et al. has published a review article on soft robot with hybrid actuating technology [20]. To the authors' best knowledge, there has not been a review including both design and control of PMs-actuated rehabilitation robots. In particular, the all-round comparisons of existing rehabilitation robots are based on the published available data, to make researchers fully aware of the limitations and advantages of diverse mechanical designs and control schemes. This paper will tell the current research gaps and future directions, promoting the advent of more compliant, adaptable, intelligent and mature robots to satisfy the sharply increasing rehabilitation demands. The rest of paper is organized as follows. Section 2 clarifies rehabilitation robots with various mechanical structures. In Section 3, introduction and comparisons of control strategies are conducted. Section 4 discusses and analyzes the research limitations and future directions. Finally, conclusions are drawn in Section 5.

2. Mechanical design of PMs-actutuated rehabilitaion robots

A PM mainly contains a braid-covered rubber tube and two closed ends. One end is usually connected to the proportional solenoid valves to regulate the pressure inside the PM, while the other exerts axial-direction contractile force [21]. As a single direction-acting element, the PM can only contract to generate pulling force. To achieve the actuated movements in multiple degree of freedoms (DOFs), PMs are always designed to work together in antagonistic, parallel or bio-inspired configurations.

2.1. Antagonistic pair-based robots

Antagonistic configuration, as one of the most frequently used actuation schemes, can provide the bidirectional assistance to the patient's joints. One PM antagonistic pair consists of two PMs connected through a cable and a pulley. By regulating the pressure inside each PM, the configuration can provide one rotational DOF assistance. Hence PM antagonistic pairs are widely utilized in upper/lower limb multi-joint exoskeletons and to help patients to complete the assigned movement tasks.

In 2002, University of Salford, UK developed a 7-DOF upper limb rehabilitation exoskeleton actuated by PM antagonistic pairs, as presented in Fig. 1(a) [22,23]. Huazhong University of Science and Technology, China, designed a 9-DOF arm rehabilitation robot fixed to a wheelchair (Fig. 1(b)) [24]. In this device, each active DOF is driven by a PM antagonistic pair. Afterwards, the team developed a novel antagonistic configuration, in which a PM is arranged in place of bicep and the torsion spring provides opposing torque [25,26]. Jiang et al. developed a 4-DOF upper limb rehabilitation robot to provide sufficient rehabilitation assistance for patients with upper limb motion dysfunctions (Fig. 1(c)) [27]. Recently, an exoskeleton for elbow joint rehabilitation was proposed by Tang et al. (Fig. 1(d)) [28]. This robot employs four size-adjustable carbon fibers to make subjects more comfortable. However, the air supply equipment is too heavy to allow subject wearing the exoskeleton to complete long-term ground training. Guo et al. introduced a joint motion radius element in 1-DOF rehabilitation robot so that the device can be adjusted to provide the required range of motion and multi-joint progressive assistance for different patient during the whole rehabilitation process [29], as shown in Fig. 1(e). Meng et al. designed a wrist exoskeleton, aimed at providing 1-DOF assistance for the patient's wrist rehabilitation (Fig. 1(f)) [30]. A novel modular shoulder exoskeleton was introduced in [31], as shown in Fig. 1(g). The exoskeleton was driven by a modular PM exoskeletal joint and can provide assistance for the patient's whole arm. Then the research team designed a modified Nested-cylinder PMs (NcPAMs), which is more powerful.

As for lower limb rehabilitation, antagonistic pair-based exoskeletons are mainly designed to provide walk power assistance. In terms of training modes, the robots can be classified as overground exoskeletons and treadmill-based orthoses, both can help to restructure the patient's walking ability. In 2007, Caldwell et al. developed a whole-body exoskeleton with seven DOFs for the upper limbs and five DOFs for each of the lower limbs (Fig. 1(h)) [32,39]. But the output force is too weak to be used in practice. Kanno et al. proposed a novel PMs-actuated walking assistive exoskeleton, as presented in Fig. 1(i) [33]. Users do not need to adjust the link length of the exoskeleton to fix their knees. HuREx, a human-inspired robotic exoskeleton, was designed for lower limb rehabilitation (Fig. 1(j)) [34]. To reduce the complexity and weight, the exoskeleton was manufactured by 3D printing and fiber reinforcement technologies [40]. Afterwards, the team developed a robotic orthosis for treadmill gait training (Fig. 1(k)) [35,41]. This orthosis provides trunk's vertical/lateral translation and the hip's passive abduction/adduction assistance for human subjects when walking on the treadmill. The hip and knee sagittal plane rotation torques are produced by PM antagonistic pairs [42]. But it can only be used for the left leg, and the maximum trajectory tracking error is up to 10°. Recently, a modified design has been published, as presented in Fig. 1(l) [36]. The knee joint is actuated by a PM antagonistic pair, and each side contains two PMs, to increase the torque and motion range of the joint. Recently, Huang et al. presented a treadmill-based gait robotic orthosis actuated by PM antagonistic pairs, as shown in Fig. 1(m) [37,43]. Inspired by the human musculoskeletal system during walking, Dzahir et al. developed a gait system (AIRGAIT) powered by antagonistic mono-articular and bi-articular PM actuators (Fig. 1(n)) [38,44,45] with larger assistance output. This high compliant lower limb rehabilitation orthosis is aimed to guide the patient's lower-limb to a designate trajectory and can adapt the compliance according to the patient's disability [46,47], as shown in Fig. 1(o).

An overview on the mechanical design and assistance capacity of antagonistic-pair robots are demonstrated in Table 1. It is noticed that PM antagonistic pairs have been widely adopted for

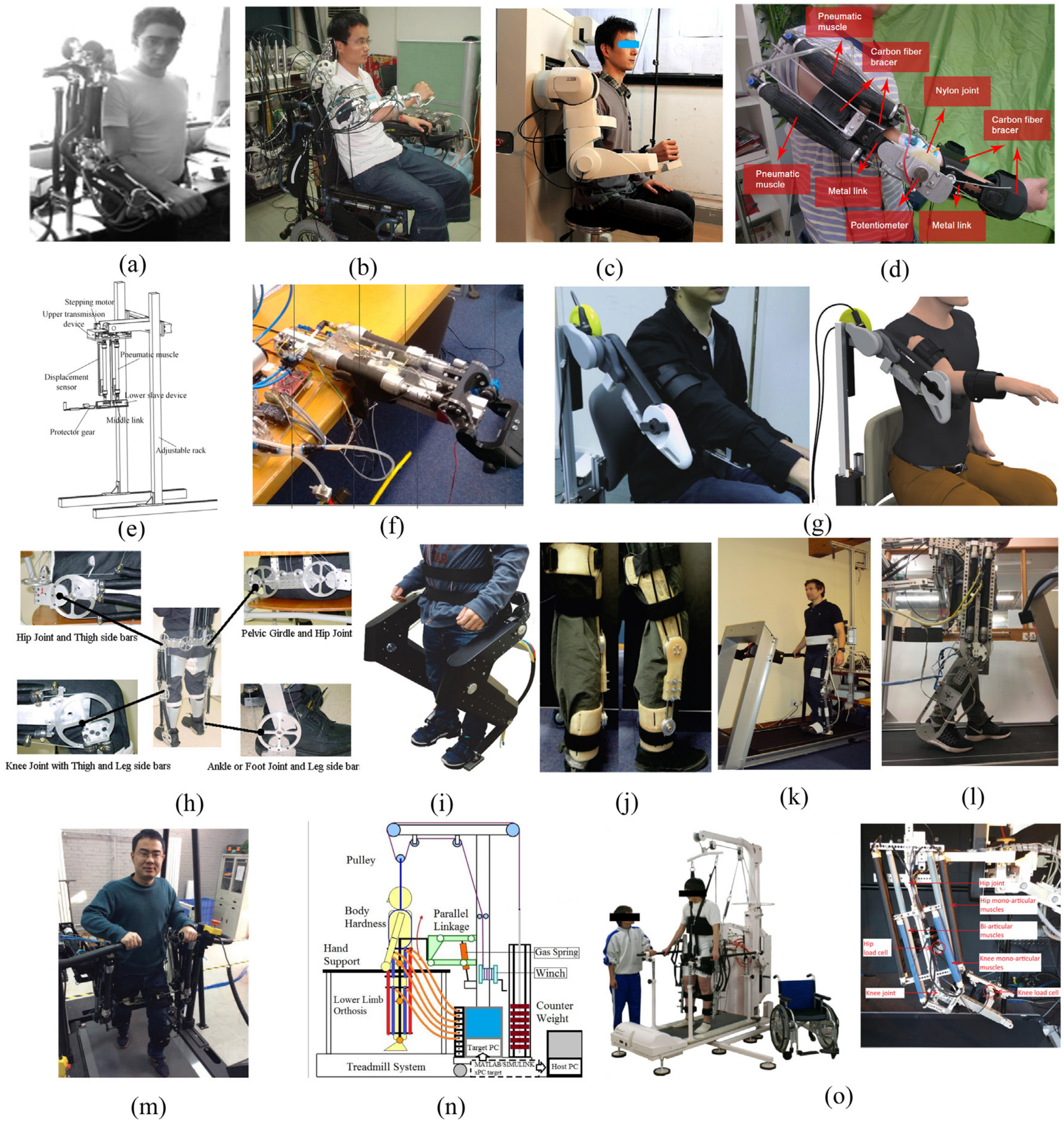

Fig. 1. Antagonistic pair-type rehabilitation robots. (a–l) is reprinted from [22,24,27–38], respectively.

almost all joints rehabilitation, especially for single-DOF joint. Since each antagonistic pair can only actuate 1-DOF motion, it is hard for them to guide and assist multi-DOF joints. Another limitation is that their assistance outputs are too small to cover the whole motion range of human joints. That means these robots may be just applicable to limited conditions and patients, instead of those who need larger assistance at the early stage of rehabilitation. To expand the assistance output, researchers have proposed several methods to modify the PMs antagonistic pairs, for example, doubling the numbers of PMs [36] and cooperating the mono-articular with bi-articular PM actuators [38,44,45].

2.2. Parallel rehabilitation robots

To achieve multi-DOF motion from one actuating joint, parallel PM configuration was proposed. Due to the high stiffness output and low inertia force, parallel configurations of PMs are mostly designed for ankle joint rehabilitation. University of Auckland developed a wearable 3-DOF ankle rehabilitation robot actuated by PMs in parallel, to correct the patient's gait pattern (Fig. 2(a)) [48]. The robot consists of two parallel platforms, a fixed platform and a moving platform that is actuated by four PMs in parallel [49]. As the PM can only provide unidirectional force, it is essential to add a redundant actuation to achieve the required motion DoFs. Since this orthosis enables patient's foot–ankle body fixed on the gaiter, the influence of knee joint's motion on the ankle can be mitigated. Likewise, the ankle rehabilitation robot proposed in [50] also employs parallel PMs to actuate the user's ankle joint (Fig. 2(b)). This orthosis allows the shinbone stay stationary during the ankle rehabilitation training. Southeast University, China, presented a humanoid lower limb exoskeleton (HLLE) to assist knee and ankle joints motion [51]. However, not much details on the robot's performance were provided. Although parallel configuration is the mainstream structure for ankle rehabilitation, there are also some parallel PMs-driven rehabilitation robots for other multi-DOF joints. For example, Andrikopoulos et al. developed a 2-DOF PMs-actuated exoskeletal wrist (EXOWRIST) for wrist joint rehabilitation (Fig. 2(c)) [52,53]. Four parallel PMs are placed on the plastic gloves around the forearm, to assist patients with the performance of main wrist activities. Since many patients have lost the controllability of their thumbs, they cannot perform main

Table 1
Overview of antagonistic pair-based robots.

Robots	Aims	Actuated DOFs	Assistance capacity	References
Upper limb exoskeleton	Helping the disabled to achieve natural motion from shoulder to the wrist	7-DOF: shoulder FE/AA, elbow FE/SP, wrist FE/AA	Approximately 20% of ROHIS	Caldwell et al. [22,23]
Arm rehabilitation robot	Recovering motor function for stroke patients	9-DOF: shoulder FE/AA/LM, elbow FE/SP, wrist FE/AA	73%∼91% of ROHM	Jiang et al. [24–26]
Upper limb rehabilitation robot	Providing assistance for patients with upper limb motion dysfunctions	4-DOF: three active DOFs and one passive DOF	–	Jiang et al. [27]
Upper-limb power-assist exoskeleton	Developed to assist physically disabled or elderly people	1-DOF: elbow FE	ROM of 0∼180° and 0∼145° for shoulder/elbow, respectively	Tang et al. [28]
Multi-joint Progressive rehabilitation robot	Providing the required range of motion and multi-joint progressive assistance	1-DOF: can be adjusted to assist knee, elbow, shoulder joint	ROM of knee, elbow, shoulder joint with ±70°, ±55° and ±40°	Guo et al. [29]
Modular shoulder exoskeleton	Designed to assist the patient's shoulder and whole arm	1 DOF: shoulder FE	Nominal maximum torque is 45 N m	Noda et al. [31]
Wrist rehabilitation robotic device	Assisting the stroke and cerebral palsy patients to achieve wrist rehabilitation exercise	1-DOF: wrist FE	ROM of up to −30°∼30° and the maximum force output up to about 60 N	Meng et al. [30]
Whole-body exoskeleton	Designed for limb retraining, rehabilitation and power assistance	17-DOF: shoulder FE/AA/LM, elbow FE/SP, wrist FE/AA, hip FE/AA/LM, knee FE, ankle DP	>41% of ROHM and >86.4% of ROHIS	Caldwell et al. [32,39]
Treadmill-based gait training robotic orthosis	Helping stroke patients to regain mobility	2-DOF: hip FE, knee FE	ROM of 0∼−85°∼−25° and ROT of 40/60 N m for knee/hip joint	Huang et al. [37,43]
Lower limb robotic orthosis	Providing treadmill training of neurologically impaired subjects	2-DOF: hip FE, knee FE 1-DOF: knee FE	ROM of 60°/30° and 90°/30° for hip/knee ROM of −3∼93°	Hussain et al. [36] Cao et al. [35,41]
Walking assist device	Assisting patients with performance of walking	2-DOF: hip FE, knee FE	–	Kanno et al. [33]
Human-inspired robotic exoskeleton (HuREx)	Developed for lower limb rehabilitation	1-DOF: knee FE	Maximum load of up to 550 N	Macdaid et al. [34]
Lower orthotic gait training system (AIRGAIT)	Designed to regain the impaired movements for spinal cord injury patients	2-DOF: hip FE, knee FE	Maximum angle extension of up to 60° at knee joint	Dzahir et al. [38,44,45], Dao et al. [46,47]

FE = flexion/extension, AA = adduction/abduction, IE = inversion/eversion, DP = dorsiflexion/plantarflexion, UR = ulnar/radial deviation, SP = supination/pronation, LM = lateral–medial rotation, ROM = range of motion, ROT = range of torque, ROHM = range of human motion, ROHIS = range of human isometric strength.

function of hands {Namazi, 2019 #36}. Shiota et al. presented a soft robotic rehabilitation system only for the thumb's movement ability reconstruction, as shown in Fig. 2(d) [54]. In this design, parallel PMs placed on the forearm enable the thumb's metacarpophalangeal joint to achieve 3-DOF motion, and a soft pneumatic actuator for bending (SPAB) is used to assist the patient's thumb for bending motion.

Aiming at the recovery for another multi-DOF joint, wrist, Zi et al. designed a hybrid-driven waist rehabilitation robot (HWRR) powered by three parallel PMs and springs (Fig. 2(e)) [55]. Recently, the PMs-driven parallel configurations have attracted the widespread attentions. A straight-fiber-type PMs-actuated 3-DOF delta mechanism was developed by Chuo University, Japan (Fig. 2(f)) [14,15]. The arms are actuated by parallel PMs through the pulley, and the end plate always remain parallel to the base plate, to achieve three translational DOFs. Its workspace is expanded, but the force output is still limited. To enable a fast response and high output, the team developed a modified version by adding magneto rheological (MR) clutches. Different from previous parallel configuration, Kang et al. designed a novel 3-DOF PM actuator with a compact and lightweight structure (Fig. 2(g)) [56]. The design consists of three PMs in parallel, and relative position of muscles is kept by eight connecting plates. By regulating pressure in each PM, this actuator can provide one translational DOF and two rotational DOFs.

Table 2 shows the comparison of parallel PMs-driven rehabilitation robots. We can see that parallel configurations are suitable for multi-DOF joints rehabilitation, such as ankle, wrist and waist joints. But the number of relevant publications is exactly small, and some of them do not provide many details about the robots' assistance capacity. The mechanical complexity of parallel robots is greater than antagonistic pair-type ones, which may place a great obstacle on the parallel robot's applications in rehabilitation. Recently, several novel designs of parallel PMs-actuators have been published [14,15,56,57], the adoption of these new parallel configurations may reduce the complexity of the rehabilitation robots. Additionally, the table demonstrates the larger output ability of parallel configurations, and they can cover the whole motion range of corresponding human joints. As these antagonistic and parallel configurations have their own special advantages and limitations, it may be a good choice to combine them together to develop multi-joint-multi-DOF rehabilitation robots.

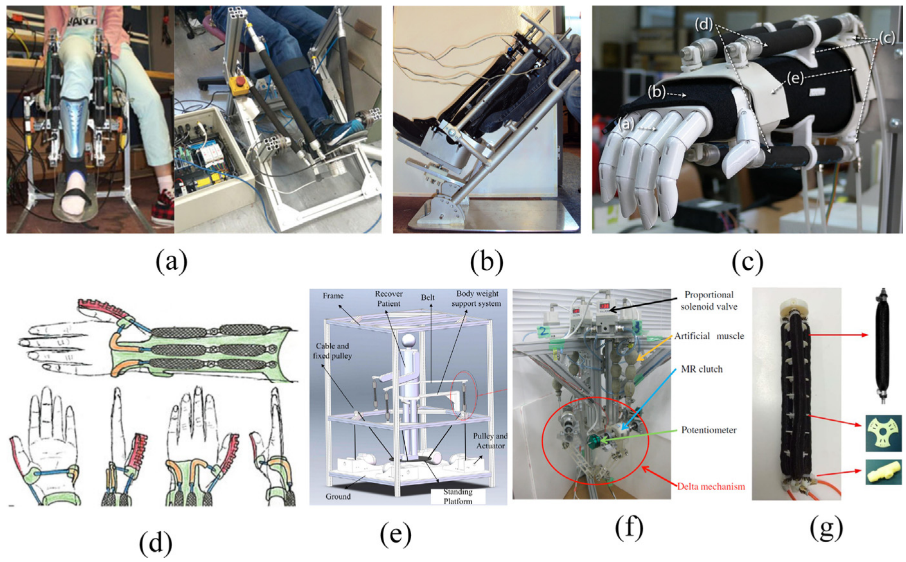

Fig. 2. Antagonistic pair-type rehabilitation robots. (a, b) is reprinted from [49,50], respectively; (c) is reprinted from [52], (d, e) is reprinted from [54,55], respectively; (f) is reprinted from [14], (g) is reprinted from [56].

Table 2
Overview of parallel rehabilitation robots.

Robots	Aims	Actuated DOFs	Assistance capacity	References
Wearable ankle robot	Providing the treatments of ankle sprain	3-DOF: ankle DP/IE/AA	100% of ROHM and ROT of 68∼120 N m	Jamwal et al. [48,49]
Compliant ankle joint rehabilitation robot	Designed for home-based gait training associated with neurological disorders	3-DOF: ankle DP/IE/AA	–	Jamwal et al. [50]
Humanoid lower limb exoskeleton (HLLE)	Enhancing the power of person's lower limb	6-DOF: knee FE and ankle DP/IE	–	Wan et al. [51]
Exoskeletal wrist prototype (EXOWRIST)	Assisting wrist rehabilitation after stroke and sport injuries	2-DOF: wrist EF/UR	ROM of −41.7°∼41.3°	Andrikopoulos et al. [52,53]
Soft robotic thumb rehabilitation system	Providing rehabilitation for patients with thumb dyskinesia	4-DOF of thumb	100% of ROHM	Shiota et al. [54]
Hybrid-driven waist rehabilitation robot (HWRR)	Providing assistance for waist injured patients during rehabilitation training	Rotational 2-DOF	–	Zi et al. [55]
Delta-type parallel-link robot	Rendering human arbitrary-force sense for rehabilitation without force sensors	Translational 3-DOF	ROM of −50°∼90°	Hirano et al. [14,15]
Parallel actuator	A multi-DOF actuator for rehabilitation robots	Rotational 2-DOF and translational 1-DOF	The maximum strain is up to 40% of the actuator's initial length	Kang et al. [56]

FE = flexion/extension, AA = adduction/abduction, IE = inversion/eversion, DP = dorsiflexion/plantarflexion, UR = ulnar/radial deviation, SP = supination/pronation, LM = lateral–medial rotation, ROM = range of motion, ROT = range of torque, ROHM = range of human motion, ROHIS = range of human isometric strength.

2.3. Bio-inspired robots design

To achieve more natural rehabilitation training, some researchers learnt from the human biological model and designed bio-inspired robots by actuating each PM independently, in which PMs imitate the working principle of human muscles. The soft ankle–foot orthotic device designed by Park et al. from Harvard University, US, is a typical example of bio-inspired PMs-actuated rehabilitation robots (Fig. 3(a)) [58,59]. In this design, three PMs are attached on the anterior part of the lower leg, close to the biological tendons. The PMs work as actual anterior muscles for dorsiflexion independently. Moreover, this robot is mainly made of soft materials, without limitation of steel attachment, so it can help ankle joint to achieve 3-DOF motions in a large workspace. Recently, Alfahaam et al. proposed a wearable glove, employing four bending PMs to drive corresponding fingers respectively, as shown in Fig. 3(b) [60]. Experimental results show that the robot can assist most human hand activities. The team further developed a new wearable glove for wrist joint rehabilitation with a similar mechanical design [60,61].

University of Michigan, US, designed a series of PMs-actuated ankle–foot orthosis, as presented in Fig. 3(d) [7,63,64]. They firstly designed two ankle–foot orthoses, one is a single-PM-actuated orthosis and the other is driven by two PMs in parallel. All these PMs are attached to the posterior of the orthoses, to provide plantarflexor torque [64]. The experimental results show that, the total force produced by two PMs is double of the force produced by a single PM. But there is no difference on the peak force. In the same year, the team proposed a modified ankle–foot orthosis (AFO) actuated by two PMs [7,63]. One of the PMs is attached to the anterior to provide dorsiflexion torque, while the second one placed on posterior part to produce plantar flexion torque. The modified orthosis can provide patients with additional dorsiflexion motion assistance, but the torque outputs are too limited to satisfy the patients' gait rehabilitation. Afterwards, a knee–ankle–foot orthosis (KAFO) was developed to meet the rehabilitation

Fig. 3. Bio-inspired rehabilitation robots. (a–c) is reprinted from [58,60,62], respectively; (d) is reprinted from [6,7,63,64], (e) is reprinted from [65], (f) is reprinted from [66], (g) is reprinted from [67], (h) is reprinted from [68], (i) is reprinted from [5,69,70].

demands for lower limbs [6]. In order to achieve larger torques to ensure the normal joint motion range, the orthosis is driven by six PMs together via stainless steel brackets. Due to the trade-off between output torque and motion range of PMs, the knee torque is smaller than the ankle torque. Hence, combining other type of actuators with PMs is a good choice to improve the torque and motion abilities of the rehabilitation robots. For example, Hyon et al. designed a novel structure by combining PMs with electric motors (Fig. 3(c)) [62]. Attributing to the expanded motion range and output torque, the robot can help patients to squat and walk. In 2014, Adolf et al. proposed a robotic ankle orthotic device for patients with chronic ankle instability (CAI) (Fig. 3(e)) [65]. As shown in Fig. 3(f), to make the device more wearable and lightweight, Irshaidat et al. proposed a soft arm exoskeleton (EpMAE) for patients performing repetitive motion therapy at home without the assist of therapists and with a lower cost [66]. Different from traditional mechanism design of supination and pronation, Zhang et al. designed a 2-DOF soft elbow rehabilitation exoskeleton with two PMs horizontally on both side of the beam while beams and the axis of joint are collinear. During the movement process, one actuator's compression enable the beam to twist and the other elongated one would help to release its pressure to beam turn back [67]. As shown in Fig. 3(g), the PM actuators completely avoids the steel structure and can be wound around the patient's arm, which fits well with the human body but is difficult to wear. Deaconescu et al. developed a soft simultaneous passive rehabilitation robot for the radiocarpal, metacarpophalangeal and interphalangeal joints of the hand (Fig. 3(h)) [68].

In recent years, a series of upper limb rehabilitation robots (RUPERT) were developed by Arizona State University, US, as shown in Fig. 3(i). RUPERT III, a 4-DOF therapeutic robot, is actuated by four PMs individually to assist shoulder extension, elbow extension, forearm supination/ pronation, and wrist extension [5,69,70]. This robot is back-drivable and safe for patients, but the gravity is not compensated and the motion range is limited. Therefore, shoulder external rotation has been added in RUPERT IV to expand the robot's workspace. Additionally, RUPERT IV is mainly made of graphite composite materials to reduce its weight, so that it can enhance the user's ability to perform activities of daily living [3,4]. To stimulate patient's muscle activities and improve the robot-assisted performance, a hybrid robot assisted system powered by surface function electrical stimulation (FES) and PMs was developed [71].

As summarized in Table 3, bio-inspired robots seem to be more mature than antagonistic and parallel robots, especially KAFO and RUPERT have been studied for years, perhaps attributing to their more simple and flexible design. Not limited to stiff support frame, the PMs even enable the fingers to perform some complex activities of human hands. From the view of theory, bio-inspired robots are supposed to cover the complete natural

Table 3
Overview of bio-inspired robots.

Robotic system	Aims	Actuated DOFs	Assistance capacity	References
Soft ankle–foot orthotic device	Providing rehabilitate for patients with neuromuscular disorders	2-DOF: ankle DP/IE	ROM of 27° (14° dorsiflexion and 13° plantarflexion)	Park et al. [58,59]
Wearable glove	Designed for power assistance rehabilitation for hands	Multi-finger FE	40%∼45% of healthy person's force	Alfahaam et al. [60]
Wrist rehabilitation exoskeleton	Providing wrist joint rehabilitation	2-DOF: wrist FE/UR	ROM of 0∼90° and 0∼70° for FE; ROM of 0∼50° and 0∼20° for UR	Alfahaam et al. [61]
RUPERT III	Designed to assist patients with spasticity and hypertonia	4-DOF: shoulder/elbow/ wrist extension, forearm supination	ROM of 15°∼85°, 0∼125°, 30°∼60°, −45°∼45°, respectively	Balasubramanian et al. [5,69,70]
RUPERT IV	Providing home-based and clinical therapies for stroke patients	5-DOF: add a shoulder external rotation based on RUPERT III	–	Balasubramanian et al. [3,4]
		1-DOF: ankle DP	Maximum torque of 70 N m/38 N m, and ROM of 0 ∼ 7°/0∼15°	Ferris et al. [7,63]
Soft arm exoskeleton (EpMAE)	Helping patients with repetitive motion therapy at home	1-DOF: elbow FE	Maximum angle of 0°∼230°	Irshaidat et al. [66]
Soft elbow rehabilitation exoskeleton	Designed to assist the rehabilitation of elbow	2 DOF: elbow FE/ DP	Maximum angle of 0°∼160° and 0°∼90° for FE and DP respectively	Zhang et al. [67]
Soft simultaneous passive hand rehabilitation robot	Providing assistance for the radiocarpal, metacarpophalangeal and interphalangeal joints	3-DOF: wrist FE, metacarpophalangeal joints FE	Maximum angle of 70°/80°for wrist FE, and 90°/100° for metacarpophalangeal joints FE	Deaconescu et al. [68].
Knee–ankle–foot orthosis (KAFO)	Assisting patients during walking	2-DOF: knee FE, ankle DP	22%∼33% and 15%∼33% of ROHIS for knee FE, and 42%∼46% and 83%∼129% of ROHIS for ankle DP	Sawicki et al. [6]
Hybrid drive exoskeleton robot (XoR)	Providing rehabilitation for the elderly, the strokes or people with spinal cord injury or stroke	10-DOF: hip FE/AA, knee FE, ankle FE/AA	Maximum angle of −120°/30°, −30°/30°, 0°/120°, −60°/30°, −30°/30°, respectively	Hyon et al. [62]
Lightweight compliant robotic ankle orthosis	Assisting gait treating for patients with chronic ankle instability (CAI)	2-DOF: ankle DP/IE	ROM of 28.4%∼76% and walking range of 10%∼72%	Adolf et al. [65]

FE = flexion/extension, AA = adduction/abduction, IE = inversion/eversion, DP = dorsiflexion/plantarflexion, UR = ulnar/radial deviation, SP = supination/pronation, LM = lateral–medial rotation, ROM = range of motion, ROT = range of torque, ROHM = range of human motion, ROHIS = range of human isometric strength.

motion ranges for both human upper and lower limbs. But in practice, the current PM-driven robots cannot reach such a wide workspace due to the limitation of PM's output force. To expend the assistance capacity of the robots, other types of actuators have been used with PMs together to assist the patients [62].

3. Control strategies of PMs-actuated rehabilitation robots

3.1. Control of antagonistic joints

In [22,23,38,44,72,73], traditional PI and PID control were utilized to achieve the trajectory tracking for an upper limb exoskeleton and a walking assistive orthosis. But results from these papers show that, robustness and accuracy of PI/PID control strategies still need to be improved. Serious respond delay was found in some schemes, for example, there is 0.2 s delay for the 1 s gait circle in [44]. To adjust the robot assistance according to the human–robot interaction, Tsagarakis et al. introduced impedance control with torque feedback [23]. The results show that the output torque errors decrease from ±2 N m to ±0.2 N m. As the spasms of the stroke patient's muscle may cause abnormal events during the rehabilitation, force/position control is employed to enhance the training safety. Ahn et al. introduced neural networks to tune the gain parameters of PID controller, and compensate the disturbance [74,75]. Then to improve the device's compliant output performance, they designed a new hybrid adaptive neural network compliant force/position controller (ADNN–PID) so that the 2-DOF robot's all nonlinear features can be dynamically identified [76]. Jiang et al. combined PID controller with position feedback to control antagonistic PM pairs [24]. The results show that there is no obvious trajectory tracking error, but existing an overshoot of about 1°. To reduce the overshoot, a neuron PI control approach was proposed by employing a neural network to tune the PI control gains [77]. Further, a feed-forward controller was utilized to relieve the system friction, which is main cause of the overshoot. Compared with traditional PI controller, overshoot of the proposed controller decreases from 6.35° to 2°. But it can only work well in a limited workspace. Likewise, researchers from Arizona State University utilized PID-based feedback control strategy for the RUPERT [4]. To ensure the maximum voluntary participation, an iterative learning controller was employed to determine and adjust the patient's reachable workspace.

Since FLC mainly depends on experiences instead of detailed and precise models, it is an effective scheme to deal with PMs-actuated robots. For example, Jiang et al. proposed a fuzzy neural network (FNN) controller for the 4-DOF upper limb exoskeleton [27]. Combined with neural network, FLC is reconstructed as a five-layer FNN controller. The parameters of the membership function layer and output layer are online updated through error back propagation training algorithm. Through comparison with classical PI controller and FLC, FNN controller shows better performance with faster response and smaller vibration in trajectory tracking experiments. However, it is hard to obtain available experience-based data, and complicated fuzzy rule base usually increases the control complexity. To reduce the number of fuzzy rules, researchers proposed fuzzy sliding surface based on self-organizing learning mechanism (ASOFSMC) [78,79]. Compared with the fuzzy sliding controller (ASMC), the steady-state error range of ASOFSMC decrease from 0.09∼0.664 mm to 0.022∼0.044 mm. Then the team employed functional approximation (FA) to update and adjust fuzzy parameters of the fuzzy sliding mode controller (ASTFC) [80]. The maximum motion error and phase lag of ASTFC decline by 42.86% and 37.5% than FSMC's, respectively. The experimental results validate the control system's excellent tracking performance to overcome external disturbance. For the power knee exoskeleton (KNEXO), Beyl et al. proposed a proxy-based sliding mode controller (PSMC), in which a virtual robot link was connected to the real link via a PID-type virtual coupling [16,17]. This control scheme is designed to deal with the chattering problem of traditional SMC and make joints' motion smoother. Meanwhile, echo state network and nonlinear disturbance observer were also employed to compensate the control disturbance for the pneumatic muscle [81–83]. Likewise, a fuzzy logic controller was employed to approximate the switching control law [84], which can compensate the nonlinear disturbance effectively. In [85], Liu et al. proposed equivalent control-based discrete SMC (DSMC-EC) and exponential reaching law-based discrete SMC (DSMC-ER), with quicker response speed and smaller initial tracking error. Through introducing a feedforward torque by combining force sensor feedback with a feedforward element, the mean tracking error of the proposed control scheme decreases to 1.7°. As the PSMC approach lacks control robustness and adaptability, a neural network proxy-base sliding mode control (NNPSMC) strategy was presented in [37]. The gains of PSMC are tuned by neural network online, enhancing the adaptability to different conditions and patients. Hussain et al. proposed a boundary layer augmented sliding mode controller (BASMC) for trajectory tracking of hip and knee joints [42]. To promote the training safety, researchers employed joint compliance control to adjust the robot's output torque based on the human–robot impedance. Then the team developed assisted-as-needed gait training strategy by employing the adaptive impedance control approach [86]. Khajehsaeid et al.proposed an adaptive back stepping fast terminal sliding mode controller [87]. According to the individual's disability level and movement ability, the controller adjusts the robotic assistance to promote the human–robot interaction and patient's participation in rehabilitation training. As to the gait training robot AIRGAIT, the fractional order derivative was employed to modify the computed torque based on the mathematical model, which significantly improved in both transient and steady-state [88]. To enable the patients to be more active in their training, a new compliance controller was proposed to adjust the robot's assistance according to the human–robot interactive torque and human active torque. Finally, the effectiveness of the proposed strategy is confirmed by various experiments with the participation of eight healthy subjects. Particularly, all the subjects report that they feel comfortable during the experiments.

In previously mentioned approaches, the trajectory and compliance are all controlled by different single-input-single-output controllers, making it impossible to achieve complete synchronization between pressure and compliance. To address this problem, Cao et al. proposed a multi-input-multi-output controller, which can control the pressure and compliance at the same time [89]. However, the integral sliding surface of SMC accumulates the trajectory errors caused by structure uncertainties, making patients uncomfortable. To deal with the structure uncertainties, chattering-free robust variable structure control law (CRVC) and Proxy-based Sliding Mode Control were proposed in [90] and [91,92]. The experimental results show that, the magnitude of angular deviations in the human-active training mode are 20° larger than passive training mode. Since better control compliance can promote patient's participation in the training, the angular deviations are acceptable.

As presented in Table 4, through adopting advanced motion control strategies, most of the robots has accomplished accurate trajectory tracking tasks. But overshoot and response delay seem to be common unsolved problems among these control schemes. The problems are mainly caused by PM's highly-nonlinear characteristics and hysteresis. Since the large overshoot will easily lead to a second harm to patients, the control robustness and stability are indispensable for rehabilitation robots. Model-based feedforward schemes have been adopted to tackle this problem [94]. Further, it can be found from Table 4 that the limitation of PM's physical properties makes it hard to operate in high frequency. While this problem seems to exert trifling effect on rehabilitation performance, as most patients are unable to perform high-frequency training tasks. From the table, it is obvious that variable PID controllers are used widely in antagonistic joint robots, perhaps attributing to their simple structures and tuning rules. But these PID-based control strategies perform not well, usually with large tracking errors and overshoots. While SMC-based and FLC-based control schemes are confirmed greater robust and stable control ability than those based on PID. In the view of human–robot interaction, impedance control and force control are the most widely adopted schemes. However, nearly half of control systems in the table ignore the interactive control development. That means these robots lack the ability of adjusting the assistance output according to the human–robot interaction. Further, aiming at providing rehabilitation assistance for patients, the most significant indexes are patient's participation and sense of safety instead of motion accuracy. In this view, some control schemes' experimental results with a high motion error are acceptable, if they are capable of promoting the patient's participation. Additionally, among all these robots' validation experiments, less than 25% of the researches recruited human subjects to evaluate the robots' performance, and only one research team conducted the clinical testing with stroke patients [16,17].

3.2. Control of parallel robots

For rehabilitation robots actuated by parallel PMs, through inverse kinematics and PM's model, the robot's trajectories are transformed to pressure inside PMs. To achieve the desired trajectory, parallel PMs must work simultaneously to produce appropriate torques and displacements at different speeds. Therefore, how to simultaneously control the multi-PMs in parallel is a challenge. Xie's team developed a simultaneous control approach for the ankle rehabilitation robot with four parallel PMs [49]. To achieve multi-PMs simultaneous control, an inverse kinematic model was introduced into the disturbance observer based FLC scheme. To further reduce the tracking errors caused by the PM's model uncertainties, a modified genetic algorithm (GA) was employed to optimize the parameters of FLC [48]. The experimental results show that the tracking error range decreased from $-3\sim6$ mm to $-2\sim5$ mm, which is 23.33% of maximum tracking error in [49]. Then a position–force feedback cascade controller was proposed to enable the movement intention-directed trajectory adaptation and encourage human–robot engagement [95]. To solve the PM's nonlinear characteristics during operation and to tackle the human–robot uncertainties in rehabilitation at a 2-DOF parallel ankle rehabilitation robot, Ai et al. proposed a novel adaptive backstepping sliding mode control (ABS-SMC) method with an observer to estimate the human–robot external disturbance

Table 4
Overview of control strategies for antagonistic joint robots.

Robotic system	Motion control strategy	Interactive control strategy	Validation	Performance	References
7-DOF upper limb exoskeleton	PID control	Impedance control with torque feedback	Trajectory tracking experiments and free motion experiments	The maximum motion error is less than 2.5%, and a fast response of 0.3 sec with an overshoot of 6%	Tsagarakis et al. [23]
Orthotic gait training system (AIRGAIT)	PI/PID controller	–	The basic function is tested by a healthy adult	The maximum angle error of 5° for the 1 s gait cycle	Dzahir et al. [38,44]
Exoskeleton robotic arm	PD control	Force control/ impedance control	Experiments of three tracking tasks	The torque decreased in less than 2 s if there is an instant spasm	Xiong et al. [72]
2-axes manipulator	Nonlinear PID control with neural network	–	Trajectory tracking experiments of sinusoidal waveforms	The motion bandwidth is less than 2 Hz	Ahn et al. [74–76]
Robotic arm	Position–position control	Force–force control	Trajectory tracking experiments of different control strategies	The response time to reach a peak torque is 1.3 sec, with a overshoot of about 1°.	Jiang et al. [24]
	Neuron PI control with feedforward control	–	Experiments of step response and position tracking for two position control schemes	The overshoot is less than 2°	Jiang et al. [77]
RUPERT	Adaptive PID-based feedback control	Iteration learning control	57 stroke patients went through a treatment	–	Huang et al. [4]
Upper limb rehabilitation robot	Fuzzy neural network (FNN) control	–	Comparison experiments of FNN controller with classical PI controller and fuzzy controller	The response time of FNN controller is fast more than 0.3 s than the other two controllers	Jiang et al. [27]
Rehabilitation robot	Adaptive self-organizing fuzzy sliding mode control (ASOFSMC)	–	Experiments of circle tracking tasks	The angle tracking error is less than 0.8°	Chang et al. [78,79]
Soft rehabilitation machine	Adaptive self-tuning fuzzy control (ASTFC)	–	Experiments of single joint rehabilitation machine	The peak–peak error is 1% and phase lag is 0.1°	Chang et al. [80]
Human-inspired exoskeleton (HuREx)	Two-layer controller: RMFE and model based PID controller		The simulation of tracking a desired trajectory	The maximum angular deviation is less than 0.97°	Cao et al. [93]
	IFT–PID control with FF controller/ FB controller	Impedance control	Comparison experiments for different control strategy	The maximum position error less than 2° with some bumps	Kora et al. [94]
	SMC	Impedance control	The simulation and experiments for trajectory tracking with variable speed	It can achieve better tracking performance at walking frequency of 1.5 Hz than 0.25 Hz	Cao et al. [40]
Power knee exoskeleton (KNEXO)	Proxy-based sliding mode control (PSMC)	Force/torque control	Simulation	The mean tracking error is 1.7°	Beyl et al. [16,17]
Treadmill-based gait training robotic orthosis	neural network proxy-base sliding mode control (NNPSMC)	–	Two healthy subjects participated in gait training	The trajectory errors are ±2.5° and ±4° for hip and knee joint, respectively	Huang et al. [37]
Lower limb robotic orthosis	Boundary layer augmented sliding mode control (BASMC)	Joint compliance control	Three healthy subjects (male/female, age 25–41 years) participated in experiments	The maximum trajectory tracking error is 10°	Hussain et al. [42]
	BASMC	Adaptive impedance control	Ten neurologically intact subjects were recruited to evaluate the system	The angular deviation is 3.96° ± 1.08° and 14.22°±3.2° in the inactive mode and active mode	Hussain et al. [86]
	CRVC	Adaptive impedance control	Ten neurologically intact subjects were recruited to evaluate the system	the trajectory-tracking errors of 4.22° and 7.1° for hip and knee joints	Hussain et al. [90]
	Multi-input-multi-output sliding mode control (MIMO SMC) for pressure and compliance		The experiments were conducted with five healthy subjects	The RMS error is of 2.11°∼11.79° for the gait circle frequency of 0.2Hz∼0.7Hz	Cao et al. [38,44,89,91,92]
AIRGAIT	Assisted-as-needed control		experiments with the participation of eight healthy subjects	The maximum comparative root mean square tracking error is less than 3°	Dao et al. [88]

so that the controller adjust the robot output to accommodate external changes [96]. However these controllers largely depend on the PM's model, to entirely avoid influence of the model on control performance, recently the team proposed an iterative feedback tuning (IFT) control scheme [97]. As a model-free method, IFT control approach can automatically adjust robot-assistance through learning from the history data. Therefore the robot can help patients to perform better in the next rehabilitation period so as to promote their participation in training. The proposed method is confirmed an excellent learning capability for repeated rehabilitation training through experiments. For the ankle rehabilitation robot presented in [50], a boundary layer augmented sliding mode control (BASMC) approach presents a robust control ability through trajectory tracking experiments. To improve the rehabilitation performance, impedance control was employed to adjust the robot's compliance for patient's maximum voluntary participation [50]. Andrikopoulos et al. designed an advanced nonlinear PID (ANPID) control system for the wrist rehabilitation exoskeleton EXOWRIST, to strengthen the motion control adaptability [53]. Through adopting an auto-adjustable control gain based on error magnitude, the steady-state errors of ANPID controller decline by nearly 50% compared with the classical PID controller. While for the straight-fiber-type PMs-actuated delta robot, Hirano et al. developed an inverse dynamic model-based PI controller to control the PMs, introducing a feedback element to compensate the end position error [14,15]. The experimental results show that steady-state error is less than 2 mm. Based on the parallel structure's inverse kinematics and PM dynamic model, Kang et al. designed an inverse controller for a 3-DOF robot with three PMs in parallel [56]. Combined with position/force/vision feedback, the control system achieves the robust control of the robot.

Table 5 demonstrates the control strategies and their performances. Only fewer than half of the robotic systems in the table own an adaptability towards the patient's disability and motion level. Modified genetic algorithm and iterative feedback tuning schemes are popular approaches to strengthen the control adaptability. Although most of the research teams have conducted validation experiments with human subjects, none of them evaluated their robot's rehabilitation performance through clinical measurements. From the view of motion control, all of these robotic rehabilitation systems have achieved high accuracy and stability in trajectory tracking experiments. In addition, among these control schemes, half of them increase the robustness and

Table 5
Overview of control strategies for parallel robots.

Robotic system	Motion control strategy	Interactive control strategy	Validation	Performance	References
Wearable ankle rehabilitation robot	Adaptive FLC with fuzzy-based disturbance observer (FBDO)	–	A healthy subject (male, age 25 years) participated in the study	Maximum tracking error is ±15 mm, and the MSE is 0 m	Jamwal et al. [48]
	Modified genetic algorithm (GA) based fuzzy feedback control	–		Maximum tracking errors are −2∼5 mm	Jamwal et al. [49]
	position–force feedback cascade controller	Force feedback control	A healthy subjects participated in experiments	The maximum tracking error are all less than 2.3%	Zhang et al. [95].
	Robust iterative feedback tuning (IFT) control	–	Motion performances are evaluated by four participants	Peak amplitude errors are less than 2°	Meng et al. [97]
	adaptive backstepping sliding mode control (ABS-SMC)	–	Five healthy subjects participated in experiments	The maximum tracking error with the interaction with subjects is 7.5 mm	Ai et al. [96]
Compliant ankle rehabilitation robot	Boundary layer augmented sliding mode control (BASMC)	Impedance control	Ten healthy subjects participated in experiments	The maximum angular deviation is 0.252 rad	Jamwal et al. [50]
Exoskeletal wrist prototype (EXOWRIST)	Advanced nonlinear PID (ANPID) control	–	A healthy subject is recruited to evaluate the device's motion capabilities	The mean absolute steady-state errors of 0.22°∼0.41°	Andrikopoulos et al. [53]
Delta-type parallel-link robot	Feedback PI control	–	Position-control and stiff-control experiments	The average errors are 1.25∼3.53 mm on each axis	Hirano et al. [14,15]
Parallel actuator	Inverse control	Force/vision feedback control	Simulations and experiments of extension and bending motion	The accuracy is approximately 2% of the initial length	Kang et al. [56]

accuracy through tuning the control parameters by position/force feedback.

3.3. Control of other robots

It has been found that an obvious correlation exists between electromyography signals, limb movements and muscle activities. EMG-based control strategies have been widely used in PMs-driven rehabilitation robots. Researchers from Harvard University proposed a proportional EMG control approach to control the corresponding muscles for ankle rehabilitation [58]. However, the results show that joint motion range, safety and stability of the approach remain to be improved. To address this problem, the team proposed a linear time-invariant (LTI) controller [59]. Through adopting the subspace system identification technique avoids complex modeling of human–robot system. However the experimental results show that, the tracking error will rise if the frequency and tracking angle increase. Likewise, a similar scheme was utilized to control a glove actuated by four bending muscles, to achieve the hand's pinch and grip movement [60]. For the soft arm exoskeleton for patients performing repetitive motion therapy at home, a Model Reference Adaptive Control (MRAC) has been proposed for adhering to target rehabilitation profiles [66]. For the PMs-actuated ankle–foot orthosis, based on proportional EMG (PM) control approach, artificial dorsiflexor and flexor are regulated by biological tibialis anterior and soleus respectively [7,63]. To relieve co-activation between the artificial flexor and dorsiflexor, the researchers combined flexor inhibition with proportional EMG control (PMFI), and the peak powers grow by nearly 30% over PM control [6]. The main unsolved problem for controlling bio-inspired rehabilitation robots is to obtain effective EMG signals. At present, it is extremely hard to obtain the complete same EMG signals from different person for the same motion, even from the same person. For RUPERT, researchers just adopted an open loop feedforward control to achieve arm reaching tasks [5]. The results show that the control scheme exists a large steady state error when the patient lacks control ability. To tackle this problem, a PID feedback controller was adopted to guide each joint's motion [3]. While there is a response delay for the robot to reach the desired angle, about 3 s. To compensate the PM's slow response, iterative learning control (ILC)-based feedforward controller was introduced [4]. Through learning from errors in previous executions, ILC optimizes the control parameters and thus improves the control performance. Then fifty-five patients were recruited to participated in the clinical testing, and the mean Fugl-Meyer score of those subjects grew from 97 to 103.5.

From Table 6, bio-inspired Habilitation robots are mainly controlled by proportional EMG control approaches. Through directly controlling the PMs by EMG signal, the robots are capable of assisting patients in a more natural way. But the majority of the current control systems still focus on the basic proportional EMG control approaches, the trajectory tracking errors are usually quite large, as shown in the table. For RUPERT, researchers recruited patients to participate the clinical testing and their robot-assisted rehabilitation performance are evaluated by professional assessment standards. Irshaidat et al. proposed a soft arm exoskeleton for patients performing repetitive motion therapy at home without the assist of therapists and with a lower cost [66].

Compared with traditional rigid actuators, PMs are more compliant and safer, which plays a vital role on the patient's rehabilitation, but their highly nonlinear and time-varying properties arise difficulties in precise control of PMs-actuated robots. PID control, fuzzy logic control (FLC), and sliding model control (SMC) are widely adopted control approaches, attributing to their ability to develop a simple and robust control system. Actually, the choice of different control strategies usually depends on the structure of PMs-actuated robots and movement requirements. Recently, in order to ensure the patient's maximum voluntary participation, researchers started to conduct research on interactive control strategies, adjusting the assistance output according to the patient's disability level, rehabilitation stage and motion intention [98]. However, it is hard to utilize the former two control

Table 6
Overview of control strategies for other robots.

Robotic system	Motion control strategy	Interactive control strategy	Validation	Performance	References
Soft ankle–foot orthotic device	Feedback proportional EMG control		Validation experiments of mechanical characterization and control function	The capability of disturbance rejection capacity is 5°	Park et al. [58]
	Linear time-invariant (LTI) control		The suitability validation with six sets of different experiments	The mean tracking error range is 7.4%∼20.2% for frequency of 0.4 Hz∼1.0 Hz with angle of 10°	Park et al. [59]
Wearable glove	Feedback proportional EMG control		Healthy males and females (age over 50) participated in experiments	The EMG signals with the glove is about 25% of which without the glove	Alfahaam et al. [60]
Arm exoskeleton	Model Reference Adaptive Control		Position control	It can vary from 0° to 180° ideally	Irshaidat et al. [66]
ankle–foot orthosis (AFO)	Proportional soleus EMG control		A healthy subject (age 30 years) test the device's performance	It can provide 36% and 123% of the peak torque for plantar flexor and dorsiflexor, respectively	Ferris et al. [7,63]
Knee–ankle–foot orthosis (KAFO)	Proportional EMG control with flexor inhibition		Three healthy male subjects participated in the study	It can provide 42% and 83% of peak power for plantar flexor and dorsiflexor, respectively	Sawicki et al. [6]
RUPERT series of robots	Open loop feedforward control	–	Ten patients went through the clinic testing	The device can expand motion workspace of about 50° for subject's shoulder/elbow/wrist, respectively	Sugar et al. [5]
	PID-based feedback control	Iterative learning control based feedforward control	57 stroke patients went through the treatment	The mean Fugl-Meyer score increases by 6.5 through treatment	Balasubramanian et al. [3]

strategies in complexed and nonlinear PMs-driven robots, due to their linear control structure or too overly complicated rules [99]. To tackle these problems, Ziegler–Nichols [100], inverse NARX fuzzy model [101], and other knowledge-based adaptive compensator [102] were employed to enhance the performance of PID control and fuzzy control [103]. Compared with PID, sliding mode controller (SMC) can switch between various control structures to adapt to the current state and is able to compensate PM's unpredicted disturbances and model uncertainties. However, due to high switching frequency, the chattering problem always exists. To tackle the problem, Xing et al. introduced a nonlinear disturbance observer to reduce the switch gain of SMC system [104]. Likewise, a fuzzy logic controller was employed to approximate the switching control law [105], which can compensate the nonlinear disturbance effectively. For the ankle rehabilitation robot driven by PMs in parallel configuration, the control difficulties not only relate to PM's highly nonlinear and time-varying characteristics, but also caused by coupling interference from multiple PMs' synchronous movement. However, few studies focused on the collaborative control between multiple PMs and the disturbance elimination. Although Cao et al. proposed a multi-input multi-output controller, which is designed to control the pressure and compliance for a single PM at the same time, instead of synchronizing the movement of multiple PMs [89].

4. Discussion

Attributing to the inherent compliance and safety, PMs are exactly appropriate to actuate rehabilitation robots. Although most of the exiting PMs-actuated rehabilitation robots have shown their assistance capacity, many common unsolved problems remain. As a bio-inspired actuator, the respond speed and accuracy of current PMs still need to be improved to simulate biological muscles. Recently, several innovative PMs were designed, such as straight-fiber-type muscles [14,15], pleated pneumatic artificial muscles [16,17], and spring over muscles [106]. Although many PMs-driven exoskeletons are claimed as wearable rehabilitation robots, most of them cannot achieve several-hour's training with the limitation of energies. With heavy weight, large occupied space, power source in previous researches arise the difficulties in practical applications for clinical treatments and patient's rehabilitation training at home. Hence it is obliged to develop wearable and cost-effective gas supply approaches, for example, a solid storage of hydrogen gas has been studied in [107,108]. Additionally, for wearable rehabilitation robots, especially upper limb exoskeleton, the heavy weight and complex mechanism of the devices cause external burden for patients and arise control difficulties. Recent researches employed advanced materials and manufacturing technology to make robots more lightweight and strengthen the output assistance, for example, using advanced soft elastic driving material [109,110], carbon fibers [111], hybrid-driven technology [112–115] and 3D printed materials [34,40,116]. Moreover the compliance and morphology of wearable robots preclude the use of many conventional sensors including encoders, metal or semi-conductor strain gauges, or inertial measurement units. To further achieve the potential of a wearable robotic system in different rehabilitation training conditions, the sensing devices are expected to be embedded in the PMs-driven flexible-bending structure, soft & smart materials and stretchable electronics [19]. Since the sensing system in wearable human–robot rehabilitation application cannot increase the burden on the patients, an advanced sensing device is supposed to own the capability of monitoring multiple physical or physiological signals at the same time. Thus some promising measurement technology, such as technology of fiber Bragg gratings, have attracted a wide spread attention. With the layered structures, it is possible for these sensors to simultaneously measure displacement [117], motion speed [21], joint angle [22], plantar pressure [23], interaction force [24], muscular tension [25], and so on. The maximum assistance output produced by the existing rehabilitation robots are limited, most of them even cannot cover the complete human natural workspace. This drawback may not exert obvious effect when patients are at early rehabilitation stage, but it precludes robots from providing further function recovery for patients after several training sessions. To address this problem, it is good to combine other type actuators or muscle-stimulating technologies with PMs, e.g., electric motors [62] and functional electrical simulation (FES) [43,118] have been studied recently. In the view of humanized design, studies on the biological musculoskeletal system among patients and healthy person will deepen the understanding of patient's rehabilitation needs. Furthermore, it also helps researchers to take full advantages of the PM's bio-mimetic functionality and medical applicability, to develop more practical and humanized rehabilitation robot for each individual patient.

In terms of control strategies of rehabilitation robots, PM's highly-nonlinear, time-varying and delay response properties arise difficulties in PMs-actuated rehabilitation robots control. The neglected or un-modeled elements of PM's dynamic models introduce uncertainness and disturbance for control system. Some recent studies have considered PM's un-modeled elements, for example, dynamic models with hysteresis element were proposed in [21]. In aspect of improving the control adaptability, the cooperation between the advanced control strategies and sensing-fusion may make sense, such as mechanical sensing [119] and bio-sensing [120]. As the state-of-the-art sensors can not only monitor the patient's real-time motion, but also catch his/her small reaction changes, the robots are capable of adjusting the control scheme on time, enhancing the control robustness and adaptability. For example, a light-weight PMs-driven walking assist system according to the patient's lower limb force online feedback has been proved its effectiveness for reducing knee joint force during walking [121]. To make patients feel safe and comfortable during training, the robot's compliance should be adjusted according to the human–robotic interaction. Some researches even considered the instant spasms of stroke patients [23]. To promote the patient's voluntary participation, advanced assist-as-needed interactive control strategy is an indispensable factor in the future. In this way, patients are allowed to stimulate and regulate the robotic assistance according to their motion intention, and they will be encouraged to participate in rehabilitation training. And the far-reaching effect of human–robot interaction on rehabilitation performance have been confirmed by large number of researches, especially motor imagery-based brain computer interface [10,122,123]. Additionally, integrating the robot-assistance with vision feedback [9, 122] and visual reality [11,124,125] will further enhance patient's voluntary participation in the training process. In the future, the intelligent control strategies and personalized training modes will be developed, making robots adaptable to various patients according to their disability levels, recovery stage, physical conditions, age difference and rehabilitation demands. The control strategies and training modes will be expected to be conducted under the guidance of medical standards [11] and professional therapists [125]. Consequently, the patients can receive professional and effective rehabilitation assistance.

Finally, most current researchers conducted trajectory tracking experiments to confirm the function of the robotic system, but just few of them carried out clinical testing validation for robot-assisted rehabilitation training [11,126,127]. Only through long training term clinical trials with a large scale of patients, the performance of rehabilitation robot system can be validated and optimized efficiently. Furthermore, the patient's rehabilitation performance needs to be evaluated by the professional rehabilitation assessment standards, such as Fugl-Meyer assessment [11], quality of life [128,129], and the patient's global impression of change [130] and the universal assessment standards [131]. Recently, the universal assessment standards has been established among rehabilitation engineering, clinical medicine and robotic engineering [131,132]. The professional clinical assessment will further help the researchers understand the patient's demands and robot's limitations, and find out the correct direction of improvement.

5. Conclusion

This paper conducts a review on mechanical structures and control strategies of PMs-actuated rehabilitation robots. Various PMs-actuated rehabilitation robots with diverse structures are discussed and compared, and the configuration characteristics are described. The information of existing advanced robot structures presented in this paper will provide inspiration and valuable knowledge for future rehabilitation robot development. Considering PM's nonlinear and time-varying prosperities, as well as variable PM-actuated structures, this paper presents well-established motion control schemes. To further promote the patient's training participation and rehabilitation performance, interactive control strategies are also highlighted. This paper is expected to be reliable guidance and comprehensive resources for researchers in the PM-actuated rehabilitation robot field.

CRediT authorship contribution statement

Jie Zuo: Conception or design of the work, Acquisition, Analysis, Interpretation of data for the work, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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