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RESEARCH ARTICLE

Design of a Minimally Actuated Lower Limb Exoskeleton with Mechanical Joint Coupling

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Abstract
Powered lower limb exoskeletons have traditionally used four or more powered joints to provide ambulation assistance for individuals with spinal cord injury. Exoskeletons with numerous powered joints commonly lost some excellent features of passive orthoses and further decreased utility due to added weight and increased control complexity. This work adopts joints coupling mechanism to design a powered exoskeleton to minimize the number of actuated joints and control complexity. Unlike conventional powered exoskeletons, the joint-coupled-powered exoskeleton only has a single motor-actuated joint for each exoskeleton leg in conjunction with a unique knee coupled system to enable their users to walk, sit, and stand. And two types of joint coupled systems are designed, respectively, hip-knee coupled and knee-ankle coupled. The joint-coupled-powered exoskeleton system allows a single actuator to power the hip motion, and allows activate knee motion through the coupled motions of the hip or ankle. More specifically, when the mechanical coupled system is activated, the knee joint is unlocked, resulting in synchronized hip-knee or ankle-knee flexion and extension. The coupling mechanism is switched on and off at specific phases of the gait (the stance phase and the swing phase) to generate the desired motions. The research work proves that minimal actuated robotic systems with joint coupled could achieve safe and natural walking.

Keywords Powered exoskeleton · Minimal actuation · Joint coupling · Single motor-actuated joint

1 Introduction

Until now, wearable exoskeleton has been extensively studied [1, 2]. In medical applications and sports rehabilitation, lower limb exoskeletons can not only help the elderly or people with muscle weakness to walk easily [3, 4], but also help groups with stroke or paraplegia walk again [5–7]. Current lower extremity medical exoskeletons mainly include passive lower extremity orthosis and powered lower limb exoskeleton.

Passive lower extremity orthosis without powered is one of the earliest devices developed to restore the leg mobility of patients with lower extremity paralysis. It is still the first-choice assistive device for paraplegic patients to avoid secondary injury. Among them, the most basic passive orthoses are Bilateral Hip–Knee–Ankle–Foot Orthosis (HKAFO) or Knee–Ankle–Foot Orthosis (KAFO) [8, 9], which are strapped to the user's leg to lock the knee and ankle joints to limit knee flexion, ankle dorsiflexion and plantar flexion. In the case of these constrained joint, patients rely on their own strength and other external devices such as crutches, walkers or parallel bars to achieve striding. A slightly advanced long leg brace is the Reciprocating Gait Orthosis (RGO) including the torso [10]. The most notable feature of RGO is the loop cable/horizontal cable/rocker installed behind the torso unit [11–13], which transmit the motion of the two hip joints for mutual coupled.

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These braces are more suitable for personal ownership due to their relatively low cost and ease of operation. However, passive orthoses still have many limitations. However, there are some limitations of passive orthoses that lead to low long-term adoption rates, such as low walking efficiency, rapid fatigue and slow walking speed [14–16]. It is reflected that the passive orthoses are often restricted by their disadvantages and overwhelmed their advantages. Performance improvement is necessary and urgent.

In the effort to improve ambulation efficiency, the powered exoskeleton systems with multiple actuators were to developed [17]. The most well-known devices emerging in the commercial market are: Ekso [18], ReWalk [19], HAL [20], and the Rex [21]. These powered exoskeletons as shown in Table 1, compared with passive orthosis, are generally equipped with four or more motors to power the knee and hip joint movement without increasing high level of fatigue. However, the external actuator costs and weight have increased sharply, which would lead to the loss of some advantageous characteristics of the passive orthosis. For instance, the purpose of increasing the number of actuated joints is to improve walking efficiency and further promote patient's accessibility to orthoses. But the increase in equipment cost is likely to have the opposite effect. Passive exoskeletons do not rely on external power supply. Instead, they use the energy absorbed from the user to improve their physical performance [22, 23]. In other words, passive exoskeletons act as the spring mechanisms that absorb the waste energy from walking cycles and release it in case of necessity. Due to their low energy, passive types are lightweight and require minimum maintenance. In addition, the doubling of the weight and the size of the device will also greatly reduce the operability and portability of the powered exoskeleton, and further affect the user's independent operability. In view of this, it is necessary for the researchers to explore effective methods to reduce the dynamic joints, allowing the lower extremity exoskeleton to provide power assistance and maintain the lightweight characteristics of the passive orthosis as much as possible.

Clinical Gait Analysis (CGA) biomechanical data for able-bodied individuals shows that the power delivered to the knee during swing phase of natural walking is mainly negative [24]. Additionally, if a locking unit is set up at the exoskeleton knee, the knee can be locked to prevent flexion without power input during stance. This indicates that the simultaneous power input of hip and knee joints does not seem to be the best but maybe a redundant measure for level ground walking. Some studies have been conducted on the feasibility of removing the knee power transmission by the lower limb exoskeleton robots. Tung et al. [25] showed that when walking on the level ground, only inertial force alone might be sufficient enough to achieve satisfactory toe clearance without excessive knee power during the swing phase for the exoskeleton knee joints. Several passive-dynamic walkers have been created that can perform a complete gait cycle and achieve a natural gait without actuation input [26–29]. Endo et al. [30] developed a quasi-passive robotic leg model with only an actuation power input at the hip to verify that the walking behaviors can be produced no energy input at the knee. The Austin exoskeleton was designed one hip actuation unit per leg and employed a bio-inspired mechanical joint coupling system allowing a single actuator to power both hip and knee motions simultaneously [25]. The Ryan Exoskeleton is directly powered by the hip actuation that is axially aligned with the user's biological hip and uses dynamic joint coupling to control knee rotation through a computer controlled locking mechanism and has been validated by several spinal cord injury patients with injury levels ranging from T5–T12 [31]. In conclusion, the joint coupling paradigm maybe an effective method to minimize

Table 1 Comparison of the weight of each exoskeleton

Exoskeleton	Country	Target patients	Number of powered joints	Weight of devices (kg)
HAL	Japan	Spinal cord injury	4	12
ReWalk	Israel	Spinal cord injury	4	23
Ekso	America	Paralysis of lower limbs	4	23
indego	America	Spinal cord injury	4	12
Rex	New Zealand	Spinal cord injury	10	38
Ailegs	China	Stroke	4	25
Fourier X1	China	Diplegia	4	18
BEAR-H1	China	Stroke	6	12
Adir	China	Spinal cord injury	4	20
i-Leg	China	Spinal cord injury	2	10

i-Leg lower limb exoskeleton is the proposed device in the paper actuation of lower limb exoskeleton, especially for newly paraplegic individuals who have not yet developed significant amounts of joint contracture or sustain high levels of spasticity.

The research introduces two novel joint coupling mechanisms that enable paraplegic individuals to walk with the use of a minimally actuated exoskeleton. The focus of the minimally actuated exoskeleton is to generate forward propulsion to aid in locomotion and eliminate the need for multi-joint active drive of traditional power exoskeleton. This paper presents early work in designing two kinds of gait generator mechanisms for a rehabilitation lower limb exoskeleton with only two actuated degrees of freedom. The primary motivation for the reduction in actuated degrees of freedom is the desire to reduce the complexity of rehabilitation exoskeleton devices. The joints coupling gait generation strategy uses key event characteristics in the gait cycle to trigger knee joint motion and makes the knee joint movement become a sub-motion of the hip or ankle joint motion. The joint coupled mechanism is a potential and creative method of the minimally actuated exoskeleton to eliminate the need of knee actuation for gait assistance. Therefore, the proposed lower limb exoskeleton in the research only sets the active power joint output for the hip joint and designs the joint coupled mechanism to activate the knee joint movement. The study also recruits several volunteers to walk with the use of a minimally actuated exoskeleton to verify the feasibility of the joint coupling mechanism. We predict that fewer actuation units will greatly reduce the weight of the exoskeleton system and lower the cost of the end user, allowing more spinal cord injury patients to try it and further improve the accessibility of lower extremity exoskeletons.

2 Design Concept

2.1 Joint Coupled Walking Mechanism

Joint coupling describes the mutual motion of flexion and extension between the multiple joints. And these coupled behaviors have been observed in some natural lower limb motions (e.g., walking, sitting, and standing) [32]. For the active–passive hybrid exoskeleton, the first task is to generate a forward walking gait to provide users with basic walking ability. Joint coupled mechanism may also have similar applicability for generating lower limb exoskeleton coupled motion. This section will focus on the manifestation of joint coupling in the gait cycle.

To explain the coupled relationship between joints and joints in walking, the characteristics of joint movement of lower limbs in a complete gait cycle are analyzed and discussed. The human gait cycle is usually divided into stance phase and swing phase [33] (Fig. 1a). The stance period represents the percentage of the gait cycle from the heel to the ground to the toe off the ground, and the swing period is the percentage after the heel is off the ground. To explain the specific performance of the lower limb joint coupled mechanism in walking, this study divides the gait cycle into four phases on the basis of the traditional gait cycle, and introduces a new gait cycle description. For the new gait cycle division rules and corresponding events listed in Fig. 1b, c, the specific characteristics are described as follows:

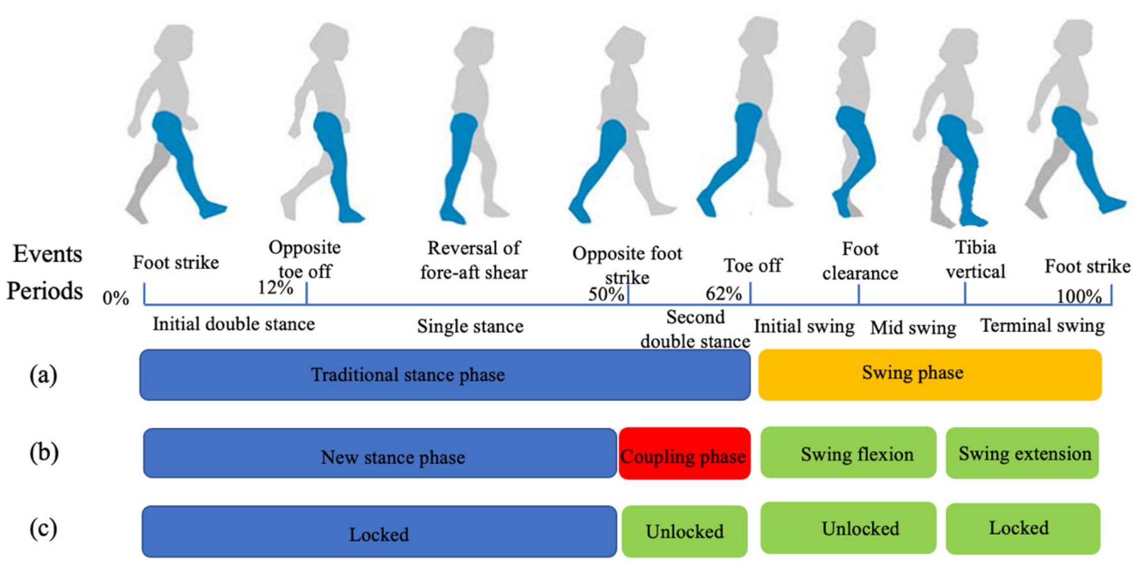


Fig. 1 Description of a walking gait cycle events. **a** Traditional gait cycle illustration; **b** new three-phase gait cycle illustration; **c** coupled activation timing

PHASE I—Stance Phase

During stance, the support leg is weight bearing and the hip goes through extension. Meanwhile, the knee is in a fully extended and continuously locked state, and it does not engage in any joint coupled to prevent the standing leg from collapsing. The main difference between this new stance and the traditional stance description is that it ends in anatomically vertical position of hip extension and the maximum position of ankle dorsiflexion, right before the knee flexion (at the Double Stance).

PHASE II—Stance Coupled Phase

This stance transits into the stance coupled phase where the hip joint continues to extent to reach the maximum extension position to unlock the knee joint, so that the knee joint begins to flex. Simultaneously, the ankle joint also reaches the maximum dorsiflexion position to unlock the knee joint. The two coupled motions match the knee flexion motion.

PHASE III—Swing-Flexion Phase

The swing-flexion stage occurs after the knee joint is unlocked, the hip joint movement transits from extension to flexion, and the ankle joint also enters the plantar flexion phase. At this stage, the knees continue to flex to guarantee sufficient toe clearance. This stage starts with the toes off the ground and terminates at the maximum angle of knee flexion.

PHASE IV—Swing-Extension Phase

In the maximum hip flexion position, the gait enters the swing-extension phase, and the knee joint is re-extended and locked to prepare for standing weight-bearing. This stage starts at the maximum hip flexion angle and ends when the knee is fully extended. In the swing-extension phase, the coupled movement is activated again.

Based on the four-phase gait cycle, two gait coupled strategies are initially proposed. The specific content is mainly embodied in two aspects: (1) the power joint is only set at the hip joint, and the knee joint uses passive joints; (2) the stance locking and swing unlocking can only be achieved when the coupled mechanism is involved in the movement of the knee joint.

The knee joint coupled designs based on the minimal actuations are respectively:

(1) Minimize Actuation through Hip-Knee Coupling.
(2) Minimize Actuation through ankle-Knee Coupling.

2.2 Exoskeleton Structure Design Concept

The inspiration for the exoskeleton design is influenced by Austin exoskeleton and Ryan Exoskeleton firstly. These devices motivate us to study the joint coupling mechanism. Secondly, the prosthetic gait mechanics of bilateral transfemoral amputees also inspirated us to quest unconventional lower limb exoskeleton device. These amputees wearing unactuated knee prostheses are usually able to achieve a higher level of walking ability by swinging the hip joint [34]. In addition, the variable damping knee-ankle prosthesis C-Leg (Ottobock) [35], allowing free swing and locked stance, is a profound inspiration for improving toe clearance and knee flexion. This observation prompted this study to reproduce the same swinging leg dynamics, that is, to lock in the standing phase and freely swing in the swing phase, which would further eliminate the need for multiple powered degree of freedoms.

3 Design of Joint Coupling Mechanism

3.1 Minimize Actuation Through Hip-knee Coupling

The concept of minimal power joints proposed in this study is that only the hip joint is setting actuator to assist in flexion and extension, and knee joint motion is generated by activating the joint coupling mechanisms. The hip-knee coupled mechanism refers to the activation of knee flexion and extension through hip flexion and extension (see Fig. 2). The gait generation strategy will use this minimal actuation and joint coupled behavior to generate a series of leg movements.

3.1.1 Gait Generation Through Hip-knee Coupling

The hip-knee coupling gait generation strategy uses key event characteristics in the gait cycle to trigger knee joint motion. The traditional knee joint actuator is replaced with a joint coupled system, and the knee joint movement becomes a sub-motion of the hip joint movement when it is activated. In this coupled movement, the knee has two states: unlocked and locked.

(1) Locked State: the knee is activated by the hip-knee coupled motion, then unlocks and swings freely.
(2) Unlocked State: the coupling mechanism is deactivated and then the knee enters a locked state without being affected by the movement of the hip joint.

The gait cycle is divided in the following order by switching between the coupled and uncoupled states. And Fig. 3 depicts the state machine that defines how the discrete states of the proposed exoskeleton gait transition.

STEP I: during stance phase, the hip-knee coupling system is deactivated and the knee remains extended locking, hip extension continues until a maximum extension angle.
STEP II: transition to the end of the stand, hip-knee coupled system begins to be activated and unlocks the

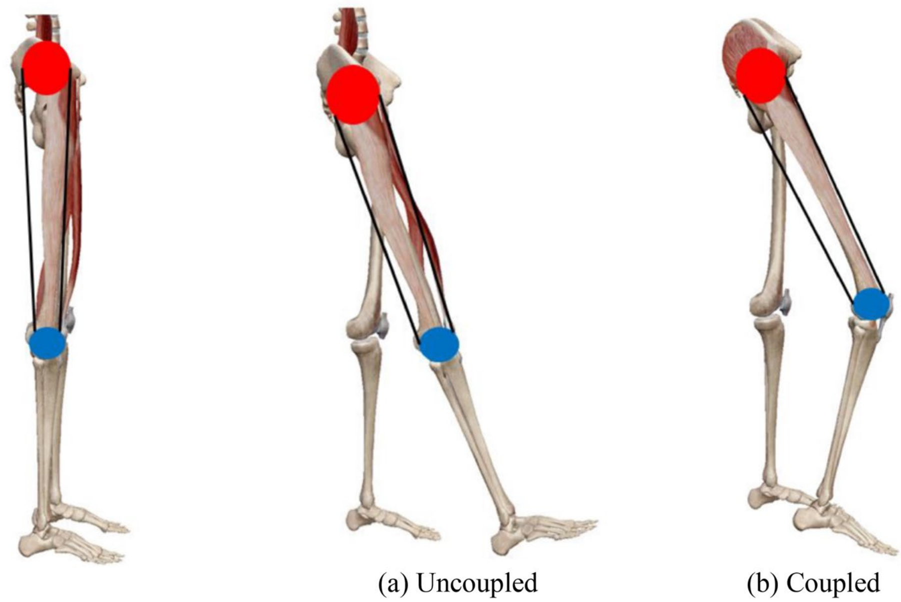


Fig. 2 Principle of hip-knee joint coupling

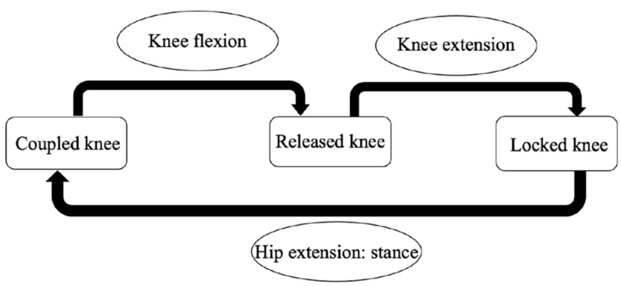


Fig. 3 State transition of the proposed exoskeleton discrete states

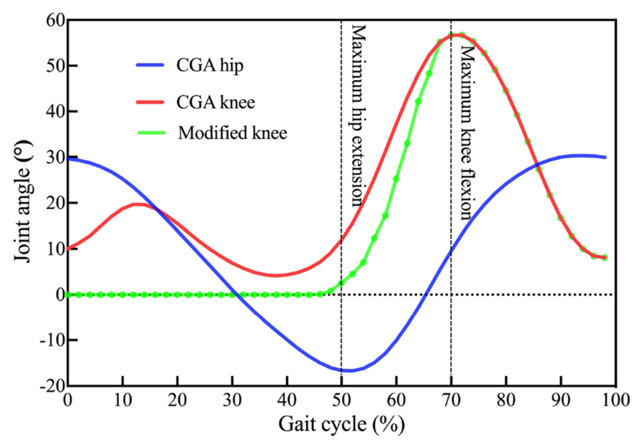


Fig. 4 Hip-knee joint coupled gait description with an adjusted knee trajectory. The hip extension assist-on state triggers the generation of knee trajectory via hip-knee joint coupled mechanism and angles of hip predict the knee condition

knee joint in the hip joint neutral position, in preparation for the pre-swing.

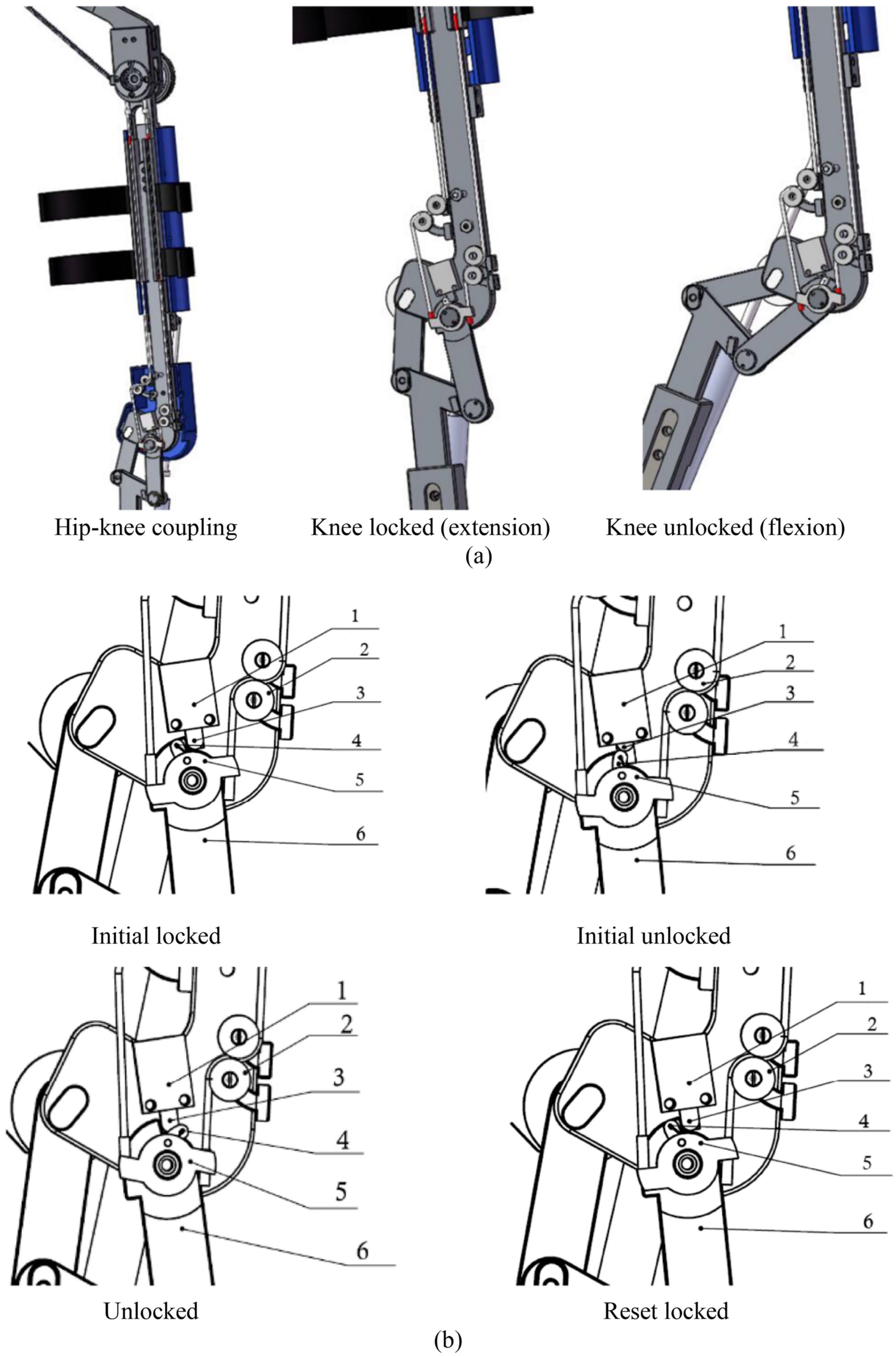
STEP III: entering the swing-flexion stage, the coupled system is deactivated again, and the knee joint appears as natural gait flexion to ensure sufficient toe clearance.

STEP IV: at the maximum hip flexion position, the swing leg enters the swing extension stage, the shank swings forward due to inertia, the knee extends, and the coupled system is reactivated to limit knee movement. At this point, the knee is locked and ready to stand.

This gait strategy aims to unlock and lock the knee. The research adopts the Clinical Gait Analysis (CGA) data by Winter as reference to plan the optimal walking trajectory of coupled gait. The CGA data were collected in a natural standing position with the torso aligned with the vertical axis. The ideal coupled gait trajectory is shown in Fig. 4. In this modified gait, the knee joint is already locked in the late swing stage, thereby ignoring the slight flexion of the knee joint in the early stage of standing.

3.1.2 Coupling Mechanism Design

3.1.2.1 Coupling Mechanism—Gait Generator The hip-knee joint coupling mechanism of the lower limb exoskeleton acts on the gait generation, which not only requires to meet the characteristics of standing phase extension and swing phase flexion, but also meet the standing phase locking and swing phase unlocking. This is an important index to ensure the safety of the supporting leg. On the other hand, the motion behavior of the knee needs to work in coordination with the hip-knee coupled mechanism, the hip-knee coupled system needs to meet the following requirements:


Hip-knee coupling
Knee locked (extension)
Knee unlocked (flexion)
(a)
1
2
3
4
5
6
Initial locked
Initial unlocked
Unlocked
Reset locked
(b)

◀**Fig. 5** Hip-knee joint coupled mechanical system. **a** Two states with engaged and disengaged configuration; **b** mechanical engagement system during standing phase and swing phase composed by torso tooth (3), torso tooth groove (1), guide wheel (2), pulley tooth (4), knee pulley (5) and a rod of the four-bar linkage with a boss (6)

(1) The knee automatically locks against supporting leg from collapsing at swing-extension phase and the complete single-leg stance phase.
(2) When the coupled mechanism is activated, the knee joint is unlocked smoothly without affecting the Swing-Flexion phase.

In the effort to meet the above requirements, a purely mechanical hip-knee coupled system was designed. As shown in Fig. 5a, the coupled mechanism is located at the end of the femur-link. It consists of a fixed pulley at the hip and a free pulley at the knee. The knee pulley is installed at the proximal end of the tibia link of the exoskeleton and allowed to freely rotate. The two pulleys are mutually restricted by a pair of wire ropes. The change of the draw rope at the hip pulley assists the rotation of the knee pulley to unlock the controllable locking knee joint mechanism to generate knee joint flexion motion.

3.1.2.2 Controllable Locking Knee System The structure of the knee joint plays a key role in the completion of the coupled motion, and it determines whether the final target motion can be achieved. As shown in Fig. 5b, the controllable locking knee system is composed by a knee pulley, a spring-loaded pulley tooth, a spring-loaded sliding torso tooth and its groove. In the free-standing state, the torso tooth stretches out from the groove to block the knee lug and the knee joint is locked. Until the hip reaches the predetermined vertical position, the torso tooth retracts into the shell with the pulley tooth pushing and the knee joint starts to flex. In the final swing-flexion stage, the knee joint is locked again, and the torso tooth is reset back to the same position as the standing state.

In the design of this knee joint mechanism, spring elements are added to many structures: (1) The torsion spring at the rotation center of the knee joint. When the knee joint reaches maximum flexion and starts to release the knee joint, the torsion spring releases energy to assist knee extension and ensure that the torso tooth is successfully re-extended due to the inertia and weight of the shank; (2) the reset springs at the pulley teeth and trunk teeth are to ensure that they can be retracted smoothly after retraction to achieve reset. All of these springs are set for the smooth execution of all links.

3.2 Minimize Actuation Through Ankle-knee Coupling

Another gait generation strategy utilizes the knee-ankle coupled movement mechanism. Similar to the hip-knee coupling, the knee-ankle coupled also adopts the concept of multi-joint coupled, which dynamically realizes the joints coupling. Knee-ankle coupled motion refers to take full advantage of the movement of the plantar flexion/dorsiflexion to operate the knee movement during walking (see Fig. 6). The knee also has two states: locked and unlocked, which are described in detail as follows.

STEP I: enter the stance phase, the knee joint is locked, and the ankle-knee coupling system has not activated the knee joint movement. The knee joint is still in the support period.
STEP II: in the double support phase, the ankle-knee coupling system starts to be activated, but the knee joint is not unlocked. Until the ankle joint movement reaches maximum dorsiflexion and the knee joint begins to flex, the knee complete unlocking.
STEP III: transition to the swing phase, the coupling system has been deactivated, and the knee joint releases to flex to increase the toe clearance.
STEP IV: at the point of maximum plantar flexion, the shank swings forward by the inertial force, and the knee extends and locks in preparation for stance. During this period, the coupled system no longer triggers the knee motion, and the knee joint movement will not be interfered by the ankle joint movement.

In the lower limb exoskeleton ankle-knee joint coupling system, the knee motion transformation is handled by the ankle motion. As shown in Fig. 7, a locking mechanism is located on the top of the shank link of the exoskeleton. It consists of a spring-loaded sliding block and a wire rope connect to the ankle. The design of the single-lock-link knee makes the spring block engage with the link tooth and locks the knee when the knee reaches the fully extended position. As the coupled mechanism is activated, the block of the locking mechanism is retracted to release the knee and assist with knee flexion. Vice versa, the block is re-stretched to lock the knee to assist with knee extension. This allows the unlocking of the knee for swing, and the locking of the knee during stance automatically. As long as the coupling mechanism is activated, the slider will be released or retracted.

3.3 Sit-stand Coupling Behavior

In addition to walking, the coupling mechanisms are also appropriate in sitting and standing operations as shown in Fig. 8. For these two behaviors, it is initiated after the feet

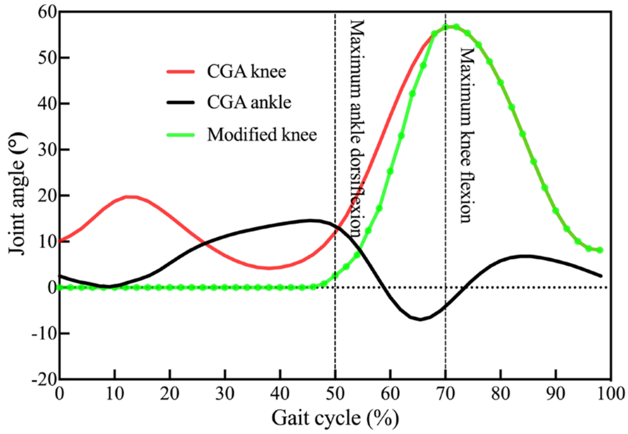


Fig. 6 Ankle-knee joint coupled gait description with an adjusted knee trajectory. The dorsiflexion assist-on state triggers the generation of knee trajectory via ankle-hip joint coupled mechanism

are brought together. And the coupling mechanism and the gas spring assist mechanism together contribute to the realization of the sitting-standing function. Before the sitting, first and foremost, the user manually controls the block to prevent the slider from moving up and down and constrained the motion of gas spring, and then the user needs to lean forward to dorsiflex the ankle joint (ankle-knee coupling) or lean backward to extend the hip joint (hip-knee coupling) to activate the coupling mechanism and unlock the knee joint. Next, the exoskeleton flexes both hips backward and the gas spring mechanism joins the movement to start compression until fully seated. Since the weight of the user is distributed through both legs, the completion of the process also requires the support of the front side or the back side of the crutches to ensure balance and safety. As a standing stage, it is the opposite of sitting posture. The user leans forward to transfer the body weight to the calf, and is activated by the gas spring and hip motor to complete the standing. Once it is completed, the coupling mechanism automatically locks the knee joint to prevent the standing leg from collapsing.

3.4 Characteristic of Joint Coupling Mechanism

Different from the extensively studied dynamic exoskeleton with multiple powered degrees of freedom, the exoskeleton in this study only has one drive unit on the hip and a mechanical gait generator on the knee joint. The hip joint is directly controlled by the actuator, while the knee joint is controlled by a coupling mechanism that transmits motion to unlock or lock the knee joint. When the mechanism is activated, the block at the knee is retracted to help the knee joint flex, and vice versa, the block is

Fig. 7 Ankle-knee joint coupled mechanism

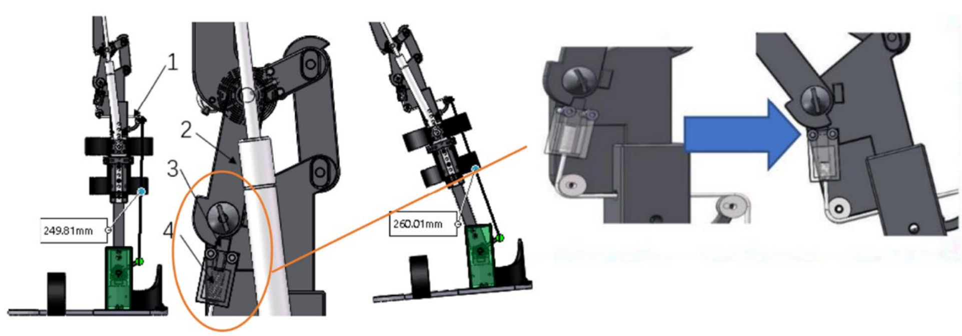
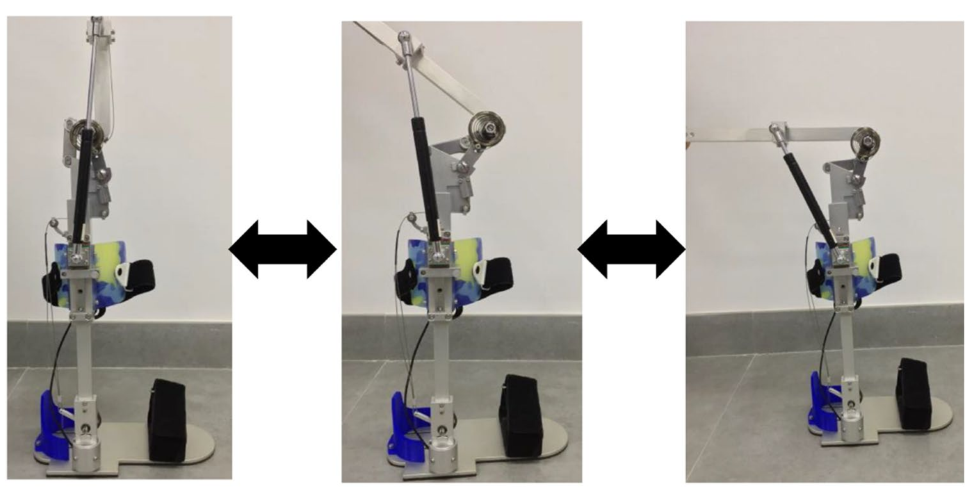


Fig. 8 Description of a behavior of standing-sitting



re-stretched to aid the knee joint stretch. This mechanism eliminates the need for knee joint drive and activates knee joint movement. The characteristic of the mechanism are reflected in:

(1) A single motor-actuated joint lower limb exoskeleton and joints coupling mechanism minimize the number of powered joints of the lower limb exoskeleton.
(2) The lower limb exoskeleton could assist human legs to realize the locomotion-centric assistive walking through the powered hip joints and the joint coupled mechanism to activate the knee joint movement, and does not set the active power joint output for the knee joint.
(3) In addition to walking, the coupling mechanisms are also appropriate in sitting and standing operations. As shown in Fig. 16, the coupling mechanism does not interfere with the switching of postures.
(4) The knee is entirely passive and a coupled locking mechanism is located at each knee. The coupling mechanism is switched on the stance phase and off at the swing phase to generate the desired knee motions and ensure walking safety.

4 Exoskeleton Design Discussion

4.1 Hip Actuation

Two types of hip actuation components are designed to provide powered rotation for the sagittal motion of the hip joint to perform hip flexion and extension. The first type is rear-mounted hip actuation component (Fig. 9a), and the second type is side-mounted hip actuation assembly (Fig. 9b). The main difference between the two is whether it is transmitted by a synchronous belt structure. The actuator assembly of both are composed of 200 W Maxon brushless DC motor 160 to 1 gear reducer harmonics. For the rear-mounted hip actuation, it is achieved indirectly through a set of drive components mounted on the upper rear of the exoskeleton. At the output of the harmonic drive, a synchronous belt transmission system indirectly transfers the motor torque to the hip joint. The transmission configuration was to minimize the hip lateral size of the exoskeleton as much as possible, with a width of only 20 mm (gear width). The exoskeleton allows the maximum range of hip joint motion to be 30° extension and 120° flexion (measured with respect to the vertical axis).

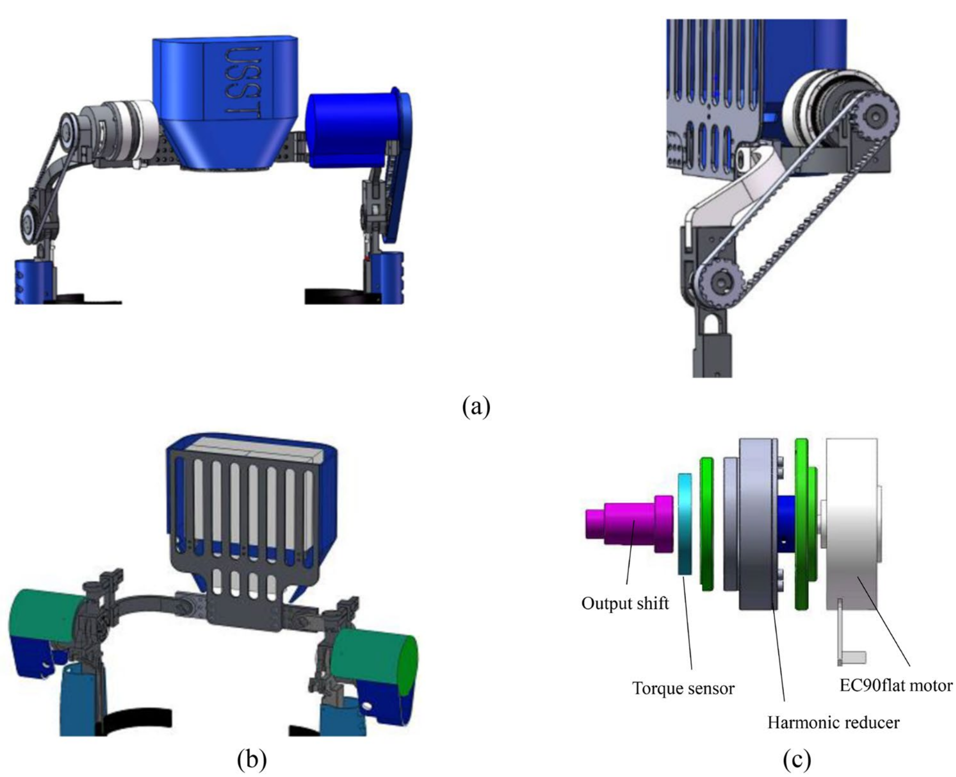


Fig. 9 Description of two kind of hip actuation assembly. **a** Rear-mounted hip actuation assembly. **b** Side-mounted hip actuation assembly. **c** Integrated combination of the modular hip actuator assembly

4.2 Designing of the Whole Machine

The exoskeleton is designed based on the architecture of the hip-knee-ankle foot orthosis, which include backpack, drive mechanisms, adjustable thigh and shank segments, and foot segment. In the device, the torque is generated by the electric motors and springs. The modular powered hip joint assembly provide the only active torque. And the passive joints were driven by the torsional springs mounted on the center of joints, thus realizing a compact and lightweight design.

The exoskeleton movement is switched by the two push-buttons at the handle of the crutch, as shown in Fig. 10. Before the exoskeleton starts to run (after it is worn), its state always starts from the sitting position. In the sitting position, long press the button, the hip actuator performs a standing operation to extend the exoskeleton and femur to a vertical position. At the same time, the air spring at the knee joint releases

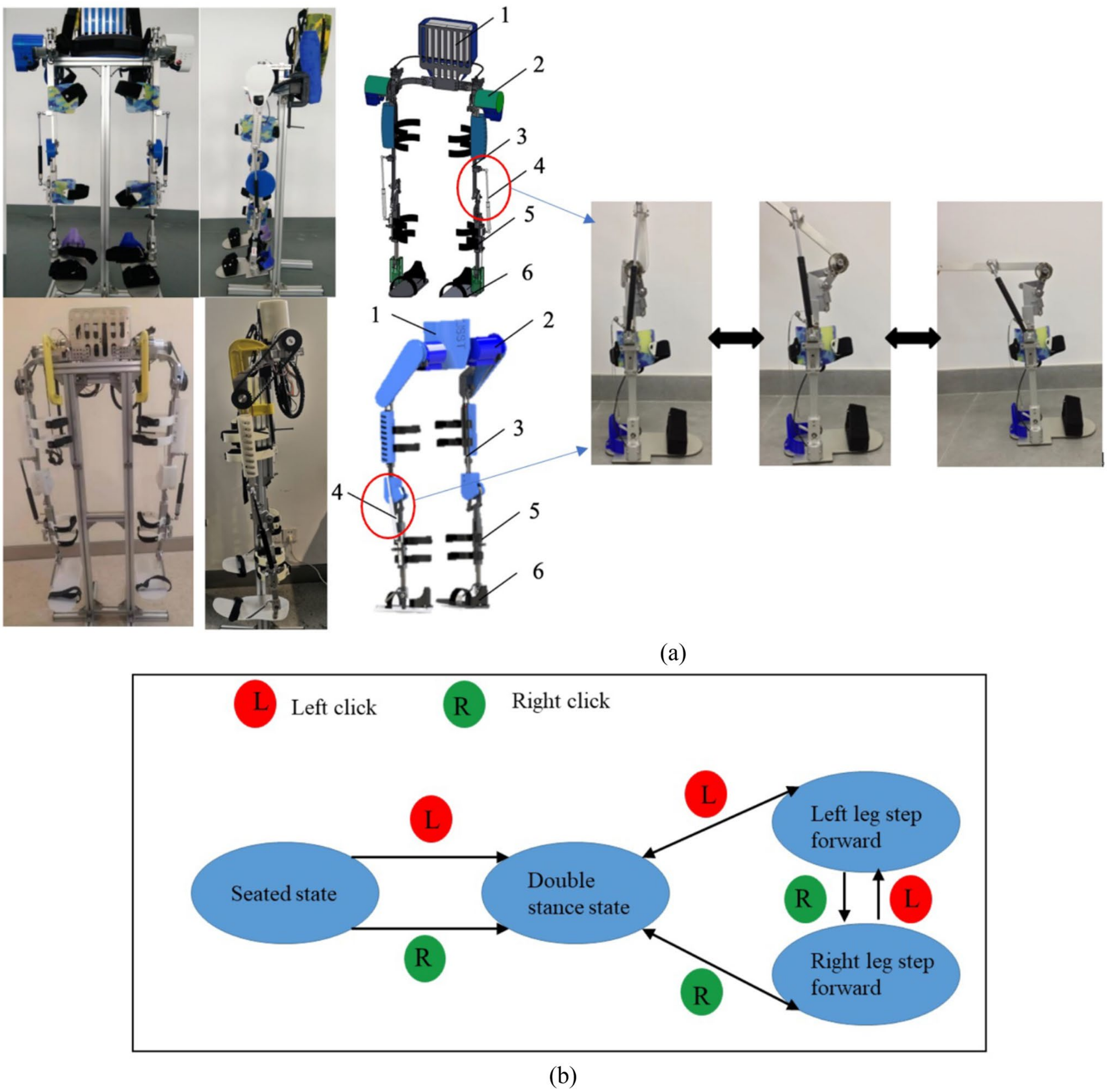


Fig. 10 Overview of two joint coupled exoskeleton designed to minimize the actuation. **a** Overview of the hip-knee joint coupled exoskeleton (top) and ankle-knee joint coupled exoskeleton (bottom), including backpack (1), actuation assembly (2), a leg assembly (3, 5, 6) and air spring booster mechanism (4). **b** Exoskeleton operation diagram

energy to extend the knee joint, and the user quickly enters a double-support state. Once in this double stance state, the user can decide whether the next operation is to sit down or move forward. Assuming that the next step starts with triggering the left button, this option is performed by flexing the left leg to approximately + 20° (heel strike) and extending the right leg to − 20°. In the same way, when the right button is triggered, move the right leg forward, extend the right leg to approximately + 20° (heel impact) and extend the left leg to − 20°. Each discretization trigger will generate an alternate forward gait, and continuous triggering of the buttons will return the legs to the standing position with the feet together. This termination step is performed by setting the standing leg to 0° and the swinging leg to 0° at the same time.

4.3 Knee Design

The knee joint is a relatively complex structure. In addition to the coupling mechanism, a spring passive assist mechanism is also designed to assist the swing-extension action. This section verifies the condition of the knee extension while healthy subject walking with the exoskeleton and evaluates the ability of the torsion spring device to enhance the extension of the knee joint.

4.3.1 Spring Torsion Design

Many swing leg models of varying complexity are designed for various purposes [36]. In this study, a double pendulum model was used to represent the thigh and shank. Assuming that the hip joint moves in space, the model is similar to the model developed for designing and controlling the prosthetic knee joint. To calculate the passive assistive knee moment, it is assumed that the weight of the foot is concentrated on the ankle. This simplification is a passive knee exoskeleton system for minimizing ankle flexion. The swinging leg model is shown in Fig. 11.

Since the knee joint is a passive joint, only inertial force is applied to the knee joint. The inertia potential energy at the knee joint is

$$T_{\mathrm{I}} = T_{\mathrm{IS}} + T_{\mathrm{IF}} \tag{1}$$

where T_{IS}, and T_{IF} represent the inertia potential energy of the shank and the foot, respectively.

$$T_{\mathrm{I}} = m_2 a l_2^* + m_{a_2} a l_2 + m_3 a s_2 \tag{2}$$

For the spring torsion, its elastic potential energy is related to the spring angle, and the calculation formula is:

$$T_{\mathrm{s}} = T'\alpha \tag{3}$$

where T_s denotes the spring torsion torque, T' denotes torsional stiffness, and α denotes the rotation angle of spring.

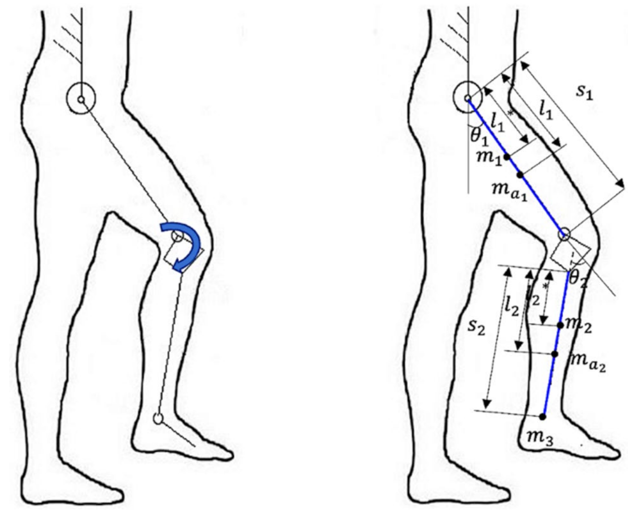


Fig. 11 Kinematics diagram of swing leg

And the torsional stiffness of the spring is mainly determined by the spring material characteristics, thickness, width and length. It can be obtained as:

$$T' = \frac{Ebh^3}{12Kl} \tag{4}$$

where b: Spring width, 4 mm; E: Elastic modulus of spring, 206 GPa; h: Spring thickness, 0.4 mm; l: unfolding length of spring working ring, 110 mm; K: coefficient, 1.25.

And the gravitational potential can be obtained as:

$$V_{\mathrm{G}} = V_{\mathrm{G_S}} + V_{\mathrm{G_F}} \tag{5}$$

with

$$V_{\mathrm{G_S}} = m_2 g\left(l_2^* \cos\left(\theta_2 - \theta_1\right)\right) - m_{a_2} g\left(l_2 \cos\left(\theta_2 - \theta_1\right)\right) \tag{6}$$

$$V_{\mathrm{G_F}} = m_3 g\left(s_2 \cos\left(\theta_2 - \theta_1\right)\right) \tag{7}$$

where $V_{\mathrm{G_S}}$, $V_{\mathrm{G_F}}$: the gravitational potential energy of the shank and the foot; m_2, m_3: the mass of the human shank and foot; m_{a_2}: the mass of the exoskeleton shank; s_2: the lengths of *shank* link; l_2^*, l_2: the distances of the center of the mass of the human/exoskeleton shank; θ_1, θ_2: the rotation angles of the hip and knee joints, respectively.

Combining Eqs. (5)–(7), the gravitational potential V_G is

$$V_{\mathrm{G}} = \left(m_2 g l_2^* + m_{a_2} g l_2 + m_3 g s_2\right) \cos\left(\theta_2 - \theta_1\right) \tag{8}$$

Assuming that the knee joint reaches a balanced state at the maximum flexion position and the maximum extension position, the inertial potential energy and elastic potential energy are all converted into gravitational potential energy. Under this condition, it requires

$$T_s + T_I = V_G \tag{9}$$

Hence, the human-exoskeleton system can realize swing-extension after selecting appropriate spring stiffness.

4.3.2 Gas Spring Booster Mechanism Design

The role of the gas spring booster mechanism is designed to help provide auxiliary torque for the posture transition from sitting to standing. When sitting down, the gas spring booster mechanism compresses and stores energy; when standing, it releases energy to achieve natural posture conversion. Based on the minimum peak joint torque reference determined by Yoshioka et al. to perform the sitting-to-standing task, we select the minimum torque value of the knee joint to be 0.51 Nm/kg, and the hip joint torque value to be 1.2 Nm/kg [37].

First select the rated force of the gas spring as 150 N. The installation position of the spring on one side of the orthosis is determined in advance. The activation moment arm of the gas spring is designed to produce a small moment when it starts to flex, and the moment increases as the flexion of the knee joint increases. The auxiliary torque generated by the gas spring should be the smallest at the beginning of the sitting posture and the highest at the beginning of the standing posture, so as to better start the posture transition.

The gas spring selection and installation position will be given in the following introduction, where:

O is the rotation center of the knee joint;
A is the lower installation point of the gas spring;
B is the upper installation point of the gas spring (Fig. 12).

Suppose the distance from the upper installation point to the center of rotation is 100 mm, $\alpha = 30°$, then $OA = 200, OZ = 0B_2 = a$,

In $\triangle AB_0B_2$, it is derived from the law of cosines that:

$$B_0B_2 = \sqrt{AB_0^2 + AB_2^2 - 2AB_0AB_2\cos\alpha} = \sqrt{200^2 + a^2} = \sqrt{2}a \tag{10}$$

In $\triangle OAB_2$,

$$AB_2 = \sqrt{OA^2 + OB_2^2} = 2a \tag{11}$$

So, the upper installation point of the gas spring is 115 mm, the center distance of the gas spring is 315 mm, the effective stroke is 85 mm, and $\alpha = 30°$.

Gas spring support torque:

$$T = F \cdot d = 150 \times 0.115 \times \cos 30° = 14.9 \text{ N m} \tag{12}$$

The additional assistive torque of motor:

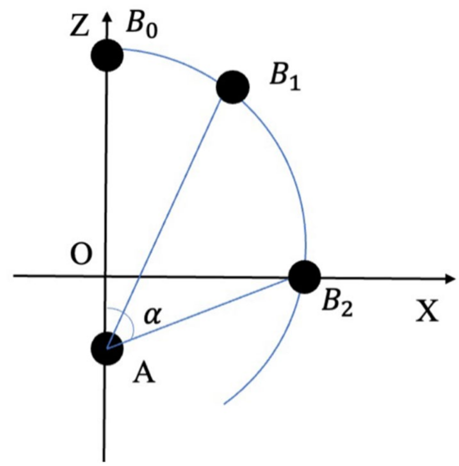


Fig. 12 Schematic diagram of the installation position of the gas spring booster structure

$$T_m = 0.51 \times G - T \tag{13}$$

4.4 Multi-sensor System Design

The multi-sensor system of the lower extremity exoskeleton is composed by inertial measurement units (IMUs, VN-100S), two torque sensors (Sunrise Instruments, M2210E) two encoders (4095ppr, MILE, Maxon Motor) and thin-film pressure sensors (force sensing resistor, FSRs 402). The exact placement of these sensors is shown in the Fig. 13. Their specific roles are as follows:

The IMUs placed on the left/right leg and the back are mainly used to detect the change of the posture angle and determine current location information during walking [38];

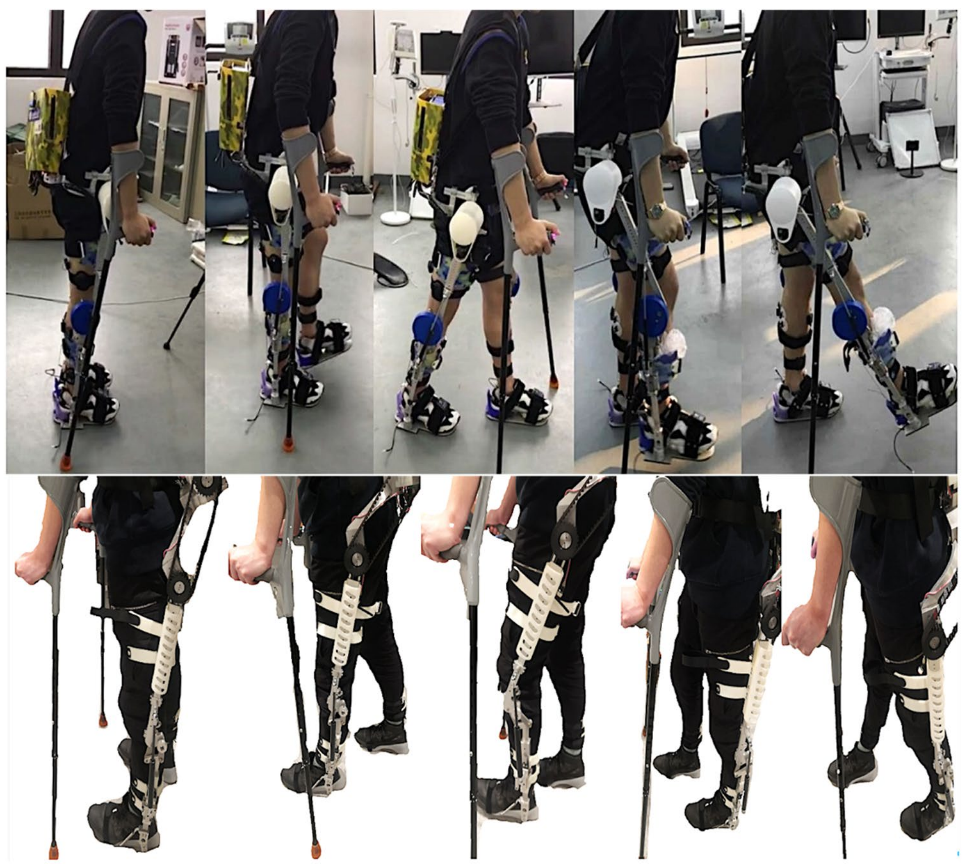
The torque sensors at the hip joints are mainly used to detect the output torque and trigger the motor to stop running in time once the hip joint torque changes suddenly, further provide feedback to the control system to ensure accurate tracking;

The FSRs at the left and right feet are used to measure the ground of forces (GRFs) and judge whether the current phase is in the stance phase or the swing phase;

The FSRs of the left and right crutches are placed on the elbow rest and the handle to determine the change of the pressure value on the left and right sides and further predict the walking intention of the wearer in advance to realize the perception function of the exoskeleton. And these FSRs mounted on the feet and crutches could also detect the GRFs and the center of pressure of the human-exoskeleton-crutch system to evaluate current human-exoskeleton system stability [38].

Fig. 13 The composition of multi-sensor system

Fig. 14 Gaits sequences of ankle-knee joint coupled gait (top) and hip-knee joint coupled gait (bottom)



5 Experimental Result and Discussion

The section is to show the initial test results of joint-coupled lower extremity exoskeleton to evaluate the functional performance from the following tests:

(1) Point tracking of Coupling Gait Trajectory
(2) Knee Spring Damper Performance Testing
(3) Sitting and standing posture transformation test
These tests are performed by a 25-year-old male whose height is 1.76 m and the weight is about 70 kg. The tests are performed after the user is familiar with walking with the exoskeleton. And Fig. 14 shows the gait sequences of hip-knee coupled exoskeleton (top) and ankle-knee mechanical coupled exoskeleton (bottom).
(4) Trajectory comparison of ambulation beneath the two coupling mechanisms

In the experiment, five volunteers were recruited (Male, 25 ± 1 years old, 173.5 ± 3.5 cm in height, 70 ± 5 kg in weight) participated in two experiments. Each subject was required to wear per exoskeleton to receive at least ten training sessions to be fully familiar with the way of the exoskeleton walking. And then, the subjects were allowed to participate in the experiment.

5.1 Point Tracking of Ambulation Joint Trajectory

Figure 15 shows the direct comparison of joint motion data with two joint-coupled exoskeletons. The position trajectory tracking plot is intended to explore the characteristics of the swing phase of the gait cycle (since the knee joint is locked during the stance phase). During the coupled mechanical gait cycle, the exoskeleton generates gait characteristics similar to the CGA reference as expected. In double standing, the wearer would generally trigger the next step after he completely transfers the weight to the new standing foot. This balance phase prolongs the standing time of the exoskeleton gait. This extend length of the balance phase also could be reduced after the user is familiar with the exoskeleton walking.

And compared with the CGA data, the hip trajectory of the coupling exoskeleton has a larger amount of hip extension angle and acceleration. The implementation of this aggressive hip joint movement is to expand the inertial force of the lower limbs, thereby increasing the motion range of

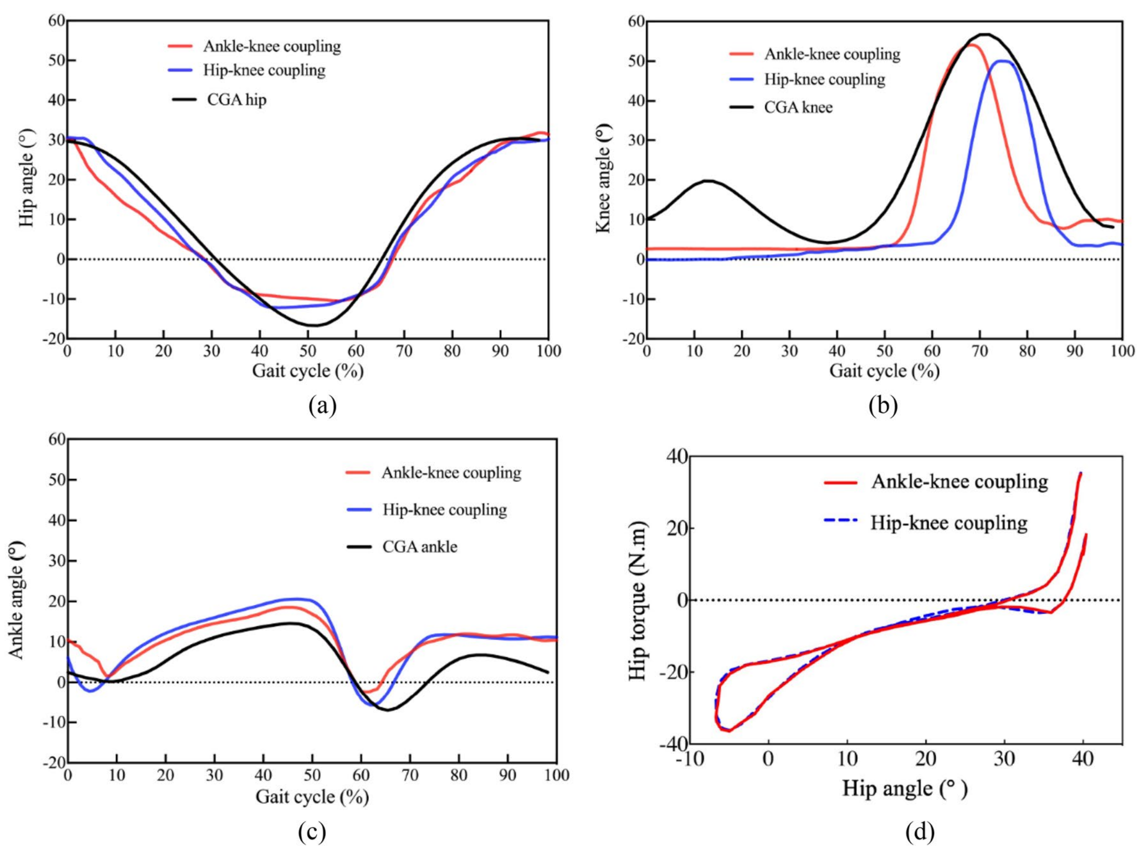


Fig. 15 Walking gait behavior in the two coupled mechanisms of the lower limb exoskeleton and comparison among three gait data

knee joint flexion and extension and the toe clearance. The experimental results also show that the flexion of the knee joint produced by dynamic joint coupled is very similar to the peak flexion angles of the CGA data, and almost the same amount of knee flexion is produced. The results further indicate that as long as there is proper hip drive, very little knee power or no knee drive is required to generate a satisfactory level walking gait.

5.2 Knee Spring Damper Performance Testing

As mentioned in the previous chapter, the passive knee exoskeleton adopts an enlarged hip joint swing trajectory to improve the level of movement. However, due to the high speed and insufficient knee damping, the knee joint may produce excessively aggressive swing-extension movements. This residual momentum could cause undesirable disturbances and spread to the user's legs.

To minimize this disturbance, a simple spring damping system was established to capture excess knee extension energy, as shown in Figs. 5 and 7, which uses a torsion spring as an energy storage element. In addition, two test conditions are defined to verify the auxiliary performance of the spring element, respectively: (1) assist with spring and (2) assist without spring. Two tests of each condition are completed for a total of four tests. This experiment is mainly to observe the changes of knee angle, peak knee angle and knee angular velocity over time to explore the effect of spring assistance on knee flexion and extension. And the experimental data and results are shown in Fig. 16.

First, the data are post-processed to analyze the kinematics data of the knee joint angle from the attitude angle transducer. The knee joint angular velocity is calculated using the approximate value of the first derivative of the knee joint angle. The following results show the overall average value of knee joint angle and knee joint angular velocity (Fig. 15) over time for each test condition, as well as the average peak knee angle reached in each case and the percentage of gait cycle corresponding to each gait phase.

Preliminary experiments have shown that, without an exaggerated hip swing trajectory, the knee cannot be fully extended without a spring. The results indicate that it is usually impossible to return to the full knee extension required for the stance phase. For a knee joint with a spring, before the knee joint swing- extension, the spring is in a compressed state due to the inertia of the calf. After entering the swing-extension, the knee joint is driven by inertia to release energy from the spring to complete fully knee extension and absorb excess energy. This is also a strategy to assist an alternative method of knee extension.

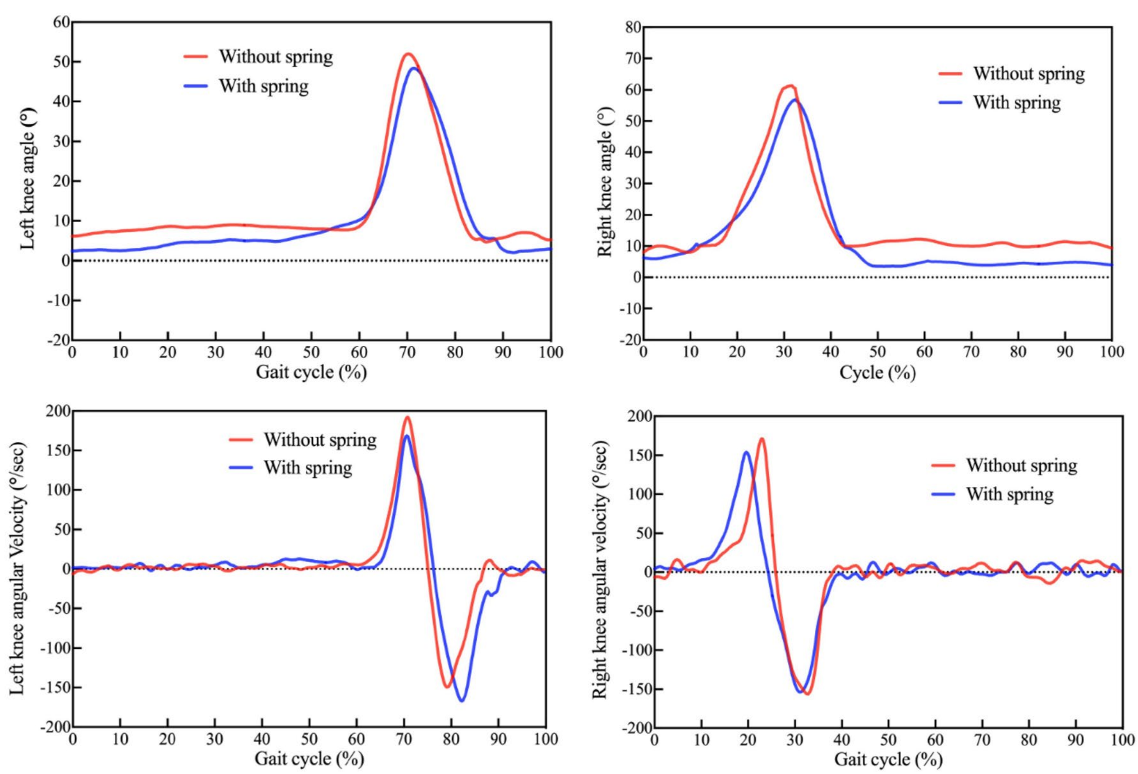


Fig. 16 Comparison of average (**a**) left and (**b**) right knee angle (top) and angular velocity (bottom) with gas spring assist and without gas spring assist. First peak is angular velocity during knee flexion and second peak is angular velocity during knee extension

In addition to assisting the swing and extension of the left and right legs, the spring can also help increase cushioning. It can be seen from the peak flexion angle. There is a small difference in peak flexion angle between the two knee joints. In the case of springs, the peak knee joint angle changes less than without springs. This change may be caused by the cushioning of the spring, which affects the peak flexion angle.

5.3 Sitting and Standing Posture Transformation Test

Finally, the posture transition experiment aims to evaluate whether the exoskeleton can achieve posture assistance from sitting to standing, and whether the gas spring assist mechanism can give positive feedback on posture transition.

Figure 17 shows the posture transition image sequence from standing-sitting to sitting-standing. It can be seen from the experimental results that with the mutual cooperation of the hip motor and the gas spring booster mechanism, the user achieves a smooth sitting-to-stand transition with the help of the exoskeleton. However, we noticed that the

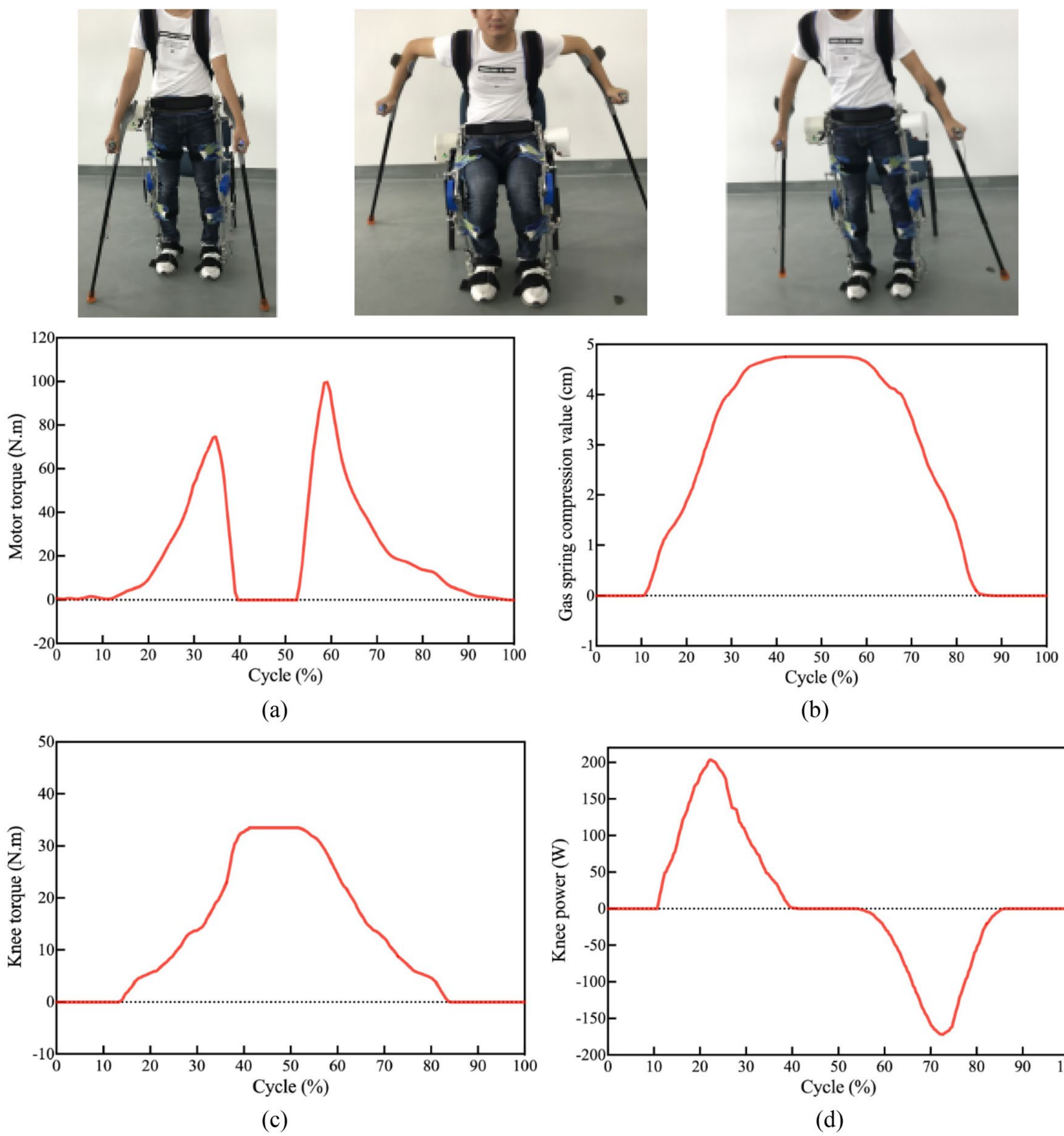


Fig. 17 Sitting and standing posture transition. **a** The image sequence of the posture transition. **b** Experimental data of sitting to standing, including motor torque, gas spring compression trajectory, knee torque with the gas spring and knee power

hip torque required for the standing-to-sitting movement is less than the hip torque required for the sitting-to-standing. This may be due to the fact that the assistive moments of the hip and knee joints are insufficient to support the torso when sitting down, causing the user to accelerate the sitting down under their own gravity. For the gas spring booster mechanism, its moment arm is designed to produce a higher moment when the knee joint is nearly fully flexed, and as the extension angle of the knee joint increases, the moment will gradually decrease. The torque generated at the knee joint is highest at the beginning of standing to better initiate knee extension.

5.4 Trajectory Comparison of Ambulation Beneath the Two Coupling Mechanisms

Figure 18 shows a direct comparison between the Ankle-knee Coupling gait and hip-knee Coupling gait for joint trajectory during walking. The testing results show that the general shape of the two experimental joint trajectory profiles generally consistent. It is can be seen that the two steps exhibit similar gait characteristics. For the hip motion trajectory, the two steps exhibit similar gait characteristics. For the knee motion trajectory, the gait could produce 55°–60° of knee flexion which provided sufficient toe-clearance during walking. The exoskeleton knee starts and ends almost full-extended to enable the locking needed at the knee during weight bearing periods. For the Ankle-knee Coupling gait, the knee and ankle motion reaching the maximum prior to hip-knee Coupling gait. The possible reason is that the motion of ankle plantar flexion reaches the maximum firstly by the wearer controlled, so that the knee joint is unlocked earlier and enters the swing phase. And for the hip-knee Coupling gait, the hip joint motion is directly controlled by the motor, the movement time is determined and accurate and less affected by the human. Therefore, the trajectories of the knee joints of the two are obviously inconsistent during the swing phase.

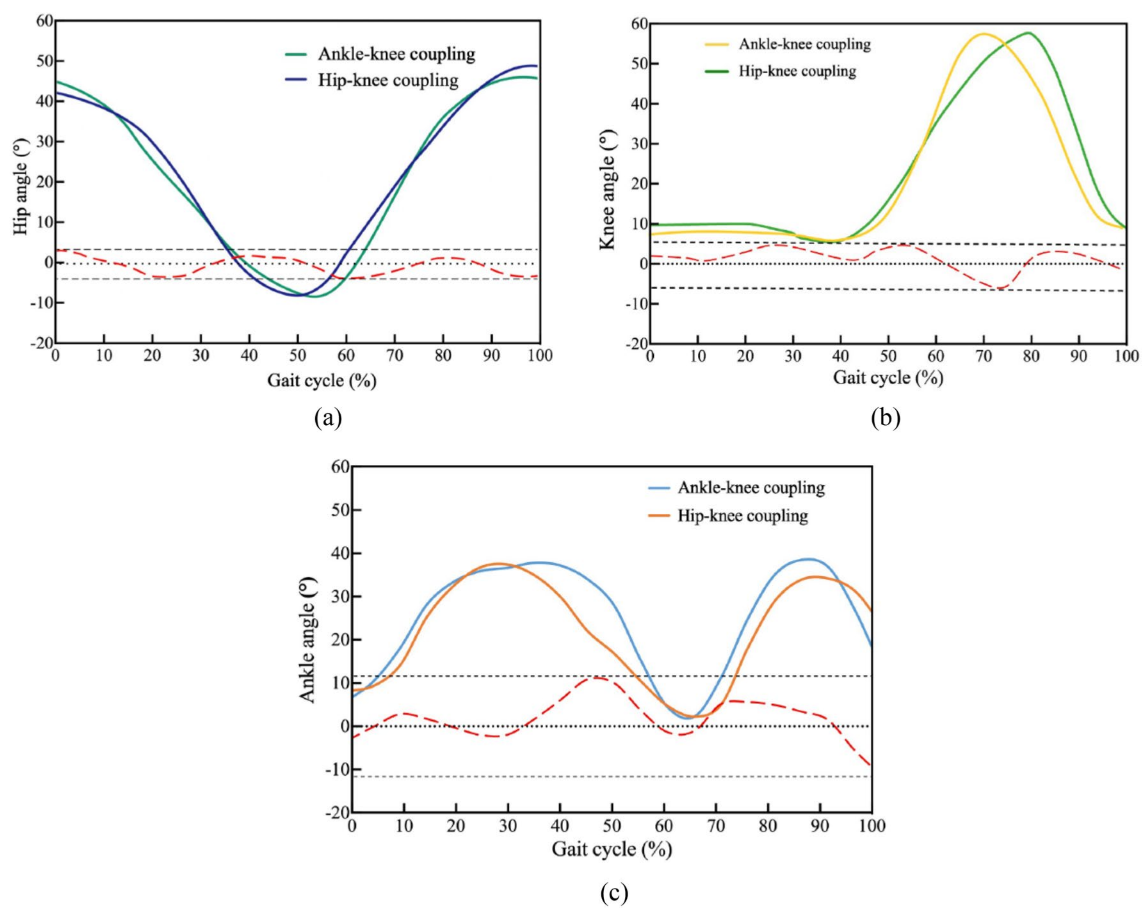


Fig. 18 Trajectory comparison of ambulation beneath the two coupling mechanisms. The solid line represents the joint motion trajectory, and the dotted line represents the average difference value between the two gaits

5.5 Knee Exoskeleton Optimization Design

The knee joint mechanism is the core component of the exoskeleton system. The locking and unlocking behavior of the knee joint is coordinated with the gait of the lower limbs to complete the basic walking function. The design of an exoskeleton knee joint has two very basic functional requirements. Firstly, the knees must be locked in the standing phase since the legs need to bear weight. Secondly, the knees must be unlocked in the swing phase since the toe clearance needs to be increased.

The optimized design of the knee joint aims to break away from the rope and adopt a more intelligent method to realize the series operation of the knee joint. The single pawl lock knee design allows the pawl on the thigh to engage with the teeth on the shank and lock the knee when the knee reaches the fully extended position. It can be seen from Fig. 19, as long as the hip joint moves to the proper position, the pawl will be released.

The knee joint transformation component includes a walking posture transformation component and a sitting posture transformation component; wherein the walking posture transformation component includes a unidirectional locking tooth and a first pawl. The first pawl is arranged on the calf rod, and the unidirectional locking tooth mechanism is arranged on the end of the thigh rod body. The sitting and standing posture transformation assembly includes a ratchet wheel, a second pawl mechanism, a third pawl mechanism, and a gas spring assembly. During walking, the push rod motor pushes the first pawl upward to clamp the unidirectional locking tooth, and the knee joint realizes the standing lock. At this time, the knee joint is standing and cannot be flexed. When the push rod motor is reset downwards, the first pawl slides down from the lock tooth synchronously to realize the reset, so that the knee joint is unlocked, and the user can perform knee flexion. The two states of the knee joint are transformed into each other, and the stance phase lock swing phase flexion is completed. At the beginning of the sitting posture, the push rod motor continues to move downwards, pushing the second pawl to move downwards, the pawl teeth contact with the ratchet teeth and lock the gas spring linkage mechanism. When the exoskeleton continues to change to the sitting position, the gas spring begins to compress and store energy until it is fully seated. At this time, the third pawl engages and locks with the ratchet

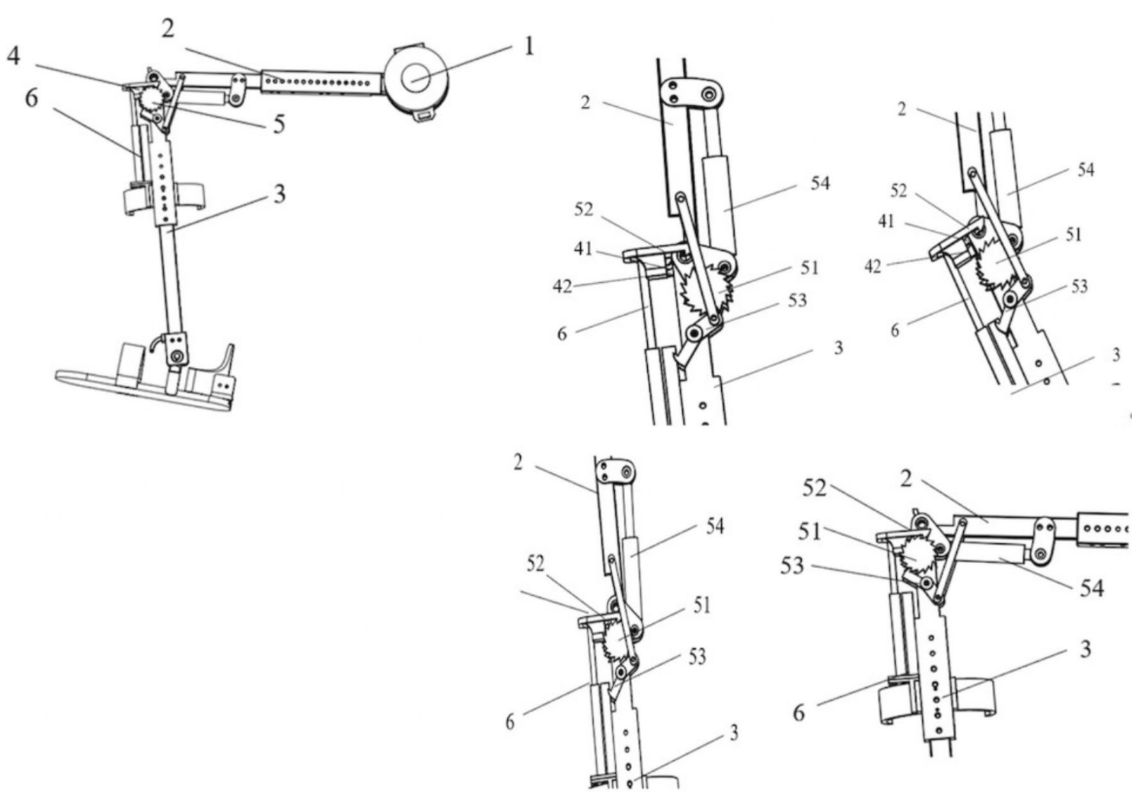


Fig. 19 Description of knee exoskeleton optimization design. 1—powered hip joint, 2—thigh link, 3—shank link, 4—walking posture transformation component, 5—sitting posture transformation component, 6—push rod motor, 41—a first pawl, 42—a unidirectional locking tooth, 51—a ratchet wheel, 52—a second pawl mechanism, 53—a third pawl mechanism, 54—a gas spring assembly. These components are coupled with each other to form the knee joint transmission mechanism

teeth to prevent the calf from being ejected by the elastic force of the gas spring.

The advantage of this mechanism is that when the knee enters the stance phase at any position, the single pawl can always instantly lock the knee joint to provide good safety performance. Even when the knee joint is not enough to reach full extension in an emergency, the knee can be safely locked.

6 Conclusion

This article mainly seeks a new method of minimally actuated rehabilitation exoskeleton devices to provide more lightweight mobility assistance for patients with lower limb paralysis. The term "minimum actuated" is particularly emphasized, because one of the main research goals of this work is to explore alternative methods of exoskeleton drive and seek a lighter and more compact joint motion assistance method. The two devices introduced in this study only use single-joint power assistance, and rely on two different types of coupling mechanisms to produce the desired ideal motion. The joint coupled mechanism has been preliminarily proved to be a potential and creative method of the minimally actuated exoskeleton to eliminate the need of knee actuation for gait assistance.

Joint coupling exoskeleton may be an important indicator to promote the further development of the exoskeleton, although its sitting and standing assistance is not as obvious as that provided by the multi-joint driven exoskeleton. Obviously, the demand for such simple, portable, mobile-centric auxiliary devices is objective [39], because these devices do not have very complex driving schemes and functions, and people are more willing to trust this device. Although they are inherently unable to perform more complex joint movements, they actually ultimately provide a higher level of maneuverability and adaptability due to their lighter weight.

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Author contributions HL: methodology, writing—original draft preparation software. HY: conceptualization. YC: writing, reviewing and editing. XT: experimental planning and interpretation of data. DW: data curation, visualization. QM: software, validation. QD: experimental design and planning.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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