Review

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Actuators and transmission mechanisms in rehabilitation lower limb exoskeletons: a review

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Abstract: Research has shown that rehabilitation lower limb exoskeletons (RLLEs) are effective tools for improving recovery or regaining lower limb function. This device interacts with the limbs of patients. Thus, actuators and power transmission mechanisms are the key factors in determining smooth human–machine interaction and comfort in physical therapy activities. A multitude of distinct technologies have been proposed. However, we questioned which consideration point in actuator selection and power transmission mechanisms are used for RLLE. A review of the technical characteristics and status of advanced RLLE designs is discussed. We review actuator selection for RLLE devices. Furthermore, the power transmission mechanisms over the years within each of the RLLE devices are presented. The development issues and possible research directions related to actuators and power transmission mechanisms are provided. Most RLLEs are still in the research phase, and only a few have been commercialized. The aim of this paper is to provide researchers with useful information for investigating technological progress and highlight the latest technological choices in RLLE development.

Keywords: actuator; lower limb exoskeleton; power transmission mechanism; rehabilitation; exoskeleton

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Introduction

Over the past decade, rehabilitation lower limb exoskeletons (RLLEs) have become indispensable due to the rapid increase in the number of patients suffering from neurological diseases, such as spinal cord injuries (SCIs) and muscle weakness [1]. A Malaysian epidemiology study conducted by Ibrahim et al. [2] indicated that vehicle accidents are the main contributors to SCIs. Similar trends worldwide were reported in the National Spinal Cord Injury Statistical Center [3] and in Kang et al.'s [4] work, where vehicle accidents dominate SCI cases, which are gradually increasing in line with the increase in human activity.

Patients suffering from spinal cord injuries normally lose motor skills and self-balancing ability while walking. Appropriate therapy or motion training through active muscle activation during a chronic phase can increase the opportunity for healing. Thus, utilizing an RLLE device is one approach that can be implemented to improve recovery or regain lower limb function. RLLE devices can be used to address the weaknesses of traditional rehabilitation interventions, such as repeatability, to provide consistent and comprehensive observations and monitoring of a patient's progress and training duration, and provide data analysis and recoding, thus reducing the burden on clinicians in hospitals and clinics [5].

RLLEs are human-oriented mechatronics systems that directly interact with patients to optimize the retention of physiological movement patterns via activity-based interventions. The RLLE device consists of a mechanical structure, actuators, sensors, power supplies and controllers [6]. The actuator system employs power transmission mechanisms, which must comply with human biomechanics. For this reason, the actuator and power transmission mechanism are the components that are crucial for ensuring that the RLLE operates in an effective, safe, comfortable and smooth motion. Therefore, regarding the use of actuators and power transmission mechanisms, characteristics such as linearity, compliance, torque, shock load effects, backlash, compactness, reliability, controllability, and noise need to be considered [7, 8].

To investigate the appropriate actuator criteria, a review of the technical characteristics and the status of advanced multiple joints of RLLE is presented. We analyze the actuator characteristics, and the power transmission mechanism technology from 1996 to 2022 is discussed. Finally, development issues and possible research directions related to actuators and power transmission mechanisms are presented. To obtain a collection of publications within the scope of our review, we performed a search using Scopus databases. The search was conducted using the following set of keywords: lower limb exoskeleton, exoskeleton, rehabilitation robotic, wearable robot and rehabilitation exoskeleton.

The number of initial articles obtained was 20,349. After reviewing them, the number of articles related to the field of review reached 500. Papers with insufficient information on actuator and power transmission designs and those pertaining to studies published in languages other than English were eliminated. As a result, 210 were selected, incorporating active actuators and power transmission mechanisms within the realm of RLLE. Subsequently, 45 research papers that met the criteria for this review underwent in-depth investigation. The focus criteria encompassed the exoskeleton's target joints (hip, knee, and ankle), rigid structure, actuation types (electric motor, pneumatic, hydraulic, and hybrid actuators), and mechanical transmission of power (gears, belts, linkages, or other mechanical systems).

Types of RLLE joints

An RLLE is a mechanical structure that mimics the lower limb extremities specifically and is designed to help patients undergo physical rehabilitation. The RLLE joint is used for enabling movement and providing stability. By replicating the RLLE joint based on human joints, the mechanical structures of an RLLE can be designed to closely match the human limb's movement. In RLLEs, the joint can be divided into two categories: multiple joints and single or partial joints. Multiple joints mean that more than one joint or all joints (hips, knees, and ankles) are actuated, while a single joint is actuated by only one joint, at the hip or knee, or ankle joint.

Types of RLLE structures

In RLLE design, the structure type can be categorized into two groups: overground devices and immobile devices [9]. Each category has different operation principles and technical requirements. In the overground types, RLLEs have been designed for patients who are able to stand and walk but require assistance with stability and mobility. These RLLEs typically provide power assistance to the patients' legs, allowing them to walk on the ground. Therefore, the walking area is not restricted. Two operation modes are employed in overground RLLEs: body weight-supported (BWS) and unsupported body weight (UBW). Among the overground types, RLLEs have been developed with the aim of increasing the independence of gait training.

However, immobile RLLEs are used for patients who are unable to stand or walk on their own due to conditions such as spinal cord injuries or severe neurological conditions. Gait training is conducted in a fixed area and a confined space. Training applications include supporting the body weight or trunk of a patient with a device structure, walking on a treadmill, and using a stationary device, such as a therapeutic exercise device. Two modes of rehabilitation exist in an immobile RLLE. The first mode is the fully assisted mode, in which a patient does not actively participate or no effort is needed in a rehabilitation session. The second mode is the assist-as-needed mode, in which an RLLE provides appropriate motion on the lower limb of the human joint by supplementing the effort already being applied by the human.

Rehabilitation approaches

RLLEs are widely used by therapists in clinics or hospitals for treatment or rehabilitation. Some devices previously at the research stage, such as ReWalk, REX Rehab, Indego Ekso, Therapy and HAL, have successfully obtained approval from the U.S. Food and Drug Administration (FDA) for clinical use and have been commercialized [10]. From a clinical perspective, for the rehabilitation of patients with ambulation impairments, such as SCI, foot drop, stroke and Parkinson's disease, two rehabilitation approaches are generally utilized: restoration of the neuromuscular system and behavioral compensation [11].

Restoration of the neuromuscular system is aimed at regaining function using preinjury motor behaviors [12]. RLLEs for rehabilitation, regaining locomotion and treating muscular weaknesses are categorized as restorative devices. The motion of the devices can be realized by trajectory-based control or non-trajectory-based control [13]. Many controller strategies have been proposed for these training approaches, such as sensitivity implication, predefined gait trajectory, and model-based control [14]. LOKOMAT [15] and ALEX [16] are examples of devices that belong in the restoration category.

Behavioral compensation refers to the use of typical motor patterns, behaviors, body segments, and assistive devices to compensate for postinjury neurologic deficits to accomplish the same or similar functions [17]. The device that assists with movement for people with chronic neuromuscular motor impairments is also a compensatory device, which is used by nondisabled subjects, such as elderly individuals, for movement augmentation. ReWalk [18] and REX [19] are examples of devices that belong in the compensation category. However, these devices have a rigid structure, are designed to be parallel to the legs of users, and are bulky. Moreover, their weight can make them difficult to use and transport. They also have limited capabilities to support rehabilitation exercises at home; thus far, these devices have been used mostly in clinical environments [20]. The other aspects that need to be considered are safety and dependability, ease of implementation and removal, and comfortability [21, 22]. Moreover, compensatory use in activities of daily living environments leads to additional requirements regarding robustness against dirt, humidity, and misuse.

Actuator selection in RLLEs

The choice of the actuation type plays an important role in RLLEs since it generally determines the performance, such as the speed, torque and portability. There are two considerations of actuator selection in RLLE development: the structure types and actuator characteristics.

Based on structure types

The actuator selection for an RLLE is strongly coupled with the structure type, i.e., overground devices and immobile devices. In the immobile RLLEs with the fully assisted mode, the actuators do not require critical compliance features, but precise position control is crucial. However, in the assisted-as-needed mode in an immobile RLLE, the requirement of compliance features and precise positioning of actuators is important. In both modes, the safety and softness of the actuator motion are important considerations [23], but the compactness, weight and energy consumption of actuators are not critical issues. The actuation system can be placed proximally on a stationary platform to reduce the weight exerted on the limbs of patients. This is an advantage in these devices, such as CORBYS [24], in which the actuator weight is transferred to the mobile or stationary platform to minimize the RLLE frame weight and bulk.

In the overground RLLEs, there are two modes: the supported body weight and unsupported body weight. Both modes need to interact with the human limb for assistance as needed during rehabilitation. Therefore, actuator compliance, precise positioning and softness characteristics are important considerations. The actuation system should effectively mimic the musculoskeletal system to ensure comfortable and smooth human–machine interactions and realistic neurological feedback. The energy consumption and compactness of the actuator system also need to be considered due to limited energy storage on the mobility device during a training session. In addition, regarding the overground RLLEs, the specification of an actuator is critical in terms of the actuator weight, friction, inertia and damping, which are sources of increased mechanical impedance.

Based on actuator characteristics

Actuators are mechanical devices that convert energy into motion. It is the component that drives RLLE joints. RLLE actuators have been classified into two categories: passive and active actuators.

Passive actuation stores potential energy and operates without any electricity. The mechanism exchanges between potential energy and kinetic energy [25]. This type of actuation is typically lighter and cheaper than the active actuator. A spring is an example of a passive mechanism, which was used in the ankle joint of HAL [26] to reduce the power consumption in the exoskeleton system. The effectiveness has been proven; however, before considering passive actuation implementation, an analysis of the joint angles is needed because it inherently depends on certain angles [27–29].

The active actuators are divided into four types of actuators: electric motors, pneumatic actuators, hydraulic actuators and hybrid actuators. All active actuators have two types of motion, i.e., linear and rotation. Each actuator has characteristics compatible with the RLLE.

Electric motor

An electric motor converts electrical energy into mechanical motion to actuate the RLLE joint. Previous reviews have indicated that electric motors are widely employed in immobile and overground RLLE devices [30]. There are many varieties found in the market, such as linear actuators, brushless DC motors and servo motors. Currently, there are numerous commercial RLLEs, such as LOKOMAT [15], EksoGT [31], REX Rehab [32], Indego Therapy [33] and HAL-Medical [26], that use electric motor actuators to drive the RLLE joint.

Electric motors are reliable, low in cost, operate silently, consist of clean actuation systems, have high precision, have a high power-to-weight ratio, are easy to install, are easy to control and easily adapt to multiple degrees of freedom (DOFs) in the sagittal, frontal and transverse planes [34, 35]. Moreover, the mechanism for power transmission of electric actuators can be achieved in various ways, such as with a tendon-driven mechanism, Bowden cables, ball screws and belts. Electric actuators do not have the fluid leakage issue that occurs in hydraulic and pneumatic actuators. Due to their advantages, electric motors are the preferred choice. However, electric motors usually need a power transmission mechanism such as a gearing system. The gearing system can reduce the speed of rotation and amplify the torque at low speeds. Nevertheless, it introduced backlash and decreased the back-drivability of the system. The review showed that electric actuators could fulfill more features needed on the widest range of RLLE devices [36].

Pneumatic actuator

A pneumatic-based actuator applies air pressure to produce an output force. Several types of actuators are used in RLLEs, namely, pleated pneumatic artificial muscle (PPAM) actuators, pneumatic muscle actuators (PMA) and linear pneumatic cylinders. These actuators generate linear motions, which must be converted to rotation by a power transmission mechanism to revolute the exoskeleton joint.

Pneumatic actuators offer their own advantages in rehabilitation RLLEs. They are lightweight, consist of cleaner actuation systems that are inherently compliant and have the ability to transmit large forces and provide soft imposed movement and a reasonable power-to-weight ratio. A pneumatic actuator enables changing forces on the legs of patients that operate on the supply pressure level. Pneumatic muscle actuators (PMAs) can produce only a pulling force or a single-direction force, whereas pneumatic cylinders produce a force in both directions. If a pair of cylinders is used, they can be set to work together in both rotation directions. Pneumatic actuators, such as PPAMs, PMAs and linear pneumatic cylinders, are employed in immobile RLLE devices [6, 37].

Pneumatic actuators can mimic natural human muscles, thus improving training comfort and the therapeutic outcome in gait rehabilitation [38]. However, all pneumatic actuators are subject to the disadvantages of poor servo control, nonlinearity, lack of portability, and lack of position and force control precision [39]. This weakness is critical for overground RLLEs and immobile RLLEs without body weight support.

Hydraulic actuator

Hydraulic actuators intake pressure and convert it into motion under controlled circumstances. A hydraulic actuator has the advantage of an excellent power-to-weight ratio and provides great force compared to an electric motor, pneumatic, hybrid, and passive types; however, this characteristic is not paramount in RLLEs because they do not require high power, such as in augmentation exoskeletons [40]. Hydraulic actuators are powerful but heavy due to the actuator cylinders, hoses and auxiliary power supply units. They are not compliant and thus are not suited for safe human interactions [41]. Moreover, hydraulic actuators have a potential risk of hydraulic fluid leakage. These leaks spread the oil, potentially contaminating other medical devices in the rehabilitation room. This problem makes it challenging to maintain cleanliness and prevent the growth of bacteria or other contaminants. Compared to pneumatic systems, which use air, electrical actuators use batteries, and gear systems require greases. Moreover, they are less prone to leaks and spills, making them less likely to create a hygiene hazard.

Hybrid actuator

A hybrid actuator is a combination of actuators, such as electric-motor-pneumatic, electric-motor-spring and electric-motor-hydraulic actuators. Hybrid actuators can improve the driving performance of RLLEs. The increase in mechanical impedance in actuators can be caused by friction, inertia and damping. Various hybrid actuator approaches have been proposed to reduce mechanical impedance. Agarwal and Deshpande [42] introduced a miniature Bowden cable-based series elastic actuator (SEA) that employed helical torsion springs, while Tagliamonte et al. [43] used an SEA consisting of a linear spring and an electric motor to drive the hips and knees in an RLLE. Kwa et al. [44] showed that a rotary SEA on an RLLE can provide high-fidelity impedance control.

Another work has shown that combining a DC motor and PAM resulted in a high strength-to-weight ratio and precise position control [45]. Studies by Wang et al. [46] and Ragonesi et al. [47] demonstrated that hybrid actuators, such as SEAs, have several advantages for use in rehabilitation RLLEs. Softness and compliant torque control can provide comfort in motion during rehabilitation activities.

An SEA with two motors, a ball screw and two springs was developed for BioComEx [48] joints. The SEA with a component arrangement has the advantage of providing high compliance characteristics for RLLE actuators. However, the limited stiffness and limited bandwidth of hybrid actuators at high forces can cause a lack of trajectory tracking. The complexity of hybrid actuator construction in RLLEs, such as SEAs and PAM-electric motors, is a weakness that has kept research at the development stage [49].

Power transmission mechanism

The power transmission mechanism is designed to deliver torque from the actuator to the RLLE joint. Some RLLEs have different power transmission designs between joint locations, i.e., hip, knee, and ankle. Each design also has advantages and disadvantages. The following discussion addresses the power transmission mechanism of the active actuator, i.e., electric motors and pneumatic, hydraulic and hybrid actuators in RLLEs from the perspective of design.

The design of the power transmission mechanism of an RLLE is categorized based on the types of actuators used. First, exoskeleton joints are actuated by a single-type actuator, such as an electric motor, pneumatic or hydraulic. This category consists of (i) a direct-driven mechanism; (ii) a fixed-hinge slider mechanism; (iii) a tendon-driven mechanism; (iv) a push–pull cable (PPC) mechanism; (v) a chain-and-gear mechanism; (vi) an antagonistic mechanism; and (vii) a double-ended-rod mechanism. Second, exoskeleton joints are actuated by a hybrid-type actuator, that is, (i) a passive-electric motor direct mechanism; (ii) an antagonistic and direct mechanism; (iii) an actuator-spiral spring mechanism; and (iv) an elastic-tendon mechanism. All these types of mechanisms are illustrated in Figure 1(A–Q).

Direct-driven mechanism

The direct-driven power transmission mechanism is usually suitable for the broadest number of electric actuator types and can be directly mounted to the hips, knees and ankles of exoskeleton joints via gear elements such as gear systems and harmonic drives, as shown in Figure 1(A); a set of bevel gears, as shown in Figure 1(B); and racks and pinions, as shown in Figure 1(C). This mechanism is used to reduce the speed and amplify the generated torque of an actuator.

One of the direct-driven power transmission mechanism concepts is based on a gearing mechanism. A harmonic gear, such as that used in KUEX-R [50], is employed. Harmonic gears are advantageous due to their relatively high torque density and easy integration with rotary electric motors. Bevel gears, such as those in NaTUre gaits [51] and LEES [52], are employed. The power transmission mechanism designed in CLE [53] consists of a planetary gearbox, a pair of bevel gears, steel-cable transmission wheels and wheel joints. Some characteristics that need to be considered when choosing these transmissions are the backlash, backdrivability, and compactness. The construction of the gear, bevel gears and rack–pinion is simple. However, this mechanism introduces backlash and friction.

The direct-driven power transmission mechanism via a rotation-to-linear converter can be realized using a rack and a pinion, or it can more conveniently be developed with a linear actuator, such as a linear electric motor and a linear hydraulic cylinder. An example of an RLLE with this mechanism is HYB-EXOS [54]. The hydraulic double-acting cylinder is mounted to a link (i.e., a thigh or shank) via a clevis, whereas the piston is mechanically linked to a joint via a custom rack-and-pinion mechanism to transform linear motion into rotational motion. This concept is suitable for the actuation of hip and knee joints in the sagittal plane. However, when employed, this mechanism will potentially cause backlash and friction.

Fixed-hinge slider mechanism

The fixed-hinge slider mechanism illustrated in Figure 1(D) is suitable for application in a linear electric motor and in pneumatic and hydraulic cylinders. In the fixed-hinge slider mechanism, both ends of the actuator are fixed via hinges to the top and bottom segments of the joint to convert linear motion into rotation motion. The DGO [55], LOKOMAT [15], ALEX [56], COWALK [57] and PGO [58] are examples of rehabilitation RLLEs in which the actuator uses a ball screw to convert the rotation of a DC motor to linear motion. The application of a ball screw mechanism has advantages, such as a high load capability and high efficiency when converting rotary motion into linear motion. This mechanism can overcome backlash in harmonic gears, bevel gears and a rack and pinion. However, friction is present in the mechanism.

The fixed-hinge slider mechanism is typically employed for a pneumatic actuator with a double-acting cylinder, i.e., extract and retract. When the linear actuator extends and retracts, it produces a torque on the joint, which then rotates based on the desired angle. POGO [59] is an example of an immobile device in which this concept is applied to actuate the legs.

A fixed-hinge slider mechanism is also convenient for a hydraulic–electric motor. An example of an RLLE that uses a fixed-hinge sider mechanism is the HBSS-exo [54]. The hydraulic–electric motor in the HBSS-exo consists of a slave linear hydraulic cylinder that is guided by a master linear hydraulic cylinder to drive the angle of the exoskeleton joint. The movement of the master linear hydraulic cylinder is

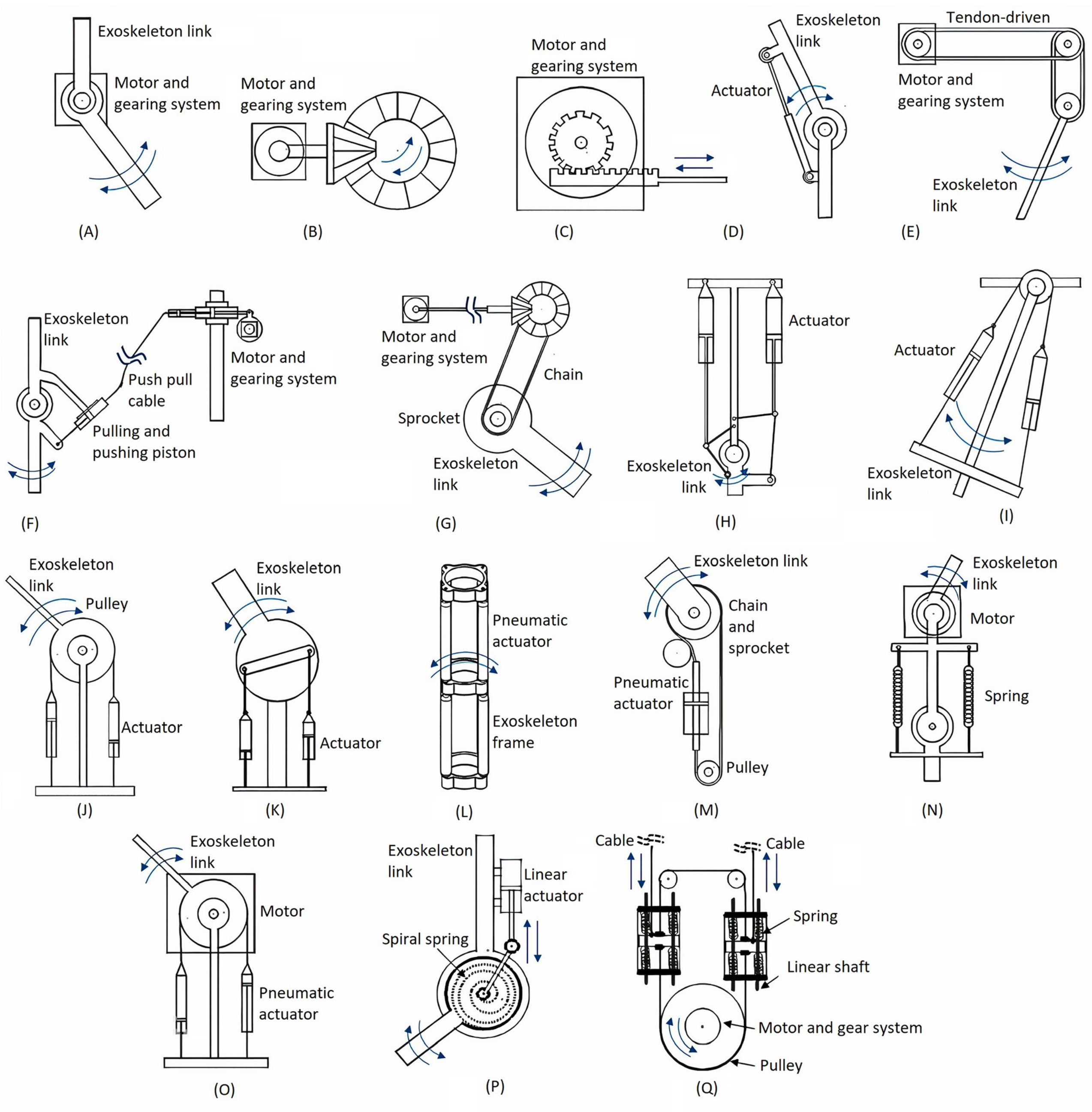

Figure 1: Power transmission mechanism (A) directly mounted via a speed reducer or a torque amplifier, (B) directly mounted via a gear train, (C) directly mounted via a rotation-to-linear converter, (D) fixed-hinge slider configuration, (E) tendon-driven configuration, (F) PPC configuration, (G) chain-and-gear configuration, (H) antagonistic pair of pneumatic actuators connected by linkages, (I) antagonistic pair of actuators connected by a pulley and belt system, (J) antagonistic pair of actuators connected by the pulley and belt system, (K) antagonistic pair of actuators connected by a lever arm mechanism, (L) antagonist pneumatic actuators mounted on brackets, (M) double-ended-rod configuration, (N) passive-actuator direct configuration, (O) antagonistic and direct power transmission, (P) actuator-spiral spring mechanism, and (Q) elastic-tendon mechanism.

controlled by the electric motor. The slave actuator can induce either antagonistic displacement or double-acting displacement. In the other types of hybrid actuators, an RLLE that applies a fixed-hinge slider mechanism is the KIT-EXO-1 [60] and exoskeleton developed by Ouyang et al. [61]. The fixed-hinge slider mechanism is easily applied on an RLLE hip, knee joint and ankle joint. However, the mechanism tends to make the device bulky at the joints.

Tendon-driven mechanism

The tendon-driven mechanism, illustrated in Figure 1(E) – is an actuator mechanism that uses double pulleys via a bendable steel tube on a flexible frame. EXPOS [62] is an example of a device in which this concept is applied to actuate the hip and knee joints. The electric motor acts as a power source to rotate the pulleys on the wearable exoskeleton. The exoskeleton joints are then connected to the pulleys via springs to maintain proper tension. The rotation angle of each pulley should be limited based on the natural range of the human joint. The electric motor, battery and controller system are mounted on a handcart to reduce the weight borne by the user as much as possible, thus increasing back-drivability on the actuator and mechanical impedance. However, the overground RLLE device and handcart are constrained by the wire via a tendon-driven mechanism.

Push–pull cable mechanism

The PPC mechanism shown in Figure 1(F) involves a power transmission concept that is similar to a tendon-driven mechanism in which a cable transfers power by pulling and pushing. The CORBYS [24] device relies on this mechanism at the hips, knee joints and ankle joints. The rotation of the electric motor, which serves as the power source, is converted to linear displacement by a slider–crank mechanism before being transmitted via the PPC. The linear displacement is then converted to rotation by another slider–crank mechanism to drive a specific joint on the exoskeleton. The specifications of the PPCs that are available on the market depend on the maximum push and pull loads or movements needed for actuation of the hips, knee joints and ankle joints. This approach introduces nonlinearity and involves relatively high friction. The increase in friction is directly proportional to the length and bending angle of the cable.

Chain-and-gear mechanism

A chain-and-gear mechanism is illustrated in Figure 1(G). This mechanism uses a chain and gear (sprocket) to transfer torque from an electrical actuator to an exoskeleton joint. Power transmission mechanisms, such as sliding shafts and universal joints, are used to provide DOFs that are consistent with natural human motion. The SUBAR [63] relies on a chain-and-gear mechanism at its joints. The electric actuator, battery and controller system are placed on a handcart to reduce the weight, and a flexible transmission cable is used to transfer the torque. The use of a handcart to carry heavy peripheral components, including actuators, batteries and controllers, can reduce the weight on the exoskeleton structure, thus increasing actuator back-drivability. Conversely, the use of a sprocket can significantly increase the torque. However, the development of this mechanism is complex and is rarely applied in RLLEs.

Implementing tendon-driven, PPC and chain-and-gear mechanisms on an RLLE as "pure force sources" is advantageous because such applications can result in the reduction of the weight at the joint and the structure of the RLLE. Additionally, this power transmission enables more space in the RLLE because the actuator is placed at other locations. The RLLE joint can be driven with less energy and inertia. This benefit is not available on an RLLE that uses a direct mechanism and mechanical slider linkage mechanism because the weight of the actuator is mounted on a joint or the structure of the RLLE. However, the tendon-driven, PPC and chain-and-gear mechanisms of power transmissions have a yielding effect and resistive force due to friction, damping and inertia in the actuator; therefore, the efficiency of the actuator can be decreased [64, 65]. This problem can be overcome by a controller system. The other weakness of tendon-driven and chain-and-gear types is that the cable and chain need to be maintained in tension. Decreased tension can introduce backlash in the actuation system.

Antagonistic mechanism

The antagonistic mechanism is suitable for pneumatic actuators. This mechanism can be developed through four possible arrangements. First, an antagonistic pair of actuators is connected by linkages. This arrangement concept, in which the actuator force is converted from a linear displacement to a rotation via four bar linkages, is illustrated in Figure 1(H). The lower and upper links are interconnected at the center by a hinge. A double-acting cylinder and PMAs are typically employed in this type of arrangement. As shown in a study conducted by Beyl et al. [66], this mechanism can be applied to leg actuations.

The second type of antagonistic arrangement consists of an antagonistic pair of pneumatic actuators connected by a pulley-and-belt system. This mechanism is illustrated in Figure 1(I) and (J). The center of the pulley is interconnected at the joint by a hinge. PMAs are typically employed in these mechanisms. Examples of such applications include RLLE-PMA [67] and EXOS-pMA [68].

The third type of antagonistic arrangement consists of an antagonistic pair of pneumatic actuators connected by a lever arm, as illustrated in Figure 1(K). This concept was applied in the design of the PIGRO [69]. In this arrangement, a pair of actuators is connected to a fixed lever arm on a pulley relative to the joint's rotational axis. The center of the pulley is interconnected at the joint by a hinge. A double-acting cylinder is typically utilized in this mechanism.

Next, the fourth type of antagonistic arrangement consists of antagonist pneumatic actuators mounted on brackets. This concept is illustrated in Figure 1(L). The KAFO [70] and the RLLE developed by Van Thuc and Yamamoto [71] are example devices in which this concept is applied to an RLLE joint. When more than one antagonistic actuator pair is employed, PAMs are typically attached around the exoskeleton joint.

The antagonistic mechanism arrangement has the advantages of a wider range of motion, the ability to maintain a normal range of human joint motion and smoother joint movements. The arrangement of pneumatic actuators in an antagonistic mechanism mimics the characteristics of human muscles [72]. These mechanisms are also suitable for actuating the joints of the hips, knees and ankles in RLLEs. However, this mechanism is bulky on the RLLE joints.

Double-ended-rod mechanism

A double-ended-rod mechanism, such as linear pneumatic double-acting cylinders, is suitable for linear motion actuators. A double-ended rod mechanism with a chain and sprocket is illustrated in Figure 1(M). Additionally, a double-acting cylinder is used to generate a linear displacement, which is converted to rotational movement by a chain connected to both ends of a piston rod via a sprocket on the top segment. Two chain tensioners are used to maintain the tautness of the chain. This mechanism is commonly employed to actuate knee and ankle joints. However, this mechanism must be adjusted for use at the hips because it does not interface well with thigh and trunk segments. An example of this mechanism is the PAGO [73]. For a mechanism that employs a chain with a sprocket or a cable with a pulley, the power transmission efficiency will decrease over time.

Passive-electric motor direct mechanism

In another work, a hybrid actuator, such as a passive-electric motor, utilizes a direct power transmission mechanism to connect the actuator to an exoskeleton joint. These joint mechanisms used in LOPES [74] and Aguirre-Ollinger and Yu [75] primarily consist of a spring that is arranged to store and release energy, which reduces the torque that must be produced by the motor. The arrangement concept is shown in Figure 1(N) and can be utilized at the hip, knee and ankle joints. However, in LOPES, a Bowden cable is employed to transfer energy from the actuator to a joint. The Bowden cable has benefits such as a tendon-driven operation, PPC and chain-and-gear, which reduce the weight at the joint and the structure of the RLLE. Additionally, the RLLE joint has more space because the actuator is placed at other locations. The RLLE joint can be driven with less energy and inertia. However, a Bowden cable can introduce friction and a yielding effect during power transmission. Therefore, the efficiency of the actuator can decrease [64, 65].

Antagonistic and direct mechanism

An antagonistic and direct power transmission mechanism, as illustrated in Figure 1(O), is suitable for use in a hybrid actuator, such as the combination of an electric motor and pneumatic actuator. This transmission mechanism was applied in the hip, knee and ankle joints of an RLLE designed for XoR [76]. The pneumatic actuators are arranged in an antagonistic mechanism, whereas the DC motor is directly driven at the joint. The antagonistic and direct power transmission mechanisms are complicated and cause the RLLE joint to become bulky. However, this mechanism can improve the actuator performance, i.e., the linearity and compliancy.

Actuator-spiral spring configuration

An actuator-spiral spring configuration, illustrated in Figure 1(P), connects the actuator and exoskeleton joint via a spiral spring. This mechanism was applied in MINDWALKER, where the linear DC motor is connected to the join via an arm and spiral spring [77]. The same mechanism was used by Li et al. [78] to drive the hip of the RLLE joint, but they used a DC rotary motor and connected it to the joint via a spiral spring and toothed belt. The spiral spring is a mechanism that stores energy and exerts a force when it is compressed or extended. It absorbs shock, provides a cushioning effect, and exhibits highly linear behavior and zero backlashes at the connection spots. It also improves the torque density and spring stiffness accuracy, thus eliminating connection backlash. However, this spring can become fatigued over time, resulting in a decrease in the tension and an overall decrease in performance. Moreover, it is challenging to achieve the exact level of tightness and uniformity needed for the spring to function correctly on the RLLE joint.

Elastic-tendon configuration

The elastic-tendon configuration illustrated in Figure 1(Q) is widely used in cable-driven actuation types, such as exosuits [79]. The power is transmitted from the actuator via the pulley and a series of elastic tendon elements. Lee et al. [80] used this configuration, where the torsion springs are connected to the motor shaft and two pulleys. The series-elastic-tendon and actuator can assign compliance to the rigid cable. The force between the human and the exosuit is identified by measuring the deformation of the torsion springs using an encoder.

Schmidt et al. [81] developed a Myosuit using an elastic-tendon configuration. The Myosuit is actuated by the DC motor and artificial tendon route along the leg from the waist to the shank to actively assist against the force of gravity at the hip and knee joints. The tendon actuators are secured by an elastic band wrapped around the shank. A cable is fixed at the motor shaft and connects via a pulley system. Moreover, it is wrapped around the motor shaft when it rotates. A rubber band, which can be used as a passive compliant mechanism, is attached at the front of the waist belt and the front of the thigh cuffs. This element stores energy and provides an antagonistic action to assist the movement of joints. Cable-driven systems are lightweight, have high torque and have increased controllability compared to fluidic actuators. They are also portable, do not have a rigid structure and are compact in design, which is helpful for activities of daily living and dealing with locomotion. Some drawbacks are the difficulty in identifying the spring constant and the complicated mechanism design. The cable-driven system also introduces friction, backlash hysteresis, and nonlinearities [82].

Several RLLE characteristics are reviewed and shown in Table 1 regarding their design aspects, including the types of actuators, types of power transmissions, structural types and operation modes.

Discussion and future directions

Studying previous studies is useful for realizing a more advantageous RLLE. The actuator type and the power transmission mechanism play key roles in RLLE development and thus greatly impact motion and human–machine interaction. When actuators are compared for RLLE applications, electric motors still offer a considerably better choice that is easy to control and compact in joint configuration than fluidic-based actuators. Electric motors are a promising technology for achieving portable devices. Batteries can be easily used to power such devices, facilitating portability and silence operation that result in comfortable patient-device usage. Pneumatic and hydraulic actuators are costly due to the frequent service needed to maintain satisfactory actuator efficiency. In addition, the auxiliary systems are complex, and the power transfer mechanism is bulky, thus limiting their portability. Table 2 summarizes the types of power transmission mechanisms with compatible actuators and their advantages and disadvantages for RLLEs.

Researchers have focused on compact pneumatic actuators. Sun et al. [96] introduced an electric motor, micropump, tank, and other components, which were integrated into a module. However, it was still bulky compared to electric motors. Actuators with characteristics such as a small volume, light weight, high power-to-weight ratio, compactness, silent operation, low bulk, low maintenance, low cost, and high-power storage capacity are in demand. Moreover, the smaller auxiliary systems that need low energy that can be supplied by batteries provide enough of the necessary power output, which will be demanded in the future.

Next, we show the comparison of actuator characteristics for RLLEs by 10 criteria, as shown in Table 3. The results show that DC motors are more suited to 10 criteria for suitable and relevant use in RLLE applications for immobile and overground application domains. To improve RLLEs, such as by improving the compliance, a hybrid actuator that contains a DC motor and passive element is also the best choice for rehabilitation domains. In contrast, hydraulic actuation is an unsuggested choice for RLLEs for both immobile and overground application domains.

In RLLE safety, a restricted range of joint rotation can be achieved through three approaches: mechanical methods, electrical methods and software-based methods. Mechanical approaches use a mechanical stopper to limit the joint's range of motion and prevent the exoskeleton from damaging itself in the case of sensor or software failure. The electrical approach is based on the control system, which limits the range of motion. The joint is equipped with a limit switch or sensor to send a signal to the control system, instructing it to halt the rotation when it is over the limit. The software-based approach involves the control algorithm, monitoring the forces and torques applied to the joint, and limiting the motion when the forces and torques exceed a certain threshold. When the forces and torques exceed a specified limit, the controller instructs the motor to shut down and sends a brake command to hold or free the joint. Other safety features need to be considered, i.e., a failsafe feature due to power failure. For example, in commercialized RLLEs, i.e., Indego and Ekso, the hips become free, and the knees lock. In ReWalk,

Table 1: Review of the RLLE technical characteristics.

Category	Exoskeleton/ inventor	Joint actuator types	Actuator types	Types of power transmission mechanisms for active actuators	Structure types	Operation modes	Stage
Electric motor	WPAL [83]	Hips (M, F, F), knees (M), ankles (F, N, N), metatarsophalangeals (F)	DC servo motor, harmonic drive gear	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	R
	Mina [84]	Hips (M, N, N), knees (M), ankles (N, N, N)	DC brushless motor, 160:1 harmonic drive	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	R
	ReWalk [18]	Hips (M, N, N), knees (M), ankles (S, N, N)	DC motor, spring	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	C
	ATLAS [85]	Hips (M, N, N), knees (M), ankles (S, N, N)	Electric brushless maxon motors, steel cable linked at knee	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	R
	DGO [55]	Hips (M, N, N), knees (M), ankles (S, N, N)	DC motor with ball screw	Slider linkage, Figure 1(D)	Immobile	BWS	R
	LOKOMAT [15]	Hips (M, N, N), knees (M), ankles (S, N, N)	DC motor linear actuator	Slider linkage, Figure 1(D)	Immobile	BW	C
	ALEX [56]	Hips (M, S, N), knees (M), ankles (S, N, N)	Linear electrical motor, spring	Slider linkage, Figure 1(D)	Immobile	UBW	R
	PGO [58]	Hips (M, N, N), knees (M), ankles (S, N, N)	AC electric linear motor with ball screw	Slider linkage, Figure 1(D)	Immobile	BWS	R
	Physiotherabot [86]	Hips (M, M, N), knees (M), ankles (N, N, N)	Servo motor (kollmorgen)	Direct mounted with gearing systems, Figure 1(A)	Immobile	UBW	R
	Gui et al. [87]	Hips (M, N, N), knees (M), ankles (N, N, N)	DC motor	Direct mounted with gearing systems, Figure 1(C)	Immobile	BWS	R
	CORBYS [24]	Hips (M, S, S), knees (M), ankles (M, S, N), pelvis	Brushless DC motor	Push–pull cable, Figure 1(F)	Immobile	UBW	R
	EXPOS [62]	Hips (M, S, S), knees (M), ankles (S, N, N)	Servo motor	Tendon-driven mechanism, Figure 1(E)	Overground	UBW	R
	SUBAR [63]	Hips (M, S, S), knees (M), ankles (S, N, N)	Servo motor	Chain-and-gear mechanism, Figure 1(G)	Overground	UBW	R
	NaTUre-gaits [51]	Hips (M, N, N), knees (M), ankles (M, N, N)	Brushless DC motors	Bevel gears, Figure 1(B) rack-and-pinion systems, Figure 1(C)	Overground	BWS	R
	BLERE [88]	Hips (M, S, S), knees (M), ankles (N, N, N)	Servo motor, harmonic reducer	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	R
	KUEX-R [50]	Hips (M, M, N), knees (M), ankles (M, M, N)	Brushless DC motor and harmonic drive	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	R
	REX rehab [32]	Hips (M, M, N), knees (M), ankles (M, M, N)	Electric motor	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	C
	EksoGT [31]	Hips (M, N, N), knees (M), ankles (S, N, N)	Electric motor, spring	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	C
	Indego therapy [33]	Hips (M, S, N), knees (M), ankles (N, N, N)	DC motor	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	C
	HAL-medical [34]	Hips (M, N, N), knees (M), ankles (S, N, N)	Electric motor	Direct mounted with gearing systems, Figure 1(A)	Overground	UBW	C

Table 1: (continued)

Category	Exoskeleton/ inventor	Joint actuator types	Actuator types	Types of power transmission mechanisms for active actuators	Structure types	Operation modes	Stage
	CLE [53]	Hips (M, S, N), knees (M), ankles (N, N, N)	Brushless DC motor, planetary gearbox, pair of bevel gear, steel-cable transmission wheel and wheel joint	Direct mounted with gearing systems, Figure 1(B)	Overground	UBW	R
	COWALK [57]	Hips (M, S, N), knees (M), ankles (M, S, N), pelvis (4 DOFs), upper body (1 DOFs)	Linear brushless DC on leg and pelvis, counter-balancing weight on upper body	Fixed-hinge slider mechanism on leg, Figure 1(D), prismatic and rack-and-pinion joint at pelvis, Figure 1(C), parallelogram linkage mechanism, pulley-wire and spring at upper body	Immobile	BWS	R
Pneumatic	Wu et al. [89]	Hips (N, N, N), knees (P), ankles (P, N, N)	Linear pneumatic cylinder	Fixed-hinge slider mechanism, Figure 1(D)	Overground	UBW	R
	EXOS-pMA [68]	Hips (P, P, P), knees (P), ankles (P, N, N)	Pneumatic muscle actuator (PMA)	Antagonistic mechanism using a pulley-and-belt, Figure 1(J)	Immobile	UBW	R
	POGO [59]	Hips (P, S, N), knees (P), ankles (N, N, N)	Pneumatic cylinder	Double-ended-rod mechanism, Figure 1(D)	Immobile	BWS	R
	PIGRO [69]	Hips (P, N, N), knees (P), ankles (P, N, N)	Linear pneumatic cylinder	Pneumatic actuators connected by a lever arm, Figure 1(K)	Immobile	BWS	R
	RLLE-PMA [67]	Hips (P, S, N), knees (P), ankles (S, N, N)	Pneumatic muscle actuator (PMA)	Antagonistic mechanism using a pulley-and-belt system, Figure 1(I)	Immobile	UBW	R
	Beyl et al. [66]	Hips (P, N, N), knees (N), ankles (N, N, N)	Pleated pneumatic artificial muscle	Antagonistic pair of pneumatic actuators connected by linkages, Figure 1(H)	Immobile	UBW	R
	Van Thuc and Yamamoto [71]	Hips (P, N, N), knees (P), ankles (N, N, N)	McKibben artificial muscle actuator	Antagonistic mechanism based on brackets, Figure 1(L)	Immobile	BWS	R
	PAGO [73]	Hips (P, N, N), knees (P), ankles (N, N, N)	Linear pneumatic cylinder	Fixed-hinge slider mechanism actuator, Figure 1(D) – a chain and sprocket, Figure 1(M)	Overground	UBW	R
	KAFO [70]	Hips (N, N, N), knees (P), ankles (P, N, N)	Artificial pneumatic muscle actuator	Antagonistic mechanism based on brackets, Figure 1(L)	Overground	UBW	R
	Bingjing et al. [90]	Hips (P, N, N), knees (P), ankles (N, N, N)	Linear pneumatic cylinder	Fixed-hinge slider mechanism, Figure 1(D)	Immobile	BWS	R
Hydraulic	MD-exos [91]	Hips (H, N, S), knees (H), ankles (S, N, N)	Hydraulic actuator	Fixed-hinge slider mechanism, Figure 1(D)	Overground	UBW	R
	HYB-EXOS [54]	Hips (H, N, N), knees (S), ankles (F, N, N)	Hydraulic actuator	Rack-and-pinion mechanism, Figure 1(C)	Overground	BWS	R
Hybrid	LOPES [74]	Hips (HY, HY, N), knees (HY), ankles (N, N, N)	Series-elastic actuator	Antagonistic mechanism, Figure 1(N) with bowden cable-based	Immobile	UBW	R
	IHMC [44]	Hips (HY, HY, S), knees (HY), ankles (S, N, N)	Rotary series elastic actuators (RSEAs), curved roller bearing and linear chain spring load	Direct mounted with gearing systems, passive-antagonist mechanism, Figure 1(N)	Overground	UBW	R
	MINDWALKER [77]	Hips (HY, HY, S), knees (HY), ankles (S, N, N)	Series elastic actuators (SEAs)	Direct mounted, Figure 1(P)	Overground	UBW	R

Table 1: (continued)

Category	Exoskeleton/ inventor	Joint actuator types	Actuator types	Types of power transmission mechanisms for active actuators	Structure types	Operation modes	Stage
	Aguilar-Sierra et al. [92]	Hips (HY, S, S), knees (HY, S), ankles (S, S, N)	Electric-harmonic drive and pneumatic artificial muscles (PAMs)	Direct mounted with gearing systems, antagonistic mechanism, Figure 1(O)	Overground	UBW	R
	HBSS-exo [93]	Hips (HY, N, N), knees (HY), ankles (HY, N, N)	Hydraulic bilateral-servo system	Fixed-hinge slider mechanism, Figure 1(D)	Overground	BWS	R
	XoR [76]	Hips (HY, S, S), knees (HY, N), ankles (HY, S, N)	Pneumatic air muscle (AM) and brushless DC motor	Direct mounted with gearing systems, antagonistic mechanism, Figure 1(O)	Overground	BWS	R
	Yu et al. [94]	Hips (N, N, N), knees (HY, N), ankles (HY, N, N)	Series-elastic actuator (SEA)	Fixed-hinge slider mechanism, Figure 1(N)	Overground	UBW	R
	KIT-EXO-1 [60]	Hip (N, N, N), knees (HY, N), ankles (HY, S, N)	Linear series elastic actuator (LSEA) – DC motor and elastic element	Fixed-hinge slider mechanism, Figure 1(D)	Overground	UBW	R
	BioComEx [57]	Hips (HY, N, N), knees (HY), ankles (HY, N, N)	Series-elastic actuator (SEA) with ball screw, two motors and two springs	Direct mounted, Figure 1(D)	Overground	BWS	R
	L2EXO-PE [39]	Hips (HY, N, N), knees (HY), ankles (S, N, N)	Clutched parallel elastic actuators and springs	Direct mounted, Figure 1(N)	Overground	BWS	R
	LEES [52]	Hips (HY, N, N), knees (HY), ankles (S, N, N)	Series elastic actuators (SEAs)	Direct mounted, Figure 1(B)	Overground	Not mention	R
	CUHK-EXO [95]	Hips (HY, N, N), knees (HY), ankles (S, N, N)	Magneto-rheological series elastic actuator with planetary gearbox and bevel gear	Consist two types: direct mounted, Figure 1(A) and direct mounted, Figure 1(B)	Overground	UBW	R
	Myosuit [81]	Hips (HY, N, N), knees (HY), ankles (N, N, N)	DC motor	Elastic-tendon configuration, Figure 1(Q)	Overground	UBW	R

M, electric motor; P, pneumatic; H, hydraulic; S, passive actuated; N, non-actuated; HY, hybrid; Q, quasi-passive; F, freely; UBW, unsupported body weight; BWS, body weight support; C, commercial stage; R, research/prototype stage; hip joint sequence, (flexion/extension; abduction/adduction; internal/external rotation); knee joint sequence, (flexion/extension; abduction/adduction); and ankle joint sequence, (dorsiflexion/plantar flexion, inversion/eversion, internal/external rotation).

the device slowly collapses [23]. These measures are very important for protecting a wearer from serious injury. These conditions require that an actuator be equipped with internal mechanical breaking or free mechanisms. Therefore, it is crucial to design a safety mechanism for actuators that is integrated with a power transmission mechanism to minimize risky situations.

The actuators and transmission mechanisms of RLLEs are not fully adjusted for ergonomic and biological features. Four points are suggested to be considered. First, the current RLLE actuators and power transmission mechanisms still face challenges regarding the misalignment between RLLEs and the joints of patients. The rigid structures of RLLEs do not replicate the human anatomy perfectly, thus causing misalignment [97, 98]. For example, the knee joint is a complex joint that is not monocentric. It provides a combination of rolling and sliding motions between the femur and the tibia, and the size of the femur and tibia bone differ among people [99]. Knee anatomy requires the development of a mechanism and configuration that matches and aligns with the human knee joint. Even if a small misalignment between the RLLE and the patient's joint occurs, it can result in unnatural and undesired translation forces, thus causing undesired parasitic forces on the patient's skeletal system during therapy sessions.

There are three sources of misalignment: migration of the instantaneous center of rotation or slippage during operation, inaccurate alignment while wearing the RLLE, and an inaccurate RLLE replicating the human anatomy [100]. This effect induces undesired interaction forces that can potentially constrain the movements of the user and cause discomfort, pain, or even injury. There are several joint mechanism designs, including self-alignment approaches: Schmidt coupling on the knee joint [101], parallel

Table 2: Comparison of the power transmission mechanism.

Category of mechanism	Type of mechanism and figure number	Compatible type of actuator	Advantage	Disadvantage
Direct mounted	Directly mounted via gear element, Figure 1(A)	Electrical motor	Suitable for the broadest number of electric actuator types and easily mounted	Tends to result in backlash and friction
	Directly mounted via set of bevel gears, Figure 1(B)	Electrical motor	Easy configuration for hips and knees	
	Directly mounted via rotation-to-linear converter, Figure 1(C)	Linear electrical motor, pneumatic and hydraulic cylinder	Easy controllability of the angle rotation with high precision	
Fixed-hinge slider	Fixed-hinge slider mechanism, Figure 1(D)	Linear electrical motor, pneumatic, hydraulic actuator, and hybrid linear type actuator	Can overcome backlash when directly mounted via gear elements, bevel gears and a rack and pinion Easy configuration for hips and knees Easy controllability of the angle rotation with high precision	Friction is present in the mechanism. Difficult to use at ankles joint
Tendon-driven	Tendon-driven mechanism, Figure 1(E)	Electrical motor	It can reduce the weight of the RLLE joint and structure, and the actuator can be placed on the ground. Thus, an RLLE joint can be driven with less energy and inertia	Constrained by the wire, yielding effect and resistive force due to friction, damping, and inertia in the actuator; thus, the efficiency of the actuator can be decreased. Need maintaining tension of cable, chain, or tendon
Push–pull cable	PPC mechanism, Figure 1(F)	Electrical motor	Easy configuration for hips and knee	
Chain-and-gear	Chain-and-gear mechanism, Figure 1(G)	Electrical motor		
Antagonistic	Linkages, Figure 1(H)	Pneumatic actuator	Ability to maintain a normal range of human joint angle and smoother joint movements. The arrangement of pneumatic actuators in an antagonistic mechanism mimics the characteristics of human muscles	This mechanism type is bulky
	Pulley-and-belt system, Figure 1(I)	Pneumatic actuator	Suitable for configured actuators on hips and knees	
	Pulley and belt system, Figure 1(J)	Pneumatic actuator		
	Lever arm, Figure 1(K)	Pneumatic actuator		
	Brackets, Figure 1(L)	Pneumatic actuator		
Double-ended-rod	Double-ended-rod mechanism, Figure 1(M)	Pneumatic actuator	The mechanism is simple and easy to install	This mechanism is challenging to use at the hips because it does not interface well with thigh and trunk segments. The efficiency will decrease over time
Passive-actuator direct	Passive-electric motor, Figure 1(N)	Hybrid actuator	Can improve the actuator performance, i.e., linearity and compliancy	The RLLE joint tend to be bulky
Antagonistic and direct	Antagonistic and direct power transmission, Figure 1(O)	Hybrid actuator	Can improve the actuator performance, i.e., linearity and compliancy	The RLLE joint tend to be bulky
Actuator-spiral spring	Actuator-spiral spring configuration, Figure 1(P)	Hybrid actuator	It stores energy and exerts a force when it is compressed or extended. The mechanism absorbs shock, provides a cushioning effect, and exhibits linear behaviors. It also improves the torque density and spring stiffness accuracy, thus eliminating connection backlash	The spring can become fatigued over time, resulting in a decrease in tension and an overall reduction in performance. Challenging to achieve the exact level of tightness of spring to function correctly on the RLLE joint
Elastic-tendon	Elastic-tendon configuration, Figure 1(Q)	Hybrid actuator	Cable-driven systems are lightweight, have high torque, and can easily be controlled compared to fluidic actuators. It is portable, which is convenient	Identifying the spring constant and assembling is challenging due to the complicated mechanism for assigning a preload. The cable-driven system has friction, backlash hysteresis, and nonlinearities

Table 3: The characteristics of the actuator are matched to the immobile and overground RLLE structure according to 10 criteria.

Criteria	Actuator characteristics	Application domain–RLLE											
		Immobile RLLEs						Overground RLLEs					
		DC motor	Pneumatic	Hydraulic	Hybrid – DC motor-passive elements	Hybrid – DC motor-pneumatic	Hybrid – DC motor-hydraulic	DC motor	Pneumatic	Hydraulic	Hybrid – DC motor-passive elements	Hybrid – DC motor-pneumatic	Hybrid – DC motor-hydraulic
Performance	Easy to control	✓	–	–	✓	–	–	✓	–	–	✓	–	–
	High bandwidth		–	✓			✓		–	✓			✓
	Good compliance		✓	–	✓	✓			✓	–	✓	✓	
Available in market	Various specifications option in the market	✓	✓	✓	–	–	–	✓	✓	✓	–	–	–
Complexity	Less complexity to configure joints	✓		–		–	–	✓	–	–		–	–
Maintenances	Less maintenance	✓	–	–	✓	–	–	✓	–	–	✓	–	–
Environment	Suitable for environmental hygiene criteria	✓	✓	–	✓	✓	–	✓	✓	–	✓	✓	–
Reliability	Linearization characteristic	✓	–	–	✓	✓	✓	✓	–	–	✓	✓	–
Size	Accepted bulkiness	✓	✓	–	✓	✓	–	✓	–	–	✓	–	–
Weight	Can transfer weight on caster walker	✓	✓	✓	✓	✓	✓		–	–		–	–
Noise level	Low noise level or silence	✓	–	–	✓	–	–	✓	–	–	✓	–	–
Suitability of usage.	Suitably used in rehabilitation robotics	✓	✓	–	✓	–	–	✓		–	✓	✓	–

self-alignment on the ankle joint [102], adjustment of the structure length via slots [103] and three DOFs via sliders and hinges [104]. A study by Bartenbach [105] has shown that misalignment compensation can be achieved by allowing the interfaces to move along the rigid exoskeleton structure. Linear ball bearings are integrated into each cuff attachment, enabling the cuffs to slide up and down the tubes of the leg device to avoid constraining forces resulting from misalignment between the patient's joint and the exoskeleton's joint. Research is also being conducted on the use of soft robotics in RLLE design. Soft robotics are made of materials that are compliant and can adapt to the shape and movements of the body, which may reduce misalignment issues [106].

Second, RLLE actuators and power transmission mechanisms should be designed in the position corresponding to the representative muscle in the human limb and the trunk to mimic the functions of muscles during motion. Thus, in RLLEs, actuators and their mechanisms should be designed with the objective of achieving natural characteristics and not interfering with physiological motion. The tendon sheath artificial muscle is an example configured with consideration of this characteristic [107]. Therefore, the flexion and extension motions of RLLEs can be employed by double-acting linear actuators and a fixed-hinge slider mechanism. The double-acting linear actuator should be arranged to mimic the function of the biceps femoris on the knee and the rectus femoris on the hip. However, if a single-acting actuator is utilized, an antagonistic mechanism should be considered to mimic the rectus femoris, the gluteus maximus on the hip and the vastus maximus and biceps femoris on the knee.

Third, we suggest that future studies on RLLE actuators and power transmission mechanism designs should focus on compliance or spring-like characteristics. The requirements of the compliance features are important for reducing mechanical impedance due to physical interactions among the exoskeleton, the patient and the ground. Usually, RLLEs that are primarily driven by single-type active actuators and configured as shown in Figure 1(A)–(P) are confronted with rigid actuation without compliance, leaving the impression of large vibration and shock. Compliance actuators, such as SEAs and variable stiffness actuators, have emerged to overcome weaknesses with regards to the compliance issue [108]. Indeed, SEAs offer the advantages of energy reduction, back-drivability and smooth motions [40, 109]. Additionally, compliance behaviors can be achieved with pneumatic actuators [33, 110]. However, designing compliance actuators remains challenging due to the complexity of adjusting the stiffness of the elastic element and spring stiffness. Furthermore, actuators with compliance characteristics should meet torque control stability and low intrinsic output impedance requirements. The light weight and compactness of overground exoskeletons are essential. Therefore, solutions to these issues are still in high demand [7, 111, 112].

Fourth, an immobile RLLE-type device using a treadmill as a walking platform does not require precise positioning, but mechanical safety is inherently important. Many studies have shown that pneumatic actuators have properties similar to human muscles. Due to these advantages, we suggest that applications of the pneumatic actuator on immobile RLLEs should be explored and subsequently marketed. To reduce the weight exerted on the patient's limb by the immobile RLLE-type, actuation systems can be placed proximally. Thus, demanding remote actuation can be realized through the pneumatic type of actuation or using Bowden cables if actuated by the electric motor. Myosuits have become prominent; thus, further research is necessary to assess their potential for replacing the rigid and heavy structure of RLLEs [106].

Conclusions

In this paper, the selection criteria of the actuator and the power transfer mechanism design were reviewed. Moreover, 210 studies on RLLE devices from 2009 to 2022 were studied. The information regarding actuators and power transmission mechanisms provided in this study will be useful guidance for researchers and developers to investigate technological implementations of RLLEs. From the state-of-the-art perspective, the actuator type and the power transmission mechanism play key roles in RLLE development and thus greatly impact its motion and safer human–machine interaction. After reviewing the wide variety of RLLE devices, electric motors and pneumatic and hybrid actuators have been used in RLLE devices in research and commercial devices. Electric motors offer a considerably good choice for both RLLE structure types, i.e., overground and immobile devices. It is in line with the actuator characteristic, in which electric motors offer a good choice due to being easier to control, compact in design, and configurable at a joint rather than fluidic-based actuators. Moreover, muscle-like actuators have the advantages of flexible structures and light weight. However, there is a demand to improve the low stiffness to ensure that the weights of bodies are supported and provide safety in human–machine interactions. Furthermore, the designed power transmission mechanism, which is classified into two categories, was investigated in this paper. First, RLLE joints are actuated by a single type actuator, that is, an electric motor, pneumatic or hydraulic. Second, exoskeleton joints are actuated by a hybrid type. There are many types of power transmission mechanisms that are being used. The characteristics of backlash, less friction, simple mechanism configuration, bulkiness, and reduced energy usage should be considered when designing the power transfer mechanism. Therefore, the trade-off between the advantages and disadvantages of each type of power transmission mechanism must be considered. Future research and development of actuators and power transmission mechanisms are expected to considerably increase simultaneously with the evolution of RLLE applications. There is a trend in developing RLLEs to assist patients with rehabilitation activities outside the clinic environment, such as at home. Therefore, more sophisticated adoption of the technology is needed. With this shift in focus, a new design or improvement of an actuator of the RLLE with characteristics such as compactness, lightness, less energy usage, and compliance is also needed.

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