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# Lower Extremity Exoskeleton for Human Spinal Cord Injury: A Comprehensive Review

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**ABSTRACT** Locomotion disorder caused by spinal cord injury (SCI) leads to a considerably decreased quality of people's lives. Although there are no known cure methods for SCI, a lower extremity exoskeleton (LEE) has a perspective to restore the locomotion ability of SCI patients. Statistics show that the number of published articles on LEEs has exponentially increased over the past 20 years; however, no reviews have been conducted to summarize these studies comprehensively. To fill up this open gap, a comprehensive review from engineering to clinical standpoint is carried out, which is based on the preferred reporting items for systematic reviews and meta-analyses' methods, including their structural designs, drive forms, control methods, and clinical assessments. A systematic discussion among them is performed while considering the main scientific and technical aspects. The analysis indicates that the actuator configuration, motor selection, state transition, trajectory tracking, transparency implementation, and clinical factor design in exoskeleton development are full of challenges, which should be investigated in more technical efforts in the future.

**INDEX TERMS** Actuator, clinical assessment, control architecture, lower extremity exoskeleton (LEE), preferred reporting items for systematic reviews and meta-analyses (PRISMA), spinal cord injury (SCI), structural design.

## I. INTRODUCTION

Spinal cord injury (SCI) is the main cause of mobility disorder and gait pathology in adults, and approximately 80 000 adults worldwide are diagnosed with traumatic SCI every year [1], [2]. Mobility disorder caused by SCI significantly impairs adults' activities of daily living [3], causing a deficit in standing balance [4] and movement control [5]. Therefore, regaining locomotion ability is particularly critical for people with SCI. Unfortunately, no cure for SCI has been found [6], [7], [8]. Conventional medical treatment, including spinal cord stimulation [7], [8] and pharmacotherapy [9], [10], can partly relieve SCI symptoms but increase the risk of side effects in lower limbs. SCI therapies are focusing on how to reduce side effects for patients. Rehabilitation therapy is considered an effective way of recovery and reintegration into society for SCI patients [11]. A great demand for customized technologies for mobility disorders has facilitated new strategies for gait rehabilitation. Equipment, such as virtual reality with haptic feedback sensors and devices [12], [13], [14], [15] and body weight-supported treadmills [2], [16], have shown some positive results in contributing to gait rehabilitation. Nevertheless, the promotion of the equipment is limited by the cost of facilities, the size of the space, and the number of professionals.

To solve these problems, lower extremity exoskeletons (LEEs) have been developed in recent years for improving gait rehabilitation quality [17], [18]. Safety, portability, and reliability are critical considerations in assistive robot design [19], especially for those users with gait abnormalities. Moreover, LEEs deserve some special attributes:

1) able to accommodate different body sizes and length adjustable;
2) lightweight, compact, and flexible;
3) easily used by low educational groups;
4) able to recognize and correct abnormal gait patterns;
5) capable of ensuring wearers' security and avoiding secondary damage to users [20], [21].

Advances in drive form, energy storage, manufacturing methods, miniaturized sensing, and embedded computational technology have promoted the development of multiple LEEs [22].

Control methods play a critical role in maintaining stable locomotion assistance of LEEs [23]. There are a lot of uncertain factors affecting LEEs' working state (such as input interference). These factors heavily disturb robotic dynamic response characteristics. Even a little disturbance from the input can lead to completely incorrect output. A normal gait profile output of LEEs relies on the effective suppression and weakening of external disturbance. A good control method enables users to imitate a normal gait, stabilize a two-foot standing, and keep a continuous balance.

Emerging prototyped LEEs have been prototyped for SCI patients, and clinical results show that these LEEs have a significant capacity for restoring locomotion ability and correcting abnormal gait [24], [25], [26], [27], [28], [29], [30], [31]. However, no reviews have been conducted to summarize these inspiring studies comprehensively from structural design to clinical assessment. To fill this open gap, this article retrospects and discusses the state-of-the-art in this area, including structural design, drive forms, control methods, and clinical assessment. The rest of this article is organized as follows. Section II states the classification and grading system of SCI. Section III describes the general control framework for LEEs. Section IV delivers the classification of LEEs. Section V discusses the characteristics of LEEs. Finally, Section VI concludes this article.

## II. SPINAL CORD INJURY

SCI is defined as damage to the spinal cord that temporarily or permanently causes functional changes [32]. To provide a theoretical basis for SCI treatment, reproducible scoring systems of SCI have been established to assist clinicians in formulating therapeutic strategies for patients with different severity levels [33]. As shown in Fig. 1(a), SCI is generally classified as incomplete and complete. According to the definition made by the American Spinal Injury Association (ASIA), if the connection between the brain's functional connections (sensory and motor command to and from the brain) to the periphery is completely lost, it is defined as complete SCI, whereas some sensory or motor functions below the level of injury are left, it is defined as incomplete injury [32], [34], [35], [36]. To grade neurological dysfunction after SCI accurately, the popular ASIS classification system is established [33], [37]. This system divides SCI into several stages based on the patient's ability to self-care, control of bowel and bladder, ambulation, as well as social interaction [37]. In this system,

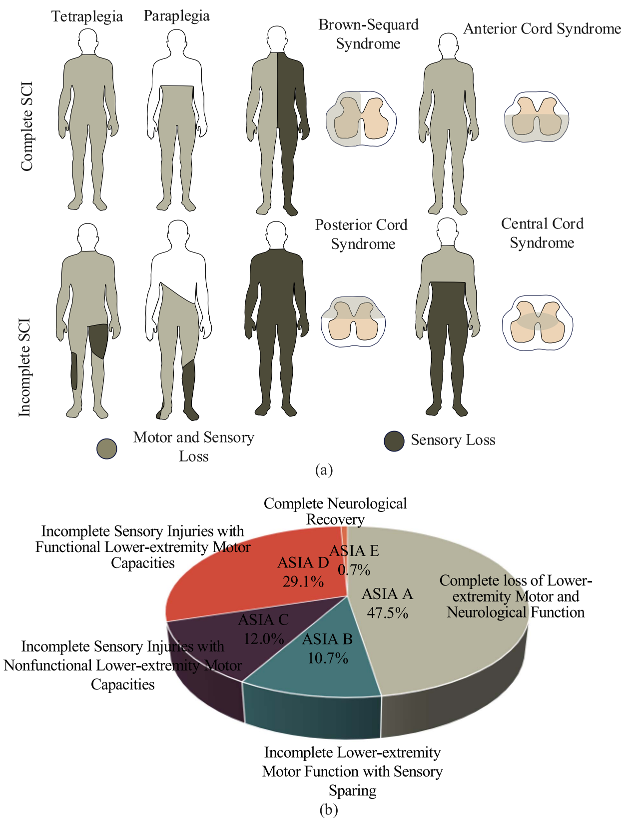


**FIGURE 1. Classification and grading of SCI. (a) Classification with examples of complete and incomplete injuries [36]. (b) ASIA grade distribution among inpatient rehabilitation persons in the NSCISC database [37], [38].**

sensory and motor functions are scored from 0–2 and 0–5, respectively [33], [37]. The ASIA impairment scale (AIS) is classified from complete loss of sensation and movement to normal motor and sensory functions [37]. The first step in the ASIS classification system is to identify the neurological level of injury [37]. Then, the zone of partial preservation is determined based on the neurological level of injury, which can be used to distinguish spontaneous and treatment-induced functional recovery and evaluate the therapeutic effect. The epidemiology of SCI based on the National Spinal Cord Injury Statistical Center (NSCISC) database shows the symptoms and ratio of patients with different injury levels [see Fig. 1(b)]. Due to the diversity and complexity of lower extremity locomotion disorder caused by SCI, LEE-based recovery therapy should be designed based on a specific control strategy.

## III. CONTROL FRAMEWORK FOR LEES

The complexity of lower extremity movement must be taken into consideration in the control methods design of the powered LEEs. The general control framework for LEEs is illustrated in Fig. 2. This framework was inspired by and extended from that of Tucker et al.'s article [22] to be applied to a wider range of devices (i.e., lower extremity prostheses and exoskeletons) and joint (i.e., hip, knee, and ankle) orthosis. The distributed control framework can be split into

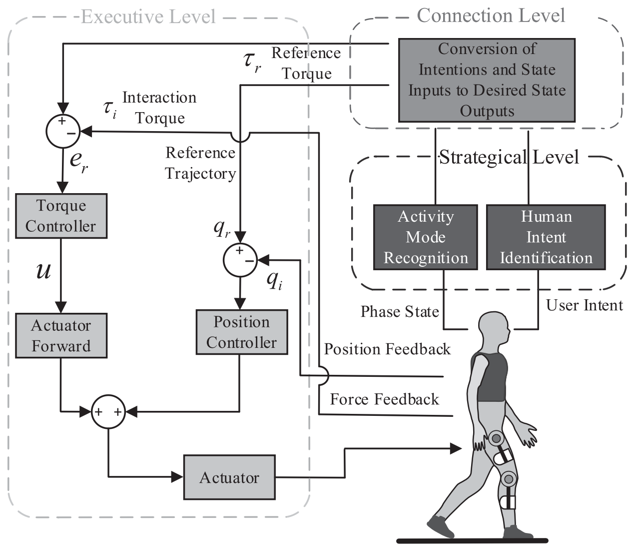


**FIGURE 2.** General control framework for LEEs.

three parts, including strategic-level, connection-level, and executive-level controllers. Executive-level controllers are the foundation of strategic-level controllers. The connection-level controller links the strategic- and executive-level controllers.

### *A. STRATEGIC-LEVEL CONTROLLER*

Strategic-level control, or task-level control, is developed based on the type of movement tasks to be implemented. Strategic-level controllers play an important role in locomotive task generation for SCI users. Locomotive tasks generally include sit-to-stand, stand-to-sit, level walking, stairs descent, stairs ascent, ramp descent, and ramp ascent [39]. An intuitive approach to developing strategic-level controllers is to employ different control methods in different gait patterns. A finite-state machine (FSM) is a commonly used strategic-level controller to detect a user's intent and design locomotive tasks. To this end, gait patterns are first recognized by FSM based on the terrain features and ground contact condition (gait phase). Second, different control methods are allocated according to different gait patterns. FSM has been widely used as a strategical-level controller in LEEs due to its applicability and reliability.

### *B. CONNECTION-LEVEL CONTROLLER*

The connection-level controller undertakes a bridge between strategic- and executive-level controllers. Connection-level controllers are employed to translate the command from the strategic-level controller and deliver it to the executive-level controller [40]. Specifically, connection-level controllers enable to translation of the user's motion intentions and locomotive tasks to a specific position or torque profile for executive-level controllers to implement [22]. At this level, the desired state of robotics or users within a gait cycle is determined and control law is applied. It may have the form of a position/velocity, torque, impedance, or admittance controller. Once the state is determined, then it will be passed to the executive-level controller to compute the error between the desired state and the current state. The error is expected to be reduced by low-level controllers. This reduction can be achieved through feedforward or feedback control, and typically relates to the kinematic and kinetic model of robotics.

### *C. EXECUTIVE-LEVEL CONTROLLER*

Executive-level controllers are the foundation of strategic-level and connection-level controllers. Position control and torque control are usually employed as executive-level controllers [40].

Position control is defined as the motion of the user that can be guided by a predefined trajectory. Under this control, assistive robots are needed to guide the subject's motion trajectory to follow a specified profile [41]. Position control has high kinematic accuracy and guarantees the user's safety when interacting with the external environment [42], and it is particularly suitable for SCI patients with severe injury levels whose motion and sensory abilities are completely lost [42], [43]. Nevertheless, position control does not allow interaction with robotics and is not suitable for versatile rehabilitation tasks [43].

Due to the easy implementation and high robustness, position control is widely used for executive-level controllers. However, it has narrow applicability and a low level of human–exoskeleton interaction [20]. Torque control can fill this gap [44]. Torque control enables users to move naturally and ensures the accurate tracking of torque profiles designed for LEEs. Under torque control, the interaction torque can be adjusted automatically based on the different types of tasks [45]. Owing to the high reliability, controllability, and applicability of torque controllers, it has a high potential of being applied to energy-saving exoskeletons [46], [47]. Moreover, a torque control method is particularly suitable for series elastic actuators' control [48].

## IV. CLASSIFICATION OF LEE PROTOTYPES FOR PEOPLE WITH SCI

The review methods are illustrated as follows. Articles are screened and selected for this comprehensive review based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) (see Fig. 3). Web of Science, Scopus, IEEE Xplore, and PubMed with the following search items are used to collect the literature on LEEs for people in SCI. Item 1 = ((Lower Body) OR (Lower Extremity) OR (Lower Extremity) OR Hip OR Leg OR Knee OR Ankle) AND Item 2 = (Exoskeleton OR Exosuit OR Orthos∗ OR (Power∗ Robot∗) OR (Rehabilitation Robot∗) OR (Active Robot∗) OR (Wearable Robot∗) OR (Lightweight Robot∗) OR (Portable Robot∗) OR (Assistive Robot∗) AND Item 3 = (SCI) OR (SCI) AND Item 4= (clinical∗ OR pilot) AND Item 5 = (walk∗ OR gait)). Fig. 3 shows that the number of papers in this area has grown exponentially over the past five years.

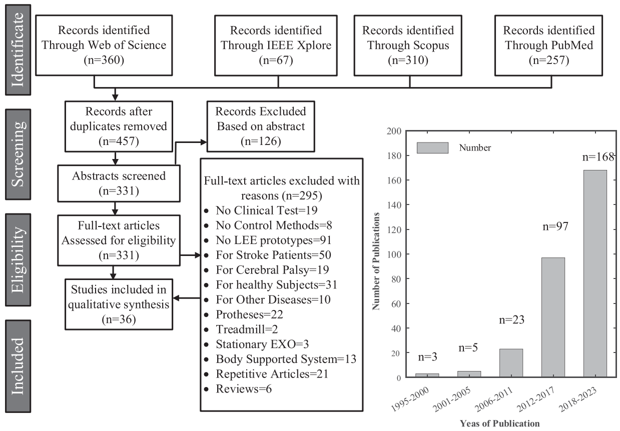


**FIGURE 3. Eligible publications screening based on PRISMA.**

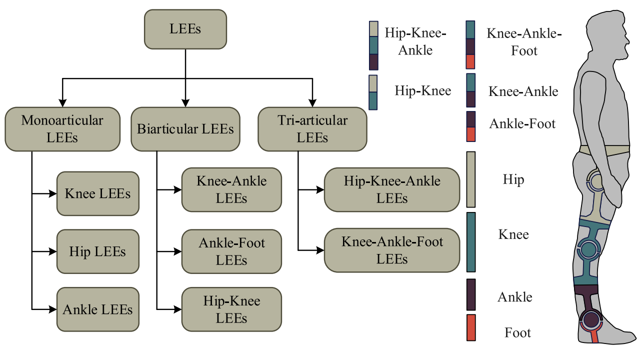


**FIGURE 4. Classification of LEE prototypes.**

Based on the number of joint actuators, LEEs can be categorized generally as monoarticular, biarticular, and triarticular (see Fig. 4). A total of 36 eligible publications include 11 triarticular LEEs, 18 are biarticular, and only 5 are monoarticular. Available information, including the structural design, control methods, and clinical assessment, is described in Table 1. In terms of structural design, some important properties, including actuation joints, active degrees of freedom, device name, and weight of selected LEE prototypes, were presented. As for control methods, strategic-level, connection-level, and executive-level controllers were delivered. In terms of clinical assessment, accessible information, including the age band of recruited subjects, type of SCI, AIS injury level, and clinical outcomes, were introduced. Furthermore, some representative LLEs were selected to present their detailed information as complementary, including but not limited to actuators, power supply, robot sensors, robot assistive components, control electronics, electronic power, and real-time communication, as described in Tables 2 and 3. Unfortunately, although related information about LEEs was searched as comprehensively as possible, some information was still not available.

### A. MONOARTICULAR LEES FOR PEOPLE WITH SCI

According to Table 1, five monoarticular LEEs were developed for people in SCI, of which one was a hip exoskeleton, two were knee exoskeletons, and two were ankle exoskeletons. Table 1 describes the accessible details of monoarticular LEEs in structural design, drive form, control methods, and clinical assessment. As seen in the table, all of them had two active degrees of freedom, of which two were driven by linear actuators [49], [50], and three were driven by BLDC [51], [52], [53]. Most of these exoskeletons supported patients with AIS levels from A to D, and only one of them was suitable for AIS T11 [49], [50], [51], [52], [53]. These exoskeletons were suitable for people with complete or incomplete SCI type [49], [50], [51], [52], [53]. As for control methods, FSM, iterative learning control, and model-based dynamic control were utilized as strategic-level controllers across the various LEEs. Position control and torque control were the most common executive-level controllers among these exoskeletons.

### B. BIARTICULAR LEES FOR PEOPLE WITH SCI

It was shown that the biarticular and triarticular LEEs were much more attractive than the monoarticular ones for SCI patients. Moreover, HK LEEs were the most popular among patients with lower extremity motor disorders. It was reported that 18 biarticular LEEs were designed for SCI patients, of which 15 were HK, 2 were KA, and 1 was AF. Table 1 reported that the exoskeleton is driven by at least two active degrees of freedom and up to four active degrees of freedom. The heaviest biarticular LEE was 28 kg [54], and the lightest one was less than 8 kg [48]. In terms of electric actuators, only 3 of these LEEs were actuated by servomotors, 14 had employed BLDC as their actuators, 1 used a series elastic actuator, and 1 used an air pump as their actuator. As for clinical subjects, SCI subjects recruited were between 30 and 64 years old. As for SCI types, only seven groups of subjects enrolled in clinical studies of these exoskeletons had complete SCI, while the rest of the subjects had incomplete SCI. In terms of control architecture, NN-based iterative learning control, FSM, phase-sequence control, optimal control, voluntary motion control, trajectory adaptation control, and buttressed Kalman filter-based control were utilized as strategic-level controllers across the various LEEs [55], [56], [57], [58]. Position control was the most popular executive-level controller among these exoskeletons.

### C. TRIARTICULAR LEES FOR PEOPLE WITH SCI

Table 1 presented 11 available triarticular LEEs for SCI patients, 3 of which were KAF, and 8 of which were HKA. These exoskeletons were reported that they have a minimum of 4 and a maximum of 6 active degrees of freedom, of which 11 were driven by BLDC motors, and 2 were driven by servomotors. SCI patients with AIS levels A–D, T4, and T6–T12 had been recruited for clinical experiments across different exoskeletons. These exoskeletons were adequate for use by complete or incomplete SCI individuals. In terms of control architecture, FSMs, dynamic movement primitives-based control, and

**TABLE 1.** Characteristics of LEE Prototypes

| Reference | | | Structural Design | | | Drive form | Clinical Assessment | | | Control method | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ref | C-EXO | Device Name | Joint | DoF | Mass | Electric Actuator | Age Band | SCI Type | AIS Levels | SL | CL | EL |
| [61] | N | Hybrid Exo | HK | 2 | NS | BLDC/ SM | 51 | C | T11 | ILC | NS | PC |
| [53] | N | RATE | H | 2 | NS | BLDC | 16-53 | I | C D | NS | NS | PC |
| [62, 63] | N | CUHK-EXO | HK | 4 | 22 kg | BLDC | NS | C | T6 | FSM | NS | PC (PD) |
| [64] | N | Angel Legs | HK | 4 | < 8kg | BLDC | 11 | I | NS | VMC | NS | TC |
| [65] | Y | EKSO Bionics | HK | 4 | NS | BLDC | > 4 | C | A | VMC | NS | NS |
| [66] | N | WBC | KA | 4 | / | GP | 30 | C | A | NS | NS | TC |
| [67] | N | HNP | AF | 2 | 7.9kg | HD | 54-59 | C | A B C | FSM | NS | PC |
| [68] | N | VariLeg | HKA | 6 | 35kg | BLDC | 40-57 | C | A B | TAC | NS | PC |
| [69] | N | NaTUre-gaits | HKA | 6 | NS | BLDC | 66 | I | C5 | NS | NS | PC |
| [70, 71] | N | Kinesis | KAF | 4 | NS | BLDC | 35-43 | I | A D | FSM | AC | HSC |
| [72] | N | HKAFO | HKA | 6 | NS | BLDC | 28-48 | C | T6 to L2 | NS | NS | PC |
| [51] | N | T-ExoD | A | 2 | NS | LA | 18-60 | C/I | A B C | NS | NS | PC |
| [73] | N | LOPES | HK | 4 | NS | BLDC | 31-63 | I | B C D | NS | IC | NS |
| [74] | N | HAL | HK | 4 | NS | DC/SM | 47 | I | T6 T7 | NS | NS | PC |
| [75] | N | KAFO | KA | 4 | NS | BLDC | 40 | I | B/T10 | TAC | NS | PC |
| [76] | N | AIDER | HKA | 4 | NS | BLDC/SM | NS | NS | T9-T12 | MDC | NS | PC |
| [77] | N | WPAL | HKA | 6 | 9kg | BLDC/ SM | 30-59 | C | T6-T12 | PSC | NS | PC |
| [78] | N | HAL-3 | HK | 4 | 15kg | BLDC | 70 | I | C, T6 | PSC | NS | PC |
| [54] | N | ABLE | K | 2 | 2.3kg | BLDC | 41 | I | T11 | SDSMC | NS | PC |
| [52] | N | AchiLEEs | A | 2 | NS | LA | 18-75 | I | C D | ILC | NS | TC |
| [79] | N | KAFOs | KAF | 6 | 3.5kg | BLDC | 42 | C | A | FSM | NS | TAC |
| [80] | N | PAM | HK | 4 | NS | BLDC | 23-61 | I | C D | FSM | ZC | PC |
| [56] | N | MindWalker | HK | 4 | 28kg | BLDC/SM | 15-37 | CS | T7-T12 | NS | IC | TC |
| [81] | N | GLLE | HK | 4 | 12.8kg | BLDC | NS | N/A | NA | NA | N/A | PC |
| [82] | Y | NaTUre-Gaits | HKA | 6 | NS | BLDC | 64 | IS | NS | SAC | NS | PC |
| [83] | Y | LOPES II | HK | 4 | NS | BLDC | NS | C | C1 | TAC | NS | TC |
| [55] | N | FES EXO | K | 2 | NS | BLDC | 30 | C | A | MDC | NS | TC |
| [84] | Y | Lokomat | HK | 4 | NS | BLDC | 31-64 | I/C | A B C D | NS | IC | PC |
| [85] | Y | Lokomat | HK | 4 | 8kg | BLDC | NS | I | D | TAC | NS | PC |
| [86] | Y | Ekso GT | HK | 4 | NS | BLDC | NS | I | T8-L2 | BKFC | NS | PC |
| [87] | Y | Lokomat | HK | 4 | NS | BLDC | 35days | NS | NS | TAC | IC | PC |
| [88] | N | HAL | HKA | 6 | NS | BLDC | NS | C | A | FSM | NS | PC |
| [89] | N | ReWalk | HKA | 6 | NS | BLDC | 22-51 | C | A /T4 | NS | NS | PC |
| [90] | N | KAFOs | KAF | 4 | 3.16kg | BLDC | 38-51 | C | A B | NS | NS | PC |

C- EXO-Commercial Exoskeleton; DoF- Degree of Freedom; SL- Strategic-level controller; CL- Connection-level controller; EL- Executive-level controller; Y- Yes; N- No; HK- Hip-Knee; H- Hip; KA- Knee-Ankle; AF- Ankle-Foot; HKA- Hip-Knee-Ankle; KAF- Knee-Ankle-Foot; A- Ankle; BLDC- Brushless Direct Current motor; GP- Gas Powered; LA- Linear Actuation; SM- Servo Motors; I- Incomplete SCI ; C- Complete SCI; ILC- Iterative Learning Control; FSM- Finite State Machine; VMC- Voluntary Motion Control; FSM- Finite State Machine; TAC- Trajectory Adaptation Control; MDC- Model-based Dynamic Control; PSC- Phase Sequence control; SDSMC- Swing Detection State Machine Control; SAC- Speed Adaptation Control; BKFC- Buttressed Kalman Filter-based Control; AC- Admittance Control; IC- Impedance Control; ZC- Zero-force Control; PC- Position Control; TC-Torque Control; PID- Proportional-integral-derivative; PI-proportional-integral; PD- proportional-derivative; HSC- Hierarchical State Control; NS- Not Specific; N/A- Not Applicable.

**TABLE 2.** Actuator Details of Joint-Based LEE Prototypes

| Ref | LEE Type | Actuated Joint | Motor Company | Motor Type | Voltage | Power Output | Gear Ratio | Gear type | Continuous Torque | Instantaneous Torque | Active DOF | Total Mass | Size Adjustable |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| [54] | MA | K | Maxon | BLDC | 24 V | 70 W | 160:1 | HD | 20.5 N.m | 60 N.m | 2 | 2.3 kg | Yes |
| [52] | MA | A | Maxon | BLDC | 24 V | 100 W | NS | BS | 32 N.m | NS N.m | 2 | 3 kg | Yes |
| [61] | BA | HK | Harmonic/ Maxon | Servomotor/ BLDC | NS | NS W | 100:1 | HD | 30 N.m/ 80 N.m | NS | 2 | NS | Yes |
| [61] | BA | HK | Maxon | BLDC | 24 V | 70 W | NS | N/A | 14.2 N.m | 35.5 N.m | 4 | 8 kg | No |
| [61] | BA | HK | Maxon | Brushed DC | 24 V | 150 W | 113:1/ 91:1 | Maxon | 25.9 Nm/ 20.8 N.m | 52/42 N.m | 4 | 22 kg | Yes |
| [68] | TA | HKA | Maxon | BLDC | 24 V | 90 W | 160:1 | HD | 89.6 N.m | NS | 6 | 35 kg | No |
| [56] | TA | HKA | Hacker | BLDC | 38 V | 1000 W | NS | BS | 100 N.m | NS | 4 | 28 kg | No |
| [71] | TA | AKF | Maxon | BLDC | 24 V | 90 W | 100:1 | HD | NS | NS | 4 | NS | Yes |

HD- Harmonic Drive; MA- Monoarticular, BA- Biarticular; TA- Tri-articular; BS- Ball-Screw.

**TABLE 3. Hardware Details of Joint-Based LEE Prototypes**

| Ref | Device Name | Strategic-level Controller | Sensors for Strategic-level | Connection-level Controller | Executive-level Controller | Sensor Type for Executive-level | Control Electronics | Real-time Communication | Power Supply |
|---|---|---|---|---|---|---|---|---|---|
| [54] | ABLE | SDSMC | IMU | NS | PID PC | Encoder | ATmega 328 | WiFi | LPB |
| [52] | AchiLEEs | AO | FSR | PI TC | PI SC | Encoder | PC | EC | LPB |
| [61] | Hybrid -EXO | ILC | FSR | NS | PC | Encoder | RTM | NS | NS |
| [61] | Angel-suit | VMC | IMU | NS | PID TC | Encoder | NI sbRIO-9651 | I2C | LPB |
| [61] | CUHK-EXO | FSM | F/I | NS | PD TC | NS | PC/Arduino | UART | LPB |
| [68] | VariLeg | TAC | FSR | NS | PID PC | Encoders | PC/STM 32 | CAN | LPB |
| [56] | MindWalker | FSM | IMU | IC | PC | Encoders | PC | EC | Battery |
| [71] | Kinesis | FSM | F/G | ILC | AC | Encoder | PC | NS | NS |

LPB- Lithium Polymer Battery; EC- EtherCAT; F/G- FSR/Gauge ; F/I- FSR/IMU.

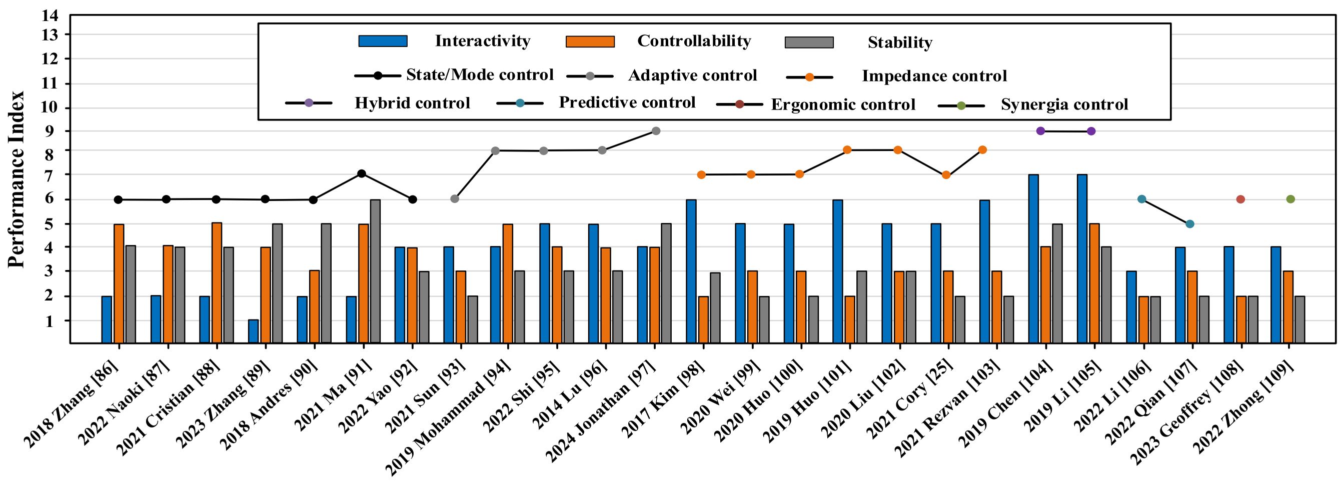


**FIGURE 5.** **Performance comparison of exoskeleton control methods [25], [86], [87], [88], [89], [90], [91], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103], [104], [105], [106], [107], [108], [109].**

phase-sequence control were employed as strategic-level controllers across different exoskeletons. Position control was commonly used as an executive-level controller among tri-articular exoskeletons [50], [52], [63], [64], [65], [66], [67], [71], [72], [74], [77], [83], [84], [85], [130].

Other than these functional differences, there are several fundamental quantitative indicators for comparing these exoskeleton devices. Indicators include the degrees of freedom of the device, load capacity, commercial price, prototype weight, and the number of static sitting locking positions completed by the prototype. Fig. 5 and Fig. 6 show the comparison of exoskeleton control strategies. Fig. 7 shows the comparison of representative prototype features under each key indicator.

### *D. CONTROL STRATEGIES ANALYSIS*

To facilitate readers rapidly and systematically obtain the technical implementation with respect to the actuation, control, and assessment of LEEs, Table 1 summarizes and compares different prototypes. To help readers get an in-depth understanding of the LEEs' control strategies, this article adopts quantitative indicators with respect to interaction (how well the LEE interacts with users), security (how safe the control signal can be extracted from users), and efficiency (how much the useful control information can be utilized) for various LEE control strategies. Each quantitative indicator is set from low to high based on fuzzy rules, and it provides a new way to evaluate LEE performances.

As shown in Fig. 5, the most widespread LEE control strategies are state/mode control and impedance control. Also, from Fig. 6, we can conclude that the merits of employing the biomedical signal that contains the users' voluntary motion have progressively become dominant. No matter what signals these control methods use (biological or mechanical signals), they highly depend on gait recognition. Based on the comprehensive gait information, the controller can realize corresponding outputs based on the different gait phase dynamics and achieve better control performance via a simple paradigm. Hence, gait recognition plays an important role in improving the control performance of the FSM. In conclusion, with the development of control strategies, the widespread methods (FSM control) and the evolutionary methods (voluntary motion control, adaptive control, impedance control, admittance control, and dynamic control) could all reach the expectations for various LEE movements providing that they are particularly designed for specific applications.

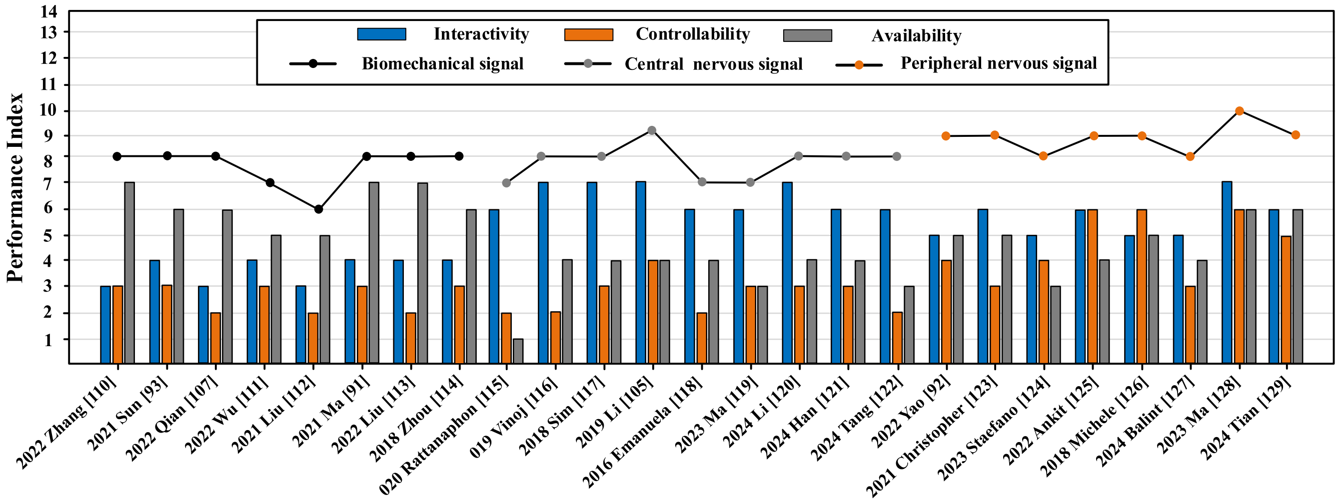


**FIGURE 6.** Performance comparison of exoskeleton control input signals [91], [92], [93], [105], [107], [110], [111], [112], [113], [114], [115], [116], [117], [118], [119], [120], [121], [122], [123], [124], [125], [126], [127], [128], [129].

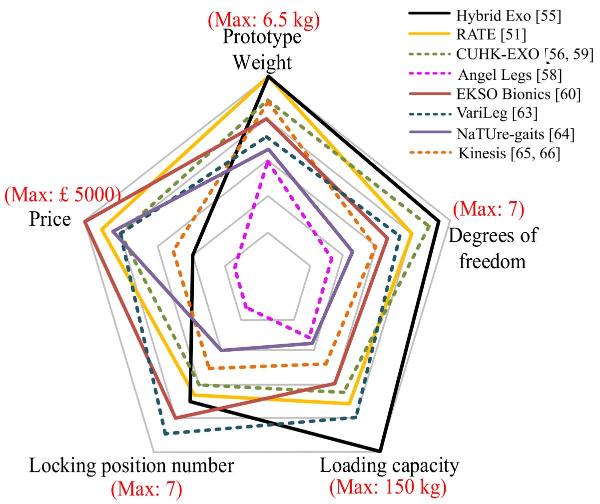


**FIGURE 7.** Performance comparison of exoskeleton prototypes.

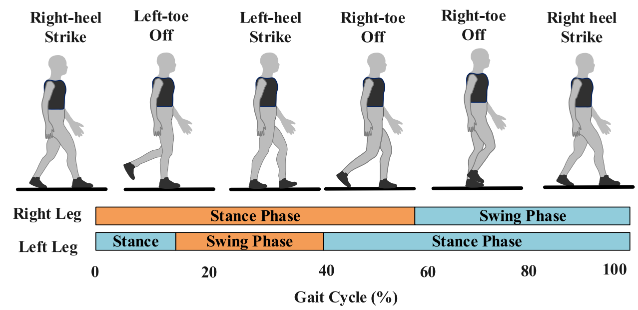


**FIGURE 8.** Lower extremity biomechanics over a walking stride.

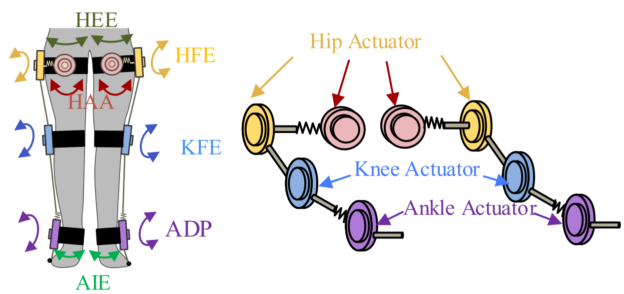


**FIGURE 9.** Degrees of freedom distribution of LEEs. Hip Endorotation/Hip Abduction/Adduction; HFE; KFE; ADP; and AIE.

## V. DISCUSSION

### A. POWERED LEES

In the actual design of LEEs, the placement of actuators should be considered carefully based on the practical use. Healthy hip and knee joints can certainly provide both power generation and power release for human activities, especially for locomotion tasks. Fig. 8 depicts the lower extremity biomechanics over a walking stride. As shown in Fig. 9, for level-walking assistance, actuators are usually placed on hip flexion/extension (HFE) and knee flexion/extension (KFE), which are important for wearers to implement a normal gait. Ankle dorsi/plantar flexion (ADP) actuation can be added to achieve high maneuverability and improved balance ability.

Active actuation at LEE hip joint capable of power generation and power release in different joint locations would better replicate the biomechanics' characteristics of the corresponding healthy joints [51], [55], [56], [59], [62]. Even though the previous declaration is accepted by most readers, it still deserves to be discussed in depth regarding how power provided in different joints could significantly improve locomotion ability and what approaches are essential to implement power propulsion for LEEs. For the hip joint, the primary deficiency of a hip-passive LEE is the lack of powered propulsion in the late stance phase. Powered propulsion has been demonstrated to do the following:

1) provide constant power for mobility;
2) ensure the initial propulsive power for the swing phase;

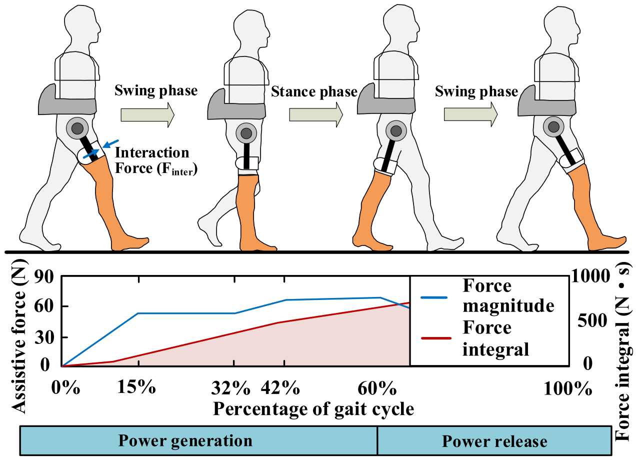


**FIGURE 10.** Hip biomechanics with exoskeleton assistance.

3) avoid the fast collision and consequent energy loss during the heel strike phase [65], [66], [67].

As shown in Fig. 10, providing power for a hip exoskeleton allows it to achieve long-distance mobility, upgrade swing phase dynamics, and eliminate impact on the lower limb. Apart from these, powered generation at the hip joint also has some significant and overlooked benefits. Chief among them is the capability of adapting hip to uneven terrains and complicated scenarios. As mentioned in [131], such adaptation needs both the characteristic of stiffness variation (e.g., [132]) and equilibrium maintenance (e.g., [52]) of the hip joint. Even though these characteristics can be implemented without a power supply at the hip joint for the structured environment, the typical approach to stiffness variation and equilibrium maintenance requires power generation, as is shown by the healthy hip during level walking [133].

Apart from the power generation, power release is also necessary to relocate the hip joint during the stance and swing phases in level walking and, to a great extent, during running and stair ascent and descent [134]. In the case of stairs ascent and descent, power release facilitates the subsequent energy transfer from the swing phase to the stance phase, allowing the user to descend stairs as usual. Primary power release occurs instantly after the heel strike during the ankle transits from a plantarflexed state to a dorsiflexed state [135]. To this end, the ankle must start to move with a plantarflexed state and then be positioned quickly during the swing phase, which generally requires power release at the ankle joint. Hence, power release should be in preparation in advance. Moreover, extra power is needed to reject disturbances, such as random shock during the swing phase. In that case, specifically at the beginning of the swing phase, the healthy ankle usually implements active dorsiflexion to reject the unexpected disturbance. This type of implementation should be an active (i.e., powered) motion [136]. Ultimately, an impaired ankle is required to retrieve healthy functionality during multiple training tasks, not just in basic activities, such as level walking, running, and stairs ascent, and other recreational activities should be included, such as dancing, skating, and skiing. Theoretically, a dysfunctional hip joint would restore voluntary motion functionality, which is only possible with a powered exoskeleton.

For the knee joint, the powered exoskeleton provides a few advantages for both the stance and swing phases [135]. As shown in Fig. 11(b), a powered knee exoskeleton would enable KFE, which allows the restoration of healthy knee joint function for sit-to-stand and stand-to-sit, besides stair ascent and descent actions. Generally speaking, a powered knee exoskeleton can more easily replicate the inherent functionality of the knee joint in loading activities, such as the KFE and subsequent stance phase in level-walking activity. This functionality significantly eliminates peak impact during heel strikes, reduces the risk of slipping, and weakens the horizontal skew of the center of body mass during locomotion.

Even if mostly the knee inertially moves with the pushing forward of the ankle or the acceleration of the thigh (e.g., the swing phase), several knee movements occur during stair ascent, slope descent, turning back, and obstacle crossing [135]. Furthermore, disturbance rejection or stumble correction actions, particularly during the early swing phase, urgently need active power at the knee joint [136]. In summary, as with the knee, active power is essential for the restoration of healthy functionality in various activities, not just basic mobility activities, such as amusement and leisure sports. Theoretically, the knee joint would implement voluntary motion as expected, which is only possible with a powered knee exoskeleton.

As shown in Fig. 11(a), to realize a tradeoff between maneuverability and lightweight design, Hip Abduction/Adduction (Haa) and ankle reversion/eversion (AIE) are usually designed as passive actuated via compliant mechanical components, such as springs or cables, to achieve a comfortable and lightweight design. Even though passive design can reduce the size and inertia of the whole exoskeleton, it also decreases maneuverability, introduces motion uncertainties, and increases control difficulties. Actuators are always accompanied by a bulky size and extra energy consumption. A neutral solution is to introduce an underactuated mechanism, which can use a minimal actuation source to drive multiple joint movements. Multiple mechanisms can be applied for underactuated design, such as crank-link and double crank mechanisms. However, this design will damage the back drivability of exoskeleton systems and lower the energy transmission efficiency due to the existence of dead points and self-locking zones. The motor and the gear ratio should be selected based on a series of factors, such as torque–velocity characteristics. For instance, in sit-to-stand, stand-to-sit, stairs descent, and stair ascent, high torque and low speed are needed. High-power-density motors with a high gear ratio should be selected. For level walking and ramp descent, a high speed and a small torque are needed. High-power-density motors with a low gear ratio should be considered. Apart from the speed and torque consideration, other factors, such as acceleration, running current, and start–stop characteristics, should be also concerned. The acceleration variation directly affects users' sense of impact. A high running

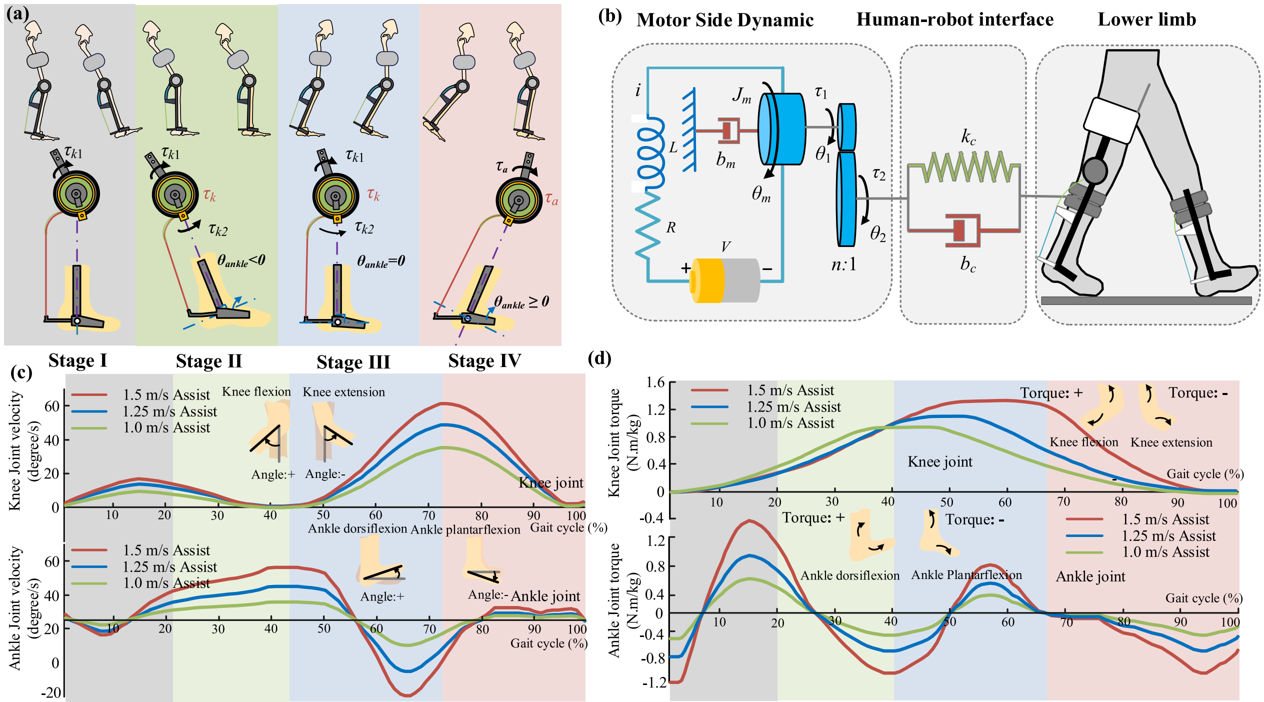


**FIGURE 11. Desired characteristics of next-generation LLEs covering three aspects: operation capability manufacturing and maintenance, as well as human–robot interaction.**

current will increase energy consumption and reduce the battery life. Unstable start–stop characteristics will bring noise and decrease motor efficiency. Multiple motor topologies [137], [138], [139], [140], [141], [142], [143], [144], [145], [146], [147], [148], [149] can be considered for LEE application in improving energy efficiency and stabilizing torque output.

Recent advances have been achieved in the prototyping and development of powered exoskeletons [50], [52], [62], [63], [64], [65], [66], [67], [71], [72], [74], [77], [83], [84], [85], [130], even though many progressive works are needed to fill the gap and fulfill the potential of powered iron man-like exoskeletons. The dynamic range of output impedance of human muscle significantly mismatched that of exoskeleton actuation, especially at the low-impedance range. Additionally, how to match the torque and power output as biological joints while reaching the range of their movements and output impedances needs to be considered in the future [18]. Although powered exoskeletons show inspiring performances on some gait restoration indicators (e.g., gait symmetry, walking distance, and metabolic cost), test results are still far away from that of healthy subjects, as in the case of EKSO bionics [60]. Besides, portability and quietness are also essential considerations for the development and prototyping of powered exoskeletons, which must provide satisfactory assistance in slimness and noise suppression. Due to these considerations, the most acceptable actuation approaches are the electric ones for the controllability and efficiency of electrical motors, especially if integrated with compliant elements, such as torsional springs [150]. Actuators fabricated by soft

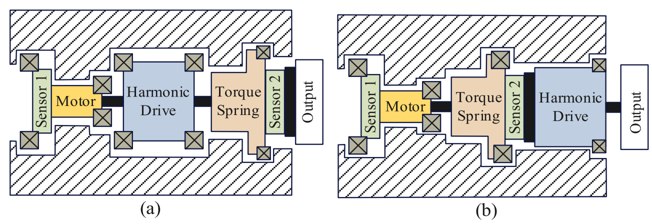


**FIGURE 12. Two configurations of LEE actuators. (a) Spring back configuration. (a) Spring front configuration.**

materials are not considered for prototyping LEE since they will introduce inherent hysteresis and low stiffness [151], [152]. A torque spring will usually be installed inside the actuator to provide the accurate torque sensing and safe interaction. The configuration of the torque spring significantly affects the characteristics of actuators. Currently, most actuators have adopted the configuration, as shown in Fig. 12(a). This configuration leads to a high back drivability but also brings a large sensing noise. The torque bandwidth is limited because the output inertia is low. The actuator in Fig. 12(b) enhances the output torque bandwidth by increasing the output inertia. The sensing accuracy can be improved although the back drivability will be influenced. The configuration in Fig. 12(a) is more suitable for actuators that have no high-frequency force input and need to be driven reversely. The configuration in Fig. 12(b) is more applicable to those actuators that have a high-frequency input and do not need to be driven reversely. Substantial achievements in the field of

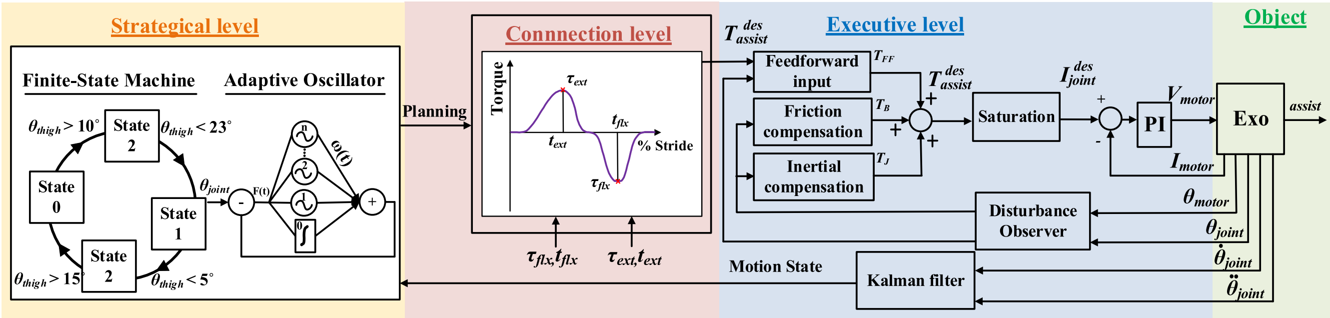


**FIGURE 13.** Hip exoskeleton control architecture, highlighting the different control levels from high-level to low-level motor control.

powered exoskeletons would contribute to the development of wearable devices capable of restoring not only voluntary motions but also the complicated locomotion patterns required for accomplishing fundamental and recreational sports and tasks for disabled people with SCI, allowing them to retrieve independence and health.

### *B. CONTROL STRATEGIES*

Existing LEEs usually adopt embedded sensors (e.g., inertial sensors, angular encoders, and force sensors) to recognize wearers' intentions and implement a control [56], [59]. This type of control has a primary weakness in not directly including users in the control loop, and this leads to troubles in implementing complex activities due to the absence of both psychological fatigue and active energy supplements [153]. Even though several luxurious exoskeletons (i.e., EK-SONR by EKSO Bionics ) offer a relatively good adaptation to various terrains and tasks, transition among them is mainly by manual operation. Accordingly, smooth switching is generally impossible and hardly implemented by the active operation of users. Unsatisfactory controllability of the LEEs harms the user's experience, lowering the acceptability of assistive robotics and, as a result, causing disuse of the device [154]. The absence of controllability, bad wearability, and poor usability are the leading causes of exoskeleton abandonment [155]. To reduce abandonment of the exoskeleton, it is, therefore, essential to design high-performance and reliable control algorithms that can provide a smooth transition in different gait phases as well as a good adaptation to different terrains and locomotion tasks for users.

Voluntary motion control can increase the user's sense of initiative and ownership. With such a control scheme, the disabled limb directly interacts with the exoskeleton to implement an operation. This scheme can be achieved by means of either manual switches or intent identification algorithms [156]. Electromyography (EMG) is commonly used for volitional control of LEEs [157]. This scheme heavily relies on the residual sensory function level of the wearers, leading to a cognitive burden and hysteretic operation. It is, thus, necessary to develop more automated strategies. Automated control schemes for powered assistive robotics can be divided into three levels: strategical level, connection level, and executive level, as stated in Fig. 13.

*1) In terms of control strategies,* designing a reliable and an efficient control strategy is considerably difficult because of the diversity of the locomotion activities, which consist of some distinct gait tasks (e.g., stairs-to-ramp variation and sit-to-stand transition) [158]. Several principles ought to be considered.

a) *The types of training tasks to perform*: Multiple locomotion tasks improve efficiency and decrease complexity.
b) *Implementing scheme*: It determines the level of cognitive fatigue and training duration.
c) *Control signals*: They impact the complexity of the control algorithm and the amount of available information.
d) *Response time*: It includes the mechatronic response time of the human–exoskeleton system and the implementation time of the command.

A central problem in LEE control is the transition from one state to another. Due to the inconsistency of kinematic and dynamic parameters between two adjacent states, a smooth transition is hard to realize. One solution is to let the speed and acceleration of the last state decrease to zero [52], [54], [56], [59], [72], [73], but it will cause extra energy consumption. The frequent brake may harm users' enthusiasm for a long-term task. Moreover, this state transition way needs users to have a lot of experience in manipulating exoskeletons, but most of the elderly users are not familiar with the manipulation way. Pretraining should be arranged for them, but this will greatly extend the recovery period.

Another issue is reference trajectory tracking. Most of the trajectory tracking is completed within a strategical level based on the dynamic model compensation or learning method [159], [160]. Since the accurate dynamic model is hard to establish due to the variable parameters, it has low tracking robustness when disturbance exists. Learning methods rely on prior and current data or images [161], [162] and cause a high burden on hardware. The learning method has a bad performance when transferred from one trajectory to another, even though it did not rely on the dynamic model. All control methods should accommodate users' features, such as joint stiffness. Besides, the distinctive friction between wearers and exoskeletons also affects the accuracy of trajectory

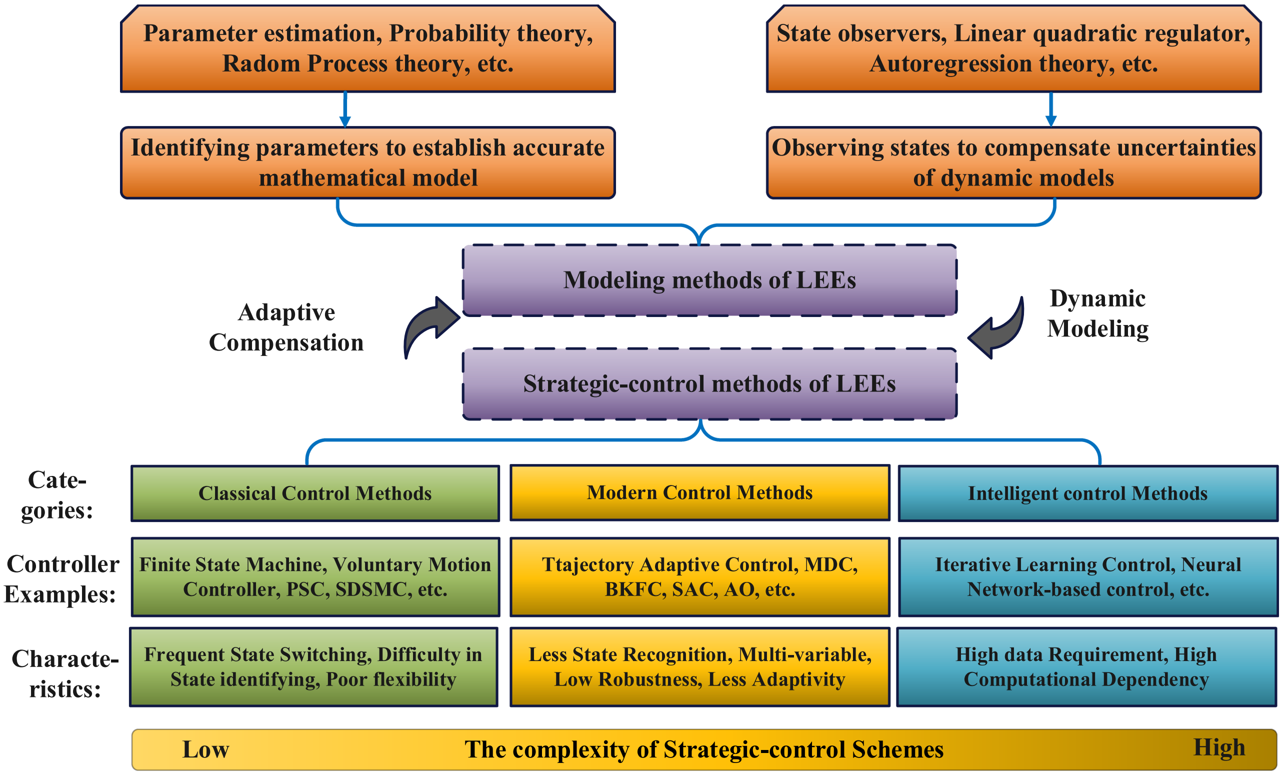


**FIGURE 14.** Main methods and characteristics of strategic control of LEEs.

tracking. To overcome the problems of computation burden and environmental uncertainties, an ideal solution is to combine the dynamic model with the learning method. A prior dynamic model is used as feedforward input to guide the end actuator to an approximate position, and leaning algorithms are used to adjust the position to be accurate and adapt to the environment's stiffness. Therefore, model-based learning methods may provide a novel perspective for LEE trajectory tracking.

Transparency is important for LEE control. Transparency refers to robotics that can apply any desired actuation force as needed by users. To provide transparency, exoskeletons are expected to generate assistive torque when users need the accurate assistance and provide minimal resistance when users do not need assistance. Transparency can be achieved by mechanical design and control algorithms. Energy-storage components, such as springs, can provide a soft interaction with robotics. But this way will enlarge the size. Algorithm-based transparency, such as impedance/admittance control [100], [101], time delay control [98], and interaction force feedback control [163], [164], [165], is easy to implement but is limited by the drifting of model parameters, uncertainties of interaction conditions, and low robustness. There is a tradeoff between transparency and high precision. High transparency always accompanies bad motion precision and vice-versa.

Additional considerations include the abnormal transition of gait phases and the level of residual sensory. It is possible that the locomotion modes of an exoskeleton wearer would be suddenly changed, such as their gait parameters and translational speed, consequently disturbing the ongoing tasks and surrounding setups. For these reasons, controllers should be developed robust to variable translational speed and changeable gait parameters, such as foot elevation height and step inclinations [166]. Sensory impairment level determines the selection of the control scheme since it impacts neurological availability, muscle activation, and locomotion functionality.

Multiple motion intent recognition, gait pattern identification, and gait phase detection algorithms must be introduced. Besides, their features and distinctions should be discussed. For gait phase recognition algorithms, a gait cycle is divided into the stance phase and swing phase. Dynamic characteristics (e.g., joint stiffness and damping parameters) of the exoskeleton are regulated based on the subphase in the cycle of the gait, which is detected based on the kinematic signals (e.g., acceleration, speed, and angles). FSMs are typically used for state switching [167]. Motion intent recognition is implemented on the basis of machine learning algorithms (e.g., neural networks, pattern recognition, and probabilistic model) that detect the motion intent or identify impedance parameters by extracting information from the user's biological or kinematic signals. Deep learning, reinforcement learning, and transfer learning are commonly adopted [168], as shown in Fig. 14. Time-invariant algorithms, such as K-nearest neighbors, logistic regression, random forest, and principle component analysis, are the most popular classifiers and have been widely verified in various input conditions, such as variable input window length and varying sliding window size [168], [169]. Specifically, various recognition algorithms were evaluated on different locomotion tasks by changing the input window length and sliding window size to maximize recognition accuracy while overcoming performance degradation. To maintain its performance in realistic environments, the algorithm can be verified in a noise environment, simulating measurement error, implementing transfer learning technology, and developing robust recognition algorithms that adapt to time-invariant scenarios. For instance, a probability-based learning model is employed to decrease prediction error both across different subjects and across various terrains for a six-classification task [170]. Motion intent recognition can also leverage nonclassification algorithms, predicting the joint mechanical moment or directly adjusting exoskeleton parameters based on the dynamic variables of neuromusculoskeletal models [171]. Recognition algorithms (e.g., machine learning algorithms) depend on the intrinsic periodicity of the gait. They are suitable for predefined locomotion modes relying on the stride time and other kinematic or dynamic constraints [172]. Recognition algorithms are generally combined with kinematic (e.g., acceleration and angles) or biological signal interfaces (e.g., EMG, electroencephalography (EEG), and mechanomyography), ensuring excellent availability and high controllability, even in an unstructured environment [123], [173], [174]. Because of its outstanding performance, the pattern recognition algorithm can be expanded both for the identification of gait patterns and for the calculation of gait cycle-related features (e.g., the duration of the stance phase and swing phase). However, several weaknesses of the pattern recognition algorithm involve the collection of a large amount of training data that must include all the desired patterns, causing the preprogrammed patterns drawn up before training might be distinct across different subjects. But in most cases, the number of available subjects is limited, not supporting significant change in preprogrammed patterns [175].

Even though significant advances have been made in the development and implementation of recognition algorithms for exoskeleton control, we sometimes still need other alternatives. Although recognition results can nearly reach 95%, the shortcomings involve a wrong recognition probably causing a severe safety accident, such as subjecting falling. Severe security principles in the exoskeletons strictly request that even a 0.01% probability of risks is not acceptable. Accordingly, it is essential to develop another approach to controlling LEEs. A possible solution could be provided by a neurological interface: exoskeletons would be leveraged with close interactions with the external surroundings based on multisensor-fusion and nonstationary signal processing technologies (i.e., wavelet analysis) [176]. The neurological interfaces allow for high-performing adaptability to varying and unstructured environments, both from the perspective of terrain diversity or scenario complexity, while keeping an outstanding implementation efficiency [177]. Multisensor-fusion techniques depend on the types of multiple input signals able to improve the algorithm generalization and

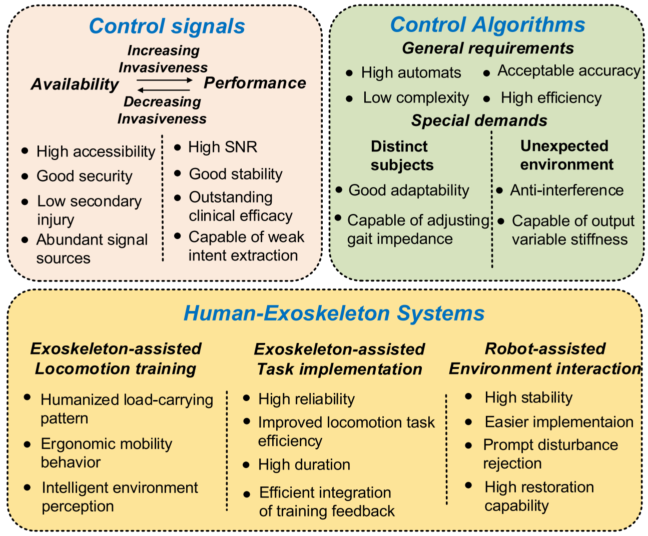


**FIGURE 15. Desired characteristics of control signals, control algorithms, and human–exoskeleton systems.**

increase recognition accuracy. Particularly, apart from the traditional signals (e.g., EMG, inertial measurement unit, and kinematics), these approaches adopt sensors able to collect environment-dependent data (i.e., Kinect [178], LeapMotion [179], LiDAR [180], [181], etc.) that are more generalized and, therefore, guarantees an undegraded performance across different subjects and an improvement in recognition accuracy. The desired characteristics of control signals, control algorithms, and human–exoskeleton systems are presented in Fig. 15.

*2) In terms of input signals,* to recognize users' motion intent, various signals can be detected through a variety of interfaces, with different levels of invasiveness. In general, they can be categorized as invasive biological interfaces (e.g., invasive EMG and invasive electroencephalograph), semi-invasive biological interfaces (e.g., semi-invasive EMG and semi-invasive electroencephalograph), and surface biological interfaces (e.g., surface EMG, surface EEG, surface mechanomyography, and noninvasive biomechanical interfaces) [47]. The last three types of interfaces are also defined as biological input-oriented signals [182].

Biomechanical interfaces or biomechanics signals adopt mechanical sensors (kinematic or dynamic [183], [184]), usually together with gait recorders regarding the biomechanics of the lower limb, that reflect the position, speed, acceleration, direction, torque, etc. [183]. The primary dominance of this type of interface is the high implementability for the exoskeleton device not requiring direct contact with subjects, guaranteeing a relatively safe interaction. However, not directly involving the user in the control loop prevents the implementation of voluntary motion control and decreases the sense of ownership, against the implement of complex tasks [157].

Biological signal interfaces can be invasive, semi-invasive, or noninvasive. Collecting the signal at the cerebral cortex level is feasible for extracting the user's motion intent and is commonly implemented by invasive electrodes or electroencephalographs [185]. However, the invasiveness of these approaches and the fact that most locomotion-oriented control loops rely on the involvement of neural activity prevents the recording of neurological signals for the control of LEEs. EEG as an alternative approach to extracting the motion intent is a typical noninvasive interface. This kind of interface has poor noise immunity and is susceptible to motion artifacts, requiring subjects to particularly concentrate on the ongoing tasks and causing a heavy burden on users. Functional near-infrared spectroscopy can also be employed for the motion intent recognition of people with impaired lower limbs (i.e., SCI patients) and could be promoted in the future.

Semi-invasive signal interfaces can be acquired through implantable EMG electrodes that record the signal of intramuscular neural activity. Semi-invasive EMG signals record the discharge sequence of muscle motor units, not recording the overall muscle activity. Hence, a specific algorithm is needed to gather information about muscular activation and the motion intent of the users. Despite the semi-invasiveness of this kind of signal, the electrode does not need repeated calibration before each trial and simplifies the procedure of the experiment. Moreover, the signal is not susceptible to movement artifacts, and the impact caused by the placement of the electrode (e.g., shifting, discomfort, ease of dropping out, and misalignment to the center of the muscle) can be removed [186]. Nevertheless, due to the semi-invasiveness and its implant-related risk, this approach is less acceptable than nonimplantable ones [186]. This approach is helpful in the elimination of the interference of redundant muscles used for applying EMG recognition technologies and helps to overcome the common disadvantages of surface EMG (e.g., ease of disconnection). The primary weaknesses of this type of approach are its invasiveness and implant-related muscle damage.

Surface EMG is a common noninvasive biological interface. Surface EMG-based control of LEEs has been widely explored [92], both independently or jointly with mechanical sensors, such as in [173]. This approach offers a voluntary control of the exoskeleton device by extracting motion intent from surface EMG recorded from the targeted muscles of the users. However, surface EMG has a poor signal-to-noise ratio due to the interference and motion artifacts, variable impedance of the skin, sweating, and electrode detachment, making this implementation more difficult [22]. Surface EMG signals have a wide subject-related variability but show a consistent feature within the same subject during the locomotion compared with invasive and semi-invasive EMG since they provide information about the intrinsic activation patterns of targeted muscles. In particular, for LEE applications, various recording sites are generally beneficial to improve the algorithm's capabilities of motion intent recognition [187]. In addition, surface EMG signals can be also utilized individually or combined with biomechanical sensors (e.g., inertial measurement unit and angular sensors) leveraging the motion intent recognition algorithms for sensor-fusion control schemes. Sensor fusion provides an effective approach to enhancing the generalization and accuracy of control algorithms, but a simplified hardware configuration is needed. The desired characteristics of the next-generation human–robot interface are shown in Fig. 16.

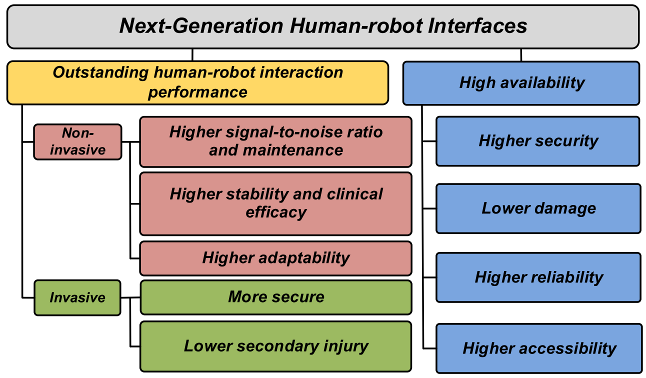


**FIGURE 16. Desired characteristics of next-generation human–robot interfaces.**

### C. CLINICAL ASSESSMENT

For SCI patients, clinical effects can be judged by the motor function recovery index and sensory function recovery index. The recruited subjects should range from AIS A to AIS D. Severe SCI patients can be recruited to investigate the exoskeleton efficacy on both motor function recovery and sensory function recovery [53], [74], [83]. Partly impaired patients with spared sensory or motor function can be used to verify the single efficacy of exoskeletons on motor or sensory recovery [49], [62], [68]. In general, the period with severe SCI injury may be longer than in partial injury patients; sensory functions are harder to recover than motor functions. So, early to receive therapy is beneficial for patients to judge the rehabilitation aim.

Rehabilitation assessment is a significant approach to quantitatively demonstrating the rehabilitation effect and acts as an important part of a training paradigm [187]. Effective rehabilitation assessment offers guidance for assisting therapists in making up customized training strategies for patients, accelerating the recovery of motor function [187]. Clinically, the 6-min walk distance (6MWD) evaluation [188] and Fugl–Meyer low-limb subscale (FMA-LE) assessment [189] are typical indicators and approaches to evaluating the rehabilitation effect for SCI patients. The 6MWD refers to the time it takes for the subject to walk for 6 min. This type of process not only requires the cooperation of different therapists and various physicians but also occupies a great area of space. The classical 6MWD approach takes up large resources of the hospital, decreasing the efficiency of other patients' recovery. For the FMA-LE methods, the patients are

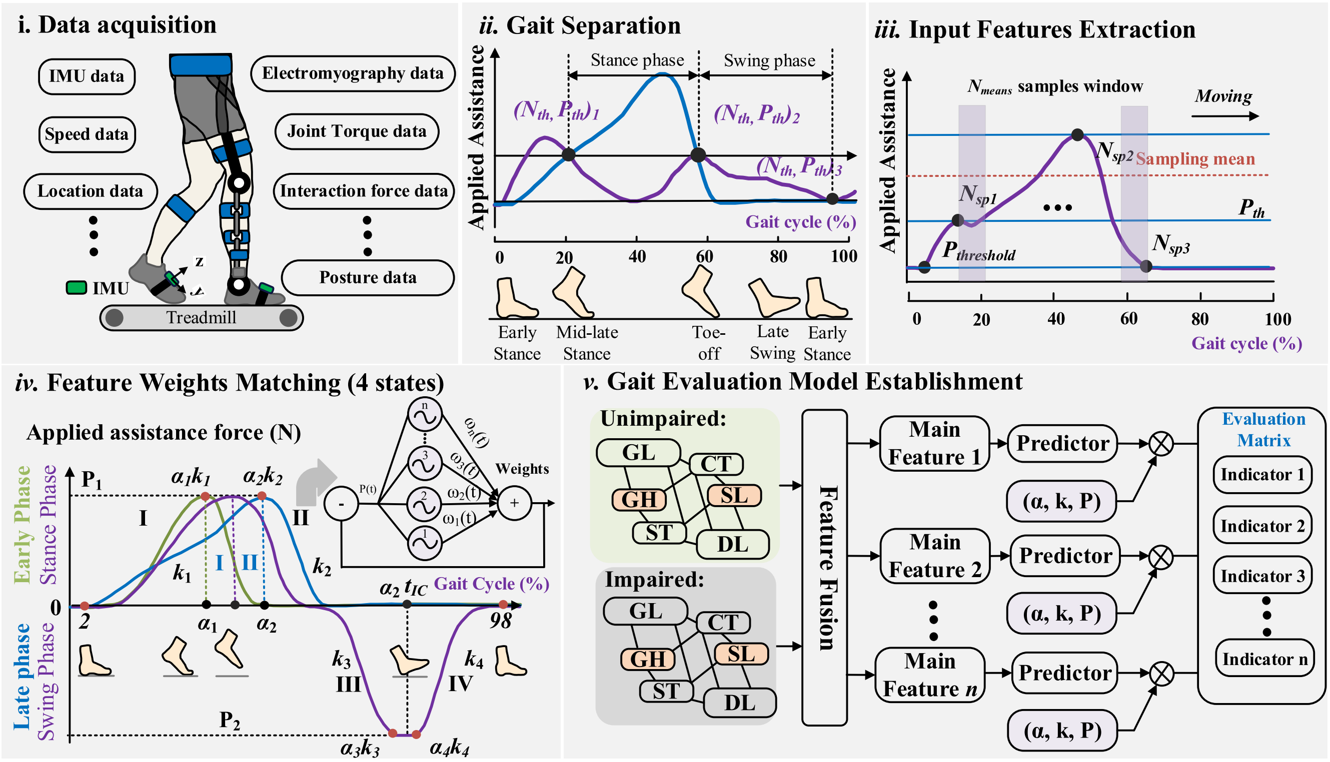


**FIGURE 17.** General framework of gait evaluation for LEE-assisted patients. Data from multiple sensors were utilized. After the gait separation and feature extraction, an online estimation algorithm was designed for matching feature weights, evaluating the gait characteristics, and establishing the gait evaluation model via obtained features, including gait length, completion time, gait height, etc.

required to implement the predefined motion alternately. The physicians subjectively score the patients' performance based on the difficulty of tasks. Subjectivity is inevitably introduced during the scoring process. To overcome this bias, multiple training schemes should be formulated for the same patient. The establishment of an intelligent, uniform, and efficient approach to assessing the rehabilitation effect for SCI patients needs to be completed urgently. However, rehabilitation tasks should be designed based on the SCI injury level. High-grade subjects should receive some repetitive passive tasks on stationary exoskeletons or perform simple walking. Low-grade subjects can implement some difficult tasks, such as running and climbing stairs. Timely adjustment of tasks is necessary for patients based on their task performance. Fatigue should be avoided during the rehabilitation process by monitoring the leg muscles' activation degree.

Clinical evaluation can adopt standard factors, such as gait disability [58], metabolic cost [58], disturbances counteracting [56], and kinematic parameters (time, speed, acceleration, etc.) [56], [59]. However, these factors are not able to reflect motion coordination and participation initiatives. These factors are easy to be disturbed by fatigue and noise. Moreover, sensory and motor function recovery cannot be reflected immediately via these factors due to the intrinsic delay of the neural-muscle system [37]. Current clinical factors are focused on external representations, such as motion accuracy and muscle strength, and neglected internal physiology features, such as the reconnection of neurons. These experiences can objectively reflect the efficacy of LLEs. Fig. 17 summarizes the general framework of gait evaluation for LEE-assisted patients. For example, Lu et al. [190] developed an unsupervised learning approach to identify key features reflecting the rehabilitation effect for stroke patients via kinematic sensors installed on the exoskeleton. Lee et al. [191] proposed an upper assistive exoskeleton to monitor the motion state of the arm and shoulder angles accurately. The accurate monitoring enables the user not only to perform initiative control but also to improve rehabilitation efficiency. Grimm et al. [192] proposed an effective assessment method of upper limb rehabilitation for patients with complete loss of motor function by observing the range of motion via exoskeleton in clinical trials. Ding et al. [193] demonstrated the feasibility of the evaluation indicator based on the force feedback signal and supervising learning approach. In conclusion, assessing patients' rehabilitation effects via exoskeleton is a practical, efficient, and convenient approach and should be promoted further in the future.

In the task-completion category, time and distance are two common indicators [194], [195]. They are popularly used as global descriptions of rehabilitation performance and are generally useful for their intuition and efficiency of use. Despite their unique merits, they are not adequate to evaluate or quantify subjects' performance on an exoskeleton system comprehensively. A good indicator should have the capability

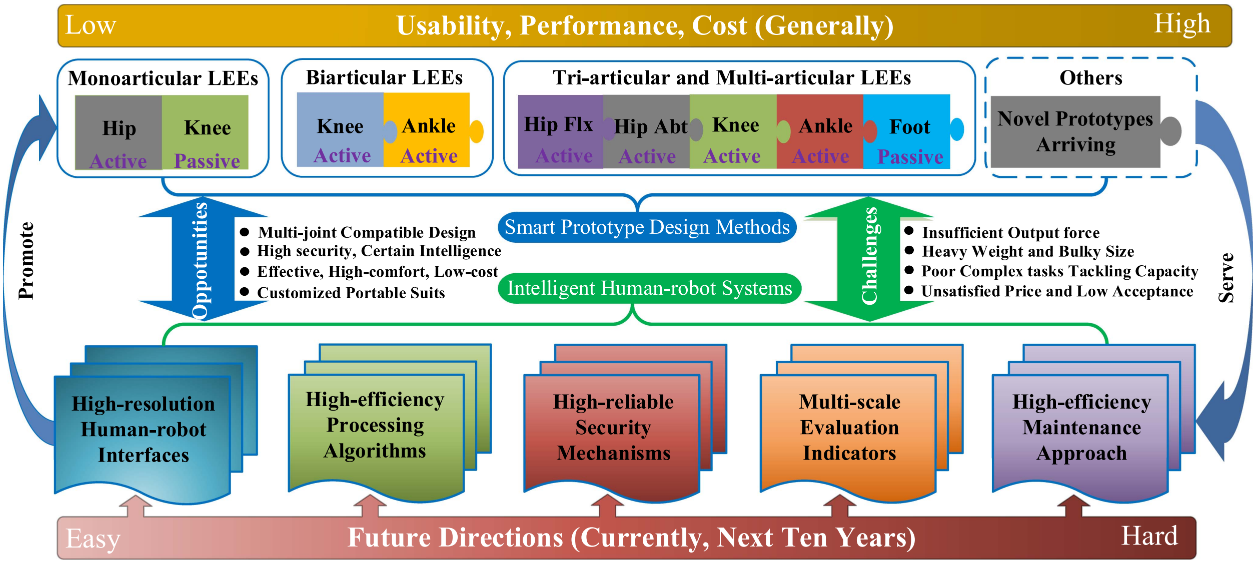


**FIGURE 18. Opportunities and challenges in next-generation LEEs.**

of maintaining stability and rejecting external disturbances. This capability is very significant since external perturbations are very common in real-life exoskeleton applications. In addition, diversity and subject independency are two other considerations in the design of indicators.

In the kinematic or kinetic category, there are a lot of widespread and useful indicators for exoskeleton evaluation. This is possible because these indicators can be obtained from the exoskeleton-related sensors easily. These helpful indicators are more capable of systematically describing the lower limb dynamics than other indicators. However, these kinematic indicators are generally challenging to use in repeated experiments due to the variation of experimental setups, data labeling, or training protocols [196]. Therefore, standard benchmarking routines help to convert the temporal profiles obtained from human joints into qualitative indicators, which is beneficial for performance comparison across different subjects and different experiments. The spatiotemporal matrix is an excellent example of standard indicators. These indicators have the potential to extract the primary features of kinematic performance in basic locomotion tasks. Furthermore, their efficacy in characterizing locomotion performance will be increased extremely when used in combination with kinematic or kinetic indicators, particularly in the presence of complex terrains or external perturbations [197]. Symmetry and coordination are two critical considerations in the development of evaluation indicators for exoskeleton performance. These two factors are tremendously crucial since they involve the clinical assessment and immediate correctness of patients' locomotion.

In the human–robot interaction category, the metabolic cost is often considered the primary indicator reflecting interaction performance. Nevertheless, this indicator should not be considered individually. Several other complementary indicators should be added to the evaluation of human–robot interaction. Biological indicators are generally adopted to characterize human–robot interaction. For example, EMG is widely used to quantify the level of muscle fatigue [198]. Musculoskeletal models are particularly developed to reflect joint torques [199]. These combined indicators are full of prospects for the future, in addition, the level of comfort when evaluating the performance of human–robot interaction. Generally speaking, studying the relationship between comfort and ergonomics has great potential to promote the development of user-oriented evaluation. These considerations, including safety, are key factors affecting the user's acceptability of the exoskeleton device and should be given the highest priority when considering the evaluation of human–robot interaction, not only from the user's perspective but also from the market expectation.

## VI. CONCLUSION AND PERSPECTIVES

Lower extremity impairment in SCI patients is an important issue, which causes decreased locomotion ability and is accompanied by syndromes that severely reduce peoples' daily lives. The complexity of the impairment leads to the challenges of rehabilitation devices, which are diverse and rely on both the social and medical conditions of subjects. The absence of controllability, bad wearability, poor usability, and other limitations in exoskeleton devices possibly lower the acceptability of assistive robotics and even cause abandonment of the exoskeleton. Due to these reasons, developing a satisfactory and high-performance LEE, capable of helping SCI patients implement fundamental tasks is especially urgent. Widespread at-home rehabilitation is still unrealistic, limited by the bulky size of rehabilitation devices and the difficulties of home monitoring. The portability of exoskeleton devices is a critical consideration in the development of at-home LEEs.

In Section V, we have discussed a series of limitations in current LEE devices for SCI patients, both regrading commercial exoskeleton devices and research-oriented LEEs. We identified the critical considerations during the development of a high-performance exoskeleton, including their usability, controllability, and stability in restoring mobility functionality. The criteria we proposed include extensive solutions in a portable design that can be fully adopted, minimizing the device size, and, thus, maximizing controllability, usability, and stability. Hence, it provides a tradeoff solution between the bulky research-oriented exoskeletons and the poor-performance commercial exoskeletons, filling up the open gap in this field.

Although much progress has been made in the development of LEEs, the commercialization of them is still far away. As shown in Fig. 18, currently most of the available monoarticular LEEs are semipassive and do not support complex tasks. Besides, exoskeleton control schemes still need to be optimized with respect to controllability and stability. Finally, the evaluation indicators on the current environment do not involve quantitative comparison, heavily relying on the subjective experience of clinicians. Although a comprehensive solution has been proposed in this article, most of the technical challenges proposed in this article still need to be addressed at a high level. These challenges potentially open a new market to the targeted groups and encourage researchers to realize ultimate goals with substantial efforts.

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