

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

ScienceDirect

journal homepage: <http://ees.elsevier.com/jot>



ORIGINAL ARTICLE

# A wearable exoskeleton suit for motion assistance to paralysed patients



Bing Chen <sup>a,b</sup>, Chun-Hao Zhong <sup>b</sup>, Xuan Zhao <sup>b</sup>, Hao Ma <sup>b</sup>,  
Xiao Guan <sup>b</sup>, Xi Li <sup>a</sup>, Feng-Yan Liang <sup>c</sup>, Jack Chun Yiu Cheng <sup>a</sup>,  
Ling Qin <sup>a,\*</sup>, Sheung-Wai Law <sup>a,\*</sup>, Wei-Hsin Liao <sup>b,\*</sup>

<sup>a</sup> Department of Orthopaedics and Traumatology and Innovative Orthopaedic Biomaterial and Drug Translational Research Laboratory of Li Ka Shing Institute of Health Sciences, The Chinese University of Hong Kong, Shatin, Hong Kong, China

<sup>b</sup> Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong, China

<sup>c</sup> Division of Biomedical Engineering, The Chinese University of Hong Kong, Shatin, Hong Kong, China

Received 16 December 2016; received in revised form 18 February 2017; accepted 27 February 2017

Available online 23 March 2017

## KEYWORDS

exoskeleton;  
motion assistance;  
paralysed patients

**Summary** *Background/Objective:* The number of patients paralysed due to stroke, spinal cord injury, or other related diseases is increasing. In order to improve the physical and mental health of these patients, robotic devices that can help them to regain the mobility to stand and walk are highly desirable. The aim of this study is to develop a wearable exoskeleton suit to help paralysed patients regain the ability to stand up/sit down (STS) and walk.

*Methods:* A lower extremity exoskeleton named CUHK-EXO was developed with considerations of ergonomics, user-friendly interface, safety, and comfort. The mechanical structure, human-machine interface, reference trajectories of the exoskeleton hip and knee joints, and control architecture of CUHK-EXO were designed. Clinical trials with a paralysed patient were performed to validate the effectiveness of the whole system design.

*Results:* With the assistance provided by CUHK-EXO, the paralysed patient was able to STS and walk. As designed, the actual joint angles of the exoskeleton well followed the designed reference trajectories, and assistive torques generated from the exoskeleton actuators were able to support the patient's STS and walking motions.

*Conclusion:* The whole system design of CUHK-EXO is effective and can be optimised for clinical application. The exoskeleton can provide proper assistance in enabling paralysed patients to STS and walk.

\* Corresponding authors. Room 312, William M.W. Mong Engineering Building, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China (W.-H. Liao); Department of Orthopaedic & Traumatology, 5/F, Clinical Science Building, Prince of Wales Hospital, Shatin, Hong Kong, China (S.-W. Law); Department of Orthopaedic & Traumatology, 5/F, Clinical Science Building, Prince of Wales Hospital, Shatin, Hong Kong, China (L. Qin). Tel: +852 3943 8341.

E-mail addresses: [qin@ort.cuhk.edu.hk](mailto:qin@ort.cuhk.edu.hk) (L. Qin), [lawsw@ort.cuhk.edu.hk](mailto:lawsw@ort.cuhk.edu.hk) (S.-W. Law), [whliao@cuhk.edu.hk](mailto:whliao@cuhk.edu.hk) (W.-H. Liao).

© 2017 The Authors. Published by Elsevier (Singapore) Pte Ltd on behalf of Chinese Speaking Orthopaedic Society. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

### The translational potential of this article

In recent years, wearable exoskeleton suits have been developed and utilised for rehabilitation and health-care purposes in the US, Europe, and Japan and showed a great potential in the market. The wearable exoskeleton suit we developed is first-of-a-kind device designed and implemented locally for paralysed patients in Hong Kong; with our innovative technologies, this device will produce great social benefits and commercial value.

## Introduction

The number of patients paralysed due to stroke, spinal cord injury (SCI), postpolio, or other related diseases in orthopaedics is increasing [1,2]. The induced paralysis puts these people at an increasing risk of secondary complications, such as osteoporosis, muscle atrophy, diabetes, insulin resistance, and pressure ulcers. Especially, SCI patients are mainly young people who need to work to support daily life [3]. All those have a heavy and long-term financial burden imposed on both families and health care systems. Thus, medical devices that can help them stand and walk are highly desirable to improve their quality of life. Traditional knee-ankle-foot orthoses (KAFOs) without actuators have been developed to provide legged mobility for some patients with impaired mobility and to reduce the occurrences of secondary complications [3]. However, KAFOs are abandoned by most of the paralysed patients due to the unnatural and metabolically expensive movements required during the use of KAFOs, such as lateral sway of the upper body, hip elevation in the swing phase, and vaulting on the contralateral leg [4]. In addition, for some paralysed patients without sufficient upper body strength, KAFOs cannot provide enough assistance and are not suitable.

During the past decade, enormous progress has been made in the development of lower extremity exoskeletons (LEEs) [5,6]. LEEs are wearable robotic systems, which can provide the wearers with user-initiated mobility by applying external force/torque to their lower limbs with the equipped actuators. They are human-machine cooperative systems and integrate both human intelligence and robot power. Currently, LEEs mainly have three applications, including human strength augmentation, gait rehabilitation, and human locomotion assistance [5]. They can augment human strength for able-bodied workers with heavy duty tasks, provide gait rehabilitation for patients with mobility disorders in the rehabilitation of musculoskeletal strength, motor control, and gait, and provide

motion assistance for paralysed patients who lose motor and sensory functions in their lower limbs.

With the increasing number of people suffering from impaired mobility, LEEs have been applied in gait rehabilitation and motion assistance. In the past few years, great improvements have been made in their performance, such as the intelligence, wearability, and portability of LEEs for motion assistance purposes, and several LEEs have been developed to help people with impaired mobility, such as ReWalk [7], HAL [8], and Vanderbilt Exoskeleton [9]. However, many challenging problems still remain in the development and application of LEEs, such as control, actuators, and human-machine interface (HMI).

In this study, we present a wearable exoskeleton suit named CUHK-EXO developed to help paralysed patients perform essential daily life motions, such as stand up/sit down (STS) and walk. The mechanical structure of CUHK-EXO is designed to be anthropomorphic to ensure maximum harmony between the wearer's motion and exoskeleton. Hip and ankle angle adjusters are designed to make the distance between the two feet smaller than that of the two hip joints as that of human beings when walking; thus, the wearer is able to transfer his/her centre of gravity (COG) left and right more easily during walking since the two feet are closer. A smart phone application (App) and a pair of smart crutches are developed as a part of HMI. Using the smart phone App, both the physical therapist and patient's family member can help the patient to operate the exoskeleton; thus, the convenience in the usage of CUHK-EXO is improved. Furthermore, more information of the human exoskeleton system (HES) can be obtained from the smart crutches, which can be used for the intelligent control of the exoskeleton. Reference trajectories of CUHK-EXO are generated based on the motion capture data with a motion capture system. As for the walking motion, the captured hip and knee joint trajectories are further modified according to the leg geometry constraints to enable sufficient toe clearance and effective walking.

In this study, the mechanical structure of CUHK-EXO is introduced first, followed by the description of the HMI of the exoskeleton. Next, the reference trajectories of the exoskeleton hip and knee joints are introduced, and the controller architecture of CUHK-EXO is presented. Finally, pilot clinical trials are performed to demonstrate the effectiveness of CUHK-EXO system.

## Mechanical design of CUHK-EXO

Function of the exoskeleton mechanical structure is to support the wearer's body weight, transfer the assistive force/torque from actuators to the wearer, and finally help the wearer to regain mobility. The mechanical structure is expected to be lightweight, strong, safe, adaptive to different wearers' body sizes, and comfortable to wear. Thus, it is

designed considering ergonomics and biomechanics of human movement to make good wearing comfort and minimal misalignment between the wearer and exoskeleton.

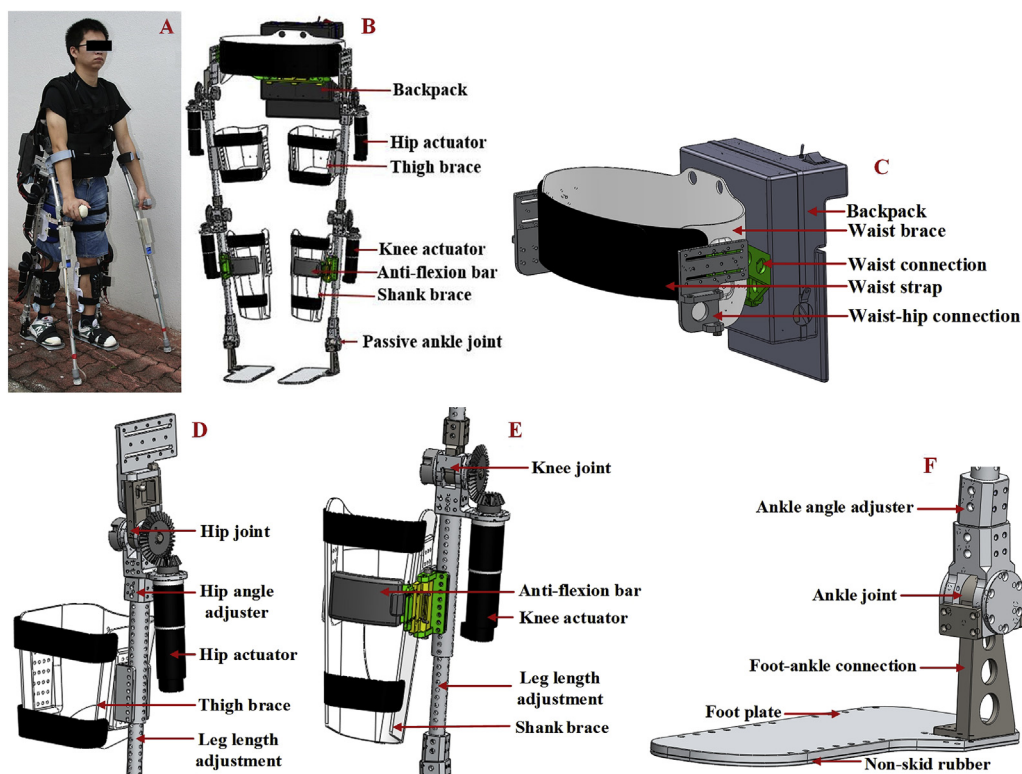
## Overall mechanical structure

Human lower limbs have seven degrees of freedom (DOFs) in each leg, with three at the hip joint, one at the knee joint, and three at the ankle joint. Generally, human gait and other daily locomotion are three dimensional and can be described in three primary planes of human body [10,11], including the frontal plane, transversal plane, and sagittal plane. The frontal plane divides the body into the anterior and posterior parts, and human lower limb motions in this plane are mainly responsible for balancing the body weight. The transversal plane divides the body into the upper and lower parts, and motions in this plane are to ensure the body advances on a straight line. The sagittal plane divides the body into the right and left parts, and motions in this plane are mainly responsible for moving the body forward. Among these planes, the sagittal plane that describes the person's forward and backward motions is the most important one. This is because in most of our movements, the largest torque and power in the lower limb joints takes place in this plane [11,12].

Theoretically, it would be better to design LEE with a similar number of DOFs to human lower limbs to achieve comfortable motion assistance. However, in practice, it is

difficult to actuate all the joints of LEE mimicking human anatomy due to the space and weight limitation. Moreover, it is not necessary to make all LEE joints active [10]. CUHK-EXO (Figure 1A) is designed with seven DOFs in total with three for the right leg and four for the left leg. Among these DOFs, the hip and knee joints in the flexion/extension direction are active to provide motion assistance in the sagittal plane, whereas the ankle joints are passive. The active joints (hip and knee flexion/extension) of CUHK-EXO are actuated by DC motors (Maxon RE40, 150 W, Maxon Motor, Sachseln, Switzerland) through planetary gearboxes and bevel gears. Since the number of DOFs of CUHK-EXO is less than that of human lower limbs, a pair of smart crutches is developed to achieve similar functions of human motions in the frontal plane and transversal plane including balancing the body weight and controlling the motion direction (Figure 1A).

The overall mechanical structure of CUHK-EXO is shown in Figure 1B. It is mainly made of aluminium alloy (7075-T651) in order to realise light weight and high stiffness. In addition, some other materials such as the steel for the transmission shaft and high-density polyethylene for the braces are used. The mechanical structure of CUHK-EXO is designed to be adjustable, and it can accommodate wearers with a range of height from 1.55 m to 1.85 m. Braces and straps are designed at the waist, thigh, shank, and foot segments to couple the wearer to the exoskeleton, and hence transmit the assistive force/torque from the exoskeleton to the wearer. Integrated padding is placed



**Figure 1** The wearable exoskeleton suit CUHK-EXO. (A) A healthy participant wearing the wearable exoskeleton suit CUHK-EXO; (B) diagram of the overall mechanical structure of CUHK-EXO; (C) waist structure of CUHK-EXO; (D) thigh structure of CUHK-EXO; (E) shank structure of CUHK-EXO. (F) foot structure of CUHK-EXO.

**Table 1** Joint motion range of human and CUHK-EXO.<sup>a</sup>

Joint	Human (°)	CUHK-EXO (°)
Hip	−65 to 120	−30 to 120
Knee	0 to (120 to −160)	0 to 120
Ankle	(−40 to −50) to 20	0 to 15

<sup>a</sup> Values for joint motion range are approximate.

around the braces to make the wearer comfortable. According to the motion range of human joints [11], the motion range of CUHK-EXO is determined as given in Table 1. In this study, signs for the joint angles are defined as follows: flexion direction of each joint angle is positive, and each joint angle is zero when the HES is in the upright posture. It can be seen from Table 1 that the joint motion ranges of the exoskeleton are designed to be smaller than that of humans to protect the wearer. These motion ranges are large enough for paralysed patients to perform basic daily life motions with the assistance of CUHK-EXO, including STS, walk, and walk upstairs/downstairs. In order to ensure the safety, mechanical stops are designed on the extreme ends of the allowed motion range of each DOF.

### Waist Structure

The mechanical structure of the exoskeleton waist part should have high stiffness and strength since it needs to withstand the weight of the swing leg of the HES to resist leg drop down in the swing phase of a gait cycle [7,12]. The waist part of CUHK-EXO is mainly composed of the backpack, waist strap, waist connection, waist brace, and waist–hip connection, as shown in Figure 1C. The motor drivers, embedded controllers, and power supply (lithium polymer batteries) of CUHK-EXO are placed in the backpack. The waist connection can be adapted to different wearers with different waist widths.

### Leg structure

Figures 1D and 1E show the thigh and shank structure of CUHK-EXO, respectively. The left hip joint (Figure 1D) has two DOFs including the hip flexion/extension and hip external rotation. After the wearer wears the exoskeleton, the DOF of the hip external rotation will be locked, whereas the right hip joint has only one DOF (flexion/extension). Both thigh and shank of CUHK-EXO are designed with a leg length adjustment mechanism to accommodate different wearers. In the thigh structure, a hip angle adjuster is designed to adjust the adduction angle of the exoskeleton leg. It makes the distance between the two feet smaller than that of the two hip joints; thus, it will be easier for the wearer to transfer his/her COG left and right during walking. The knee joint has one flexion/extension DOF. In order to prevent the wearer's knee joint from bending in the standing posture, an antiflexion bar is designed in the shank structure (Figure 1E). The antiflexion bar is designed to be adjustable with three DOFs to better fit for different wearers.

### Foot structure

The foot structure of CUHK-EXO is shown in Figure 1F. The ankle joint has one DOF (plantarflexion/dorsiflexion). Due to the hip angle adjuster, the ankle angle adjuster is also designed to make the foot parallel with the ground. The foot is composed of the foot plate and non-skid rubber. The foot plate is connected to the ankle joint rigidly, and the non-skid rubber is placed on the sole to increase the frictional force between the foot and ground. In addition, four force-sensing resistor (FSR) sensors are placed at specific points between the foot plate and non-skid rubber to measure the ground reaction force (GRF) applied to the foot.

### HMI of CUHK-EXO

User-friendly HMI is developed for CUHK-EXO. A smart phone App, a pair of smart crutches, and a multiple sensor system are designed to make the information exchange among the wearer, therapist, and exoskeleton smoother and more effective [13].

### Design of smart phone App

In the initial training stage of paralysed patients, the patients are not familiar with the exoskeleton; thus, physical therapists will help the patients to operate the exoskeleton through the developed smart phone App. In this study, the smart phone App is designed for both therapists and patients (Figure 2A). The therapists can operate the exoskeleton through the buttons in the Operation view (Figure 2B), and they can also monitor the exoskeleton joint angles and torques in real time through the Motion Monitoring view (Figure 2C). However, the paralysed patients can check their performance summary when using the exoskeleton through the Performance Evaluation view (Figure 2D). The developed smart phone App improves the safety and convenience in the usage of CUHK-EXO.

### Design of smart crutches

In order to help the wearer keep balance and support the body weight, a pair of smart crutches is developed as shown in Figure 2E. The crutches are designed with FSR sensors, inertial measurement units (IMUs), Bluetooth modules, microcontroller units (Arduino Micro, ARDUINO, Milan, Italy), and lithium polymer batteries (7.4 V/850 mAh). The FSR sensors are placed at the bottom of crutches to measure the GRFs applied to crutches, thus, the wearer's effort (supporting force from the wearer's arms) can be estimated during the motion assistance. The IMUs are used to acquire the crutches orientation information. Using the Bluetooth modules, the sensor data are sent to the main controller in the backpack. The right crutch is designed with several buttons to control the power on/power off of CUHK-EXO and select the motion types. Also, its handle has ergonomic design so that the wearer can hold the crutch and press the buttons comfortably. With the smart crutches, more information of the HES can be obtained for the



**Figure 2** Human–machine interface of CUHK-EXO. (A) Login In view of smart phone App; (B) Operation view of smart phone App; (C) Motion Monitoring view of smart phone App; (D) Performance Evaluation view of smart phone App; (E) design of the smart crutches. App = application; FSR = force-sensing resistor; IMU = inertial measurement unit.

intelligent control, and the wearer can operate CUHK-EXO conveniently, comfortably, and safely.

### Multiple sensor system

A multiple sensor system is established for CUHK-EXO to acquire the information of the HES for feedback control. Encoders and potentiometers are mounted at CUHK-EXO hip and knee joints to obtain the joint angle and angular

velocity information. IMUs are mounted at the crutches and the exoskeleton trunk and shanks to acquire the orientation information. In addition, FSR sensors are designed at the feet and crutches to measure the GRFs. With these sensor data, feedback control of the exoskeleton is realised. The wearer's motion intention can also be estimated based on the multiple sensor system.

Three operation modes are developed for CUHK-EXO corresponding to the different training stages of paralysed patients. In the initial stage, the physical therapist or the

patient's family member can help the patient to operate CUHK-EXO through the smart phone App. In the second stage, the patient can operate the exoskeleton himself/herself through the crutch buttons. In the final stage, the patient can operate the exoskeleton with natural movements of the upper body, and his/her motion intention is automatically detected by the exoskeleton through the multiple sensor information.

## Development of reference trajectories

Reference trajectories of CUHK-EXO hip and knee joints are determined through preliminary tests using the motion capture system (Vicon Motion Systems Ltd., Oxford, UK).

## Motion pattern designed for paralysed patients

A reference STS motion pattern is designed for paralysed patients based on the discussion with clinical doctors, as shown in Figure 3. The stand-up motion includes the sitting

posture, trunk flexion, hip flexion, hip and knee extension, and standing posture, and the sit down motion includes the standing posture, trunk flexion, hip flexion, hip and knee extension, and sitting posture. In the STS motion, the wearer uses a pair of crutches to help support and balance his/her body weight, and the crutches are placed at different positions (front or back) in different phases of the STS motion.

A human gait cycle is composed of alternating stance phase and swing phase [14,15]. During the use of CUHK-EXO, the wearers need to use a pair of smart crutches to help keep balance and transfer their COG with the help of their upper body strength. Thus, the walking pattern designed for paralysed patients with CUHK-EXO is different from that of healthy people, as shown in Figure 4. It includes two single-leg stance phases (SLSPs) and two double-leg stance phases (DLSPs). During each phase, there are at least three supporting points for the HES to maintain balance. During the DLSP, both legs of the HES are in the stance phase, and the wearer will swing the crutches forward one by one and place them at proper positions. During

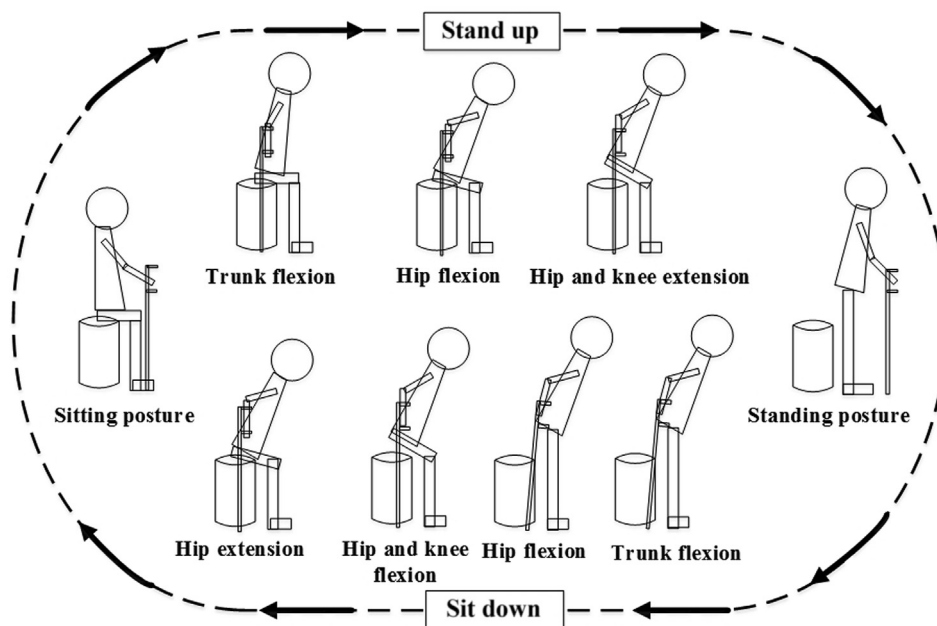


Figure 3 The stand up/sit down motion pattern for paralysed patients.

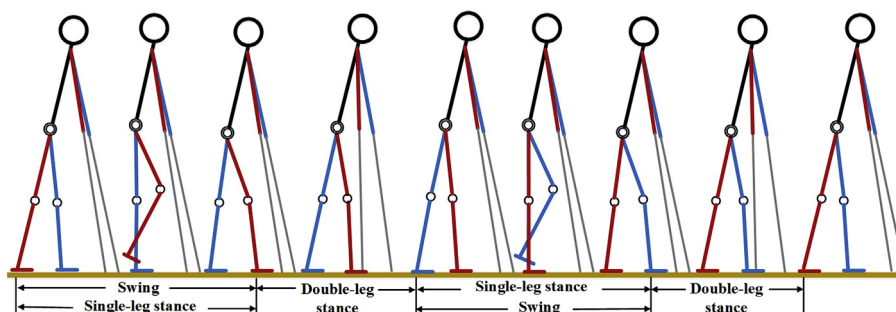


Figure 4 A gait cycle in the walking pattern designed for paralysed patients. The patient uses a pair of crutches to help keep balance and support. The grey lines represent the crutches.

this phase, the wearer will also try to move his/her COG from the rear leg to the front leg with the upper body strength. During the SLSP, one leg of the HES will be swung forward with the assistance of the exoskeleton, and the other leg is in the stance phase. In addition, both crutches are on the ground.

### Development of reference trajectories

Preliminary tests were performed with the motion capture system (Figure 5A) to obtain reference trajectories of the exoskeleton hip and knee joints. In the testing, a healthy participant wore CUHK-EXO without turning on actuators. Sixteen reflective markers were attached at anatomical landmarks of the lower body of the HES. Then, the participant performed the STS and walking motions according to the motion pattern designed for paralysed patients. Three dimensional kinematic data of the participant's lower body in the STS and walking motions were obtained. Due to the unmatched joint functions between the participant's lower limbs and the designed exoskeleton, the captured data in the walking motion were modified to provide effective joint trajectories for the exoskeleton actuation. In the modification, joint angles at special timing were obtained based on the HES leg geometry constraints. Finally, using the curve fitting tool in the software MATLAB (MathWorks, Natick, Massachusetts, USA), the normalised reference trajectories of CUHK-EXO in the STS and walking motions were obtained, as shown in Figure 5. For different wearers, the designed reference trajectories, such as the gait period and amplitude, were modified according to their physical characteristics.

### Trajectories comparison

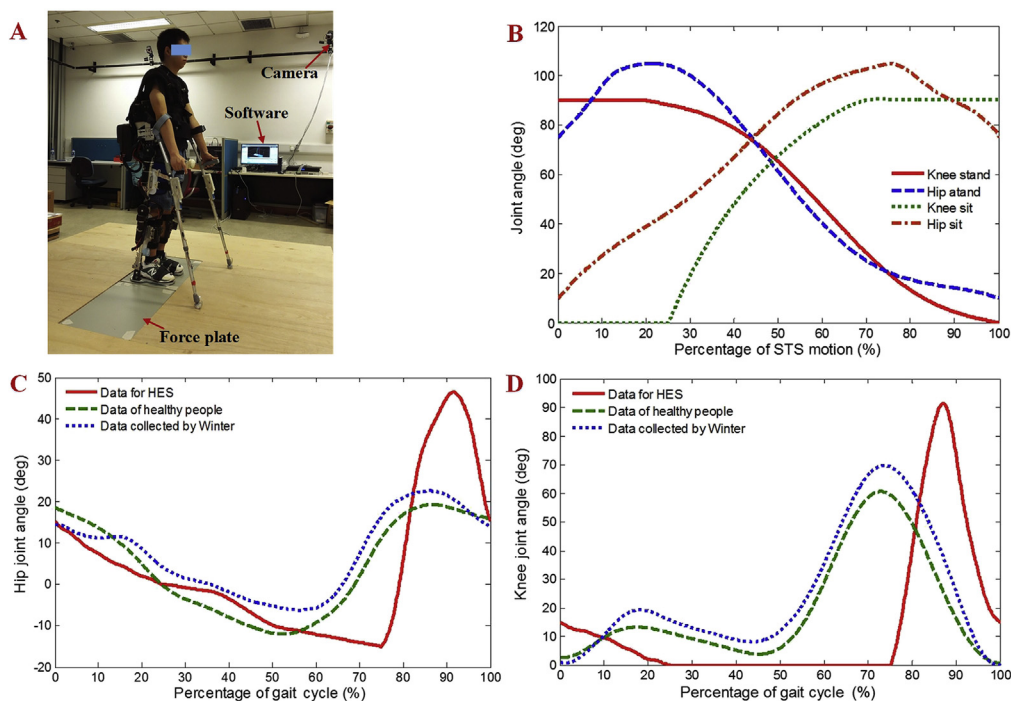
For the purpose of comparison, gait data of healthy people in a normal walking pattern collected in this study (dashed green line) and that of Winter [16] (dotted blue line) are also illustrated in Figures 5C and 5D. It can be seen that the peak joint angles of the exoskeleton hip and knee joints are larger than those of healthy people. The stance phase of the HES is also longer than that of healthy people (1–75% vs. 1–60% of the gait cycle). In addition, knee joints of the HES stance leg in the whole SLSP and the rear stance leg in the whole DLSP are straightened to well support the wearer's body weight, which is also different from that of healthy people. However, we can see that the developed reference trajectories for the HES have similar shapes and trends to that of healthy people; therefore, paralysed patients can walk with a nearly natural gait with the assistance of the exoskeleton.

### Performance evaluation and testing results

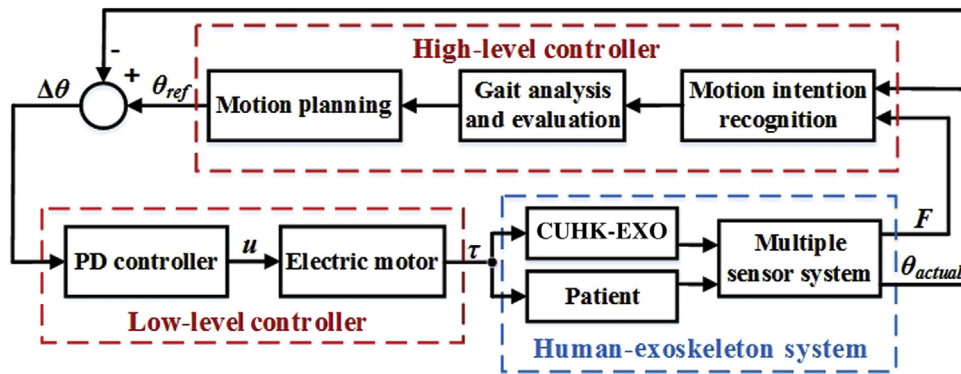
To evaluate the performance of CUHK-EXO, clinical trials in paralysed patients were conducted. The exoskeleton control architecture, clinical trials of STS and walking assistance, and testing results are presented in the following subsections.

### Control architecture of CUHK-EXO

CUHK-EXO is mainly developed for paralysed patients who lose the motor and sensory functions in their lower limbs.



**Figure 5** Reference trajectories of the exoskeleton hip and knee joints. (A) Optical motion capture system; (B) reference trajectories in the stand-up/sit down motion; (C) trajectories of hip joints in the walking motion; (D) trajectories of knee joints in the walking motion.



**Figure 6** Control architecture of CUHK-EXO. The function of the high-level controller is to generate reference trajectories for the exoskeleton according to the wearer's motion conditions, and that of the low-level controller is to regulate the actuators to output desired motions for the wearer. PD = proportional-derivative.

Control techniques based on electromyography signals or voluntary force/torque from the wearer's lower limbs applied to the exoskeleton are not suitable. In this study, position control is adopted, and the exoskeleton is controlled to follow the predefined reference trajectories. The control architecture of CUHK-EXO includes a high-level controller and a low-level controller as shown in Figure 6. The high-level controller is implemented in a PC, and it is designed to recognise the wearer's motion intention, analyse and evaluate his/her motion conditions, and finally generate reference trajectories for the exoskeleton. The low-level controller is implemented in the microcontroller Arduino DUE (ARDUINO, Milan, Italy), and its function is to collect the feedback sensor data, send them to the high-level controller, and regulate the actuators to output desired motions. Finally, assistive torques are generated from the exoskeleton actuators. Since the exoskeleton is well attached to the wearer through braces and straps, the wearer is able to perform daily life motions with the motion assistance from CUHK-EXO.

### Pilot clinical trials of STS assistance

Pilot clinical trials with a paralysed patient were conducted to validate the effectiveness of the whole system design of CUHK-EXO. The tests were conducted under the clinical ethical approval that was reviewed and approved by the Joint Chinese University of Hong Kong – New Territories East Cluster Clinical Research Ethics Committee (Joint CUHK-NTEC CREC, Ref. No.: 2015.262). The patient had poliomyelitis, and he had a limited sensory function but without any strength in his lower limbs. He used a wheelchair for mobility in his daily life. He is currently aged 28 years (1.65 m, 66 kg) and suffered from the disease when he was 2 years old. An informed consent was obtained from him before conducting the trials.

First, clinical trials of the STS assistance were performed. The exoskeleton and wearer form a closed loop as a human-exoskeleton cooperative system. The wearer's efforts are needed during the use of the exoskeleton; therefore, it is essential to train the patient to use the exoskeleton system. Before conducting the STS tests, the patient was trained to place the crutches at proper positions since the crutches should be placed at different

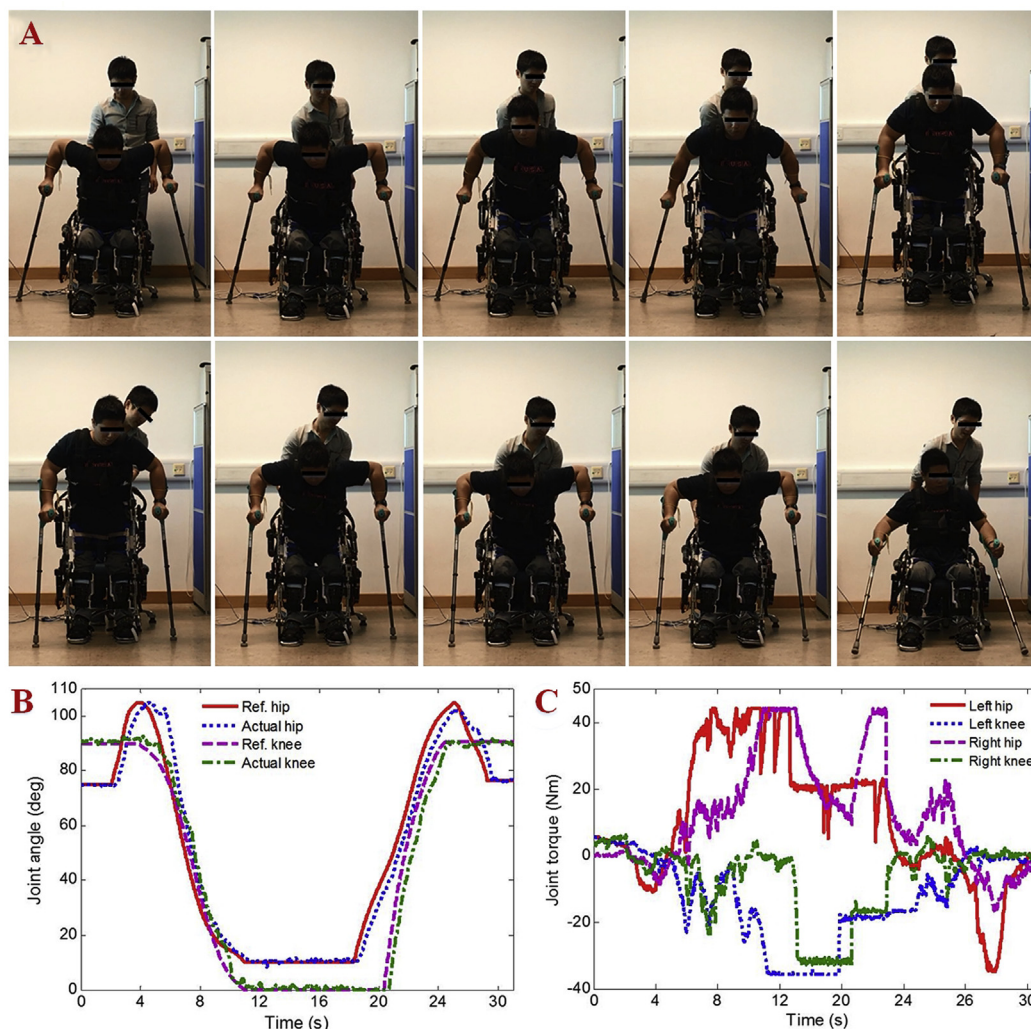
positions during different phases of the STS motion. All the training and clinical trials were performed under the supervision of physical therapists. Snapshots of the STS test are shown in Figure 7A. In the testing, the first author of this paper stood behind the patient to protect him from potential unexpected falling in the case of system failure. Two certified physiotherapists were engaged in all stages of trials. The patient was asked to report adverse events in all the training and clinical trials.

In the testing, the patient was initially in the seated position. Then, he put his arms back with the crutches and pressed the button corresponding to the stand-up motion. After that, the hip joints of CUHK-EXO started to flex to incline the patient's trunk forward, and subsequently both the exoskeleton hip and knee joints extended to help the patient stand up. Finally, he put his arms and crutches from back to front and stood up. A similar procedure was followed for the sit down motion. First, the patient put his arms from front to back with the crutches and pressed the button corresponding to the sit down motion. The exoskeleton hip joints started to flex to incline his trunk forward, and then both the exoskeleton hip and knee joints flexed to help the patient sit down. Finally, the patient's buttocks touched the chair and he got into the sitting posture. The reference trajectories and actual joint angles of the exoskeleton hip and knee joints in the STS motion are shown in Figure 7B, and the corresponding assistive torques are shown in Figure 7C. The duration for the stand-up motion is from 2 s to 11 s, and that for the sit down motion is from 18 s to 27 s. It can be seen that the assistive torques are large enough to help the patient perform the STS motion.

### Pilot clinical trials of walking assistance

Second, pilot clinical trials of the walking assistance were performed. The walking motion was more complicated than the STS motion, and the patient needed more training to maintain balance and transfer his COG. Corresponding to different training stages, different devices were used to help him to keep balance and protect him. In the first stage, he was trained to walk in a standard set of parallel bars, and he held the parallel bars to help support and





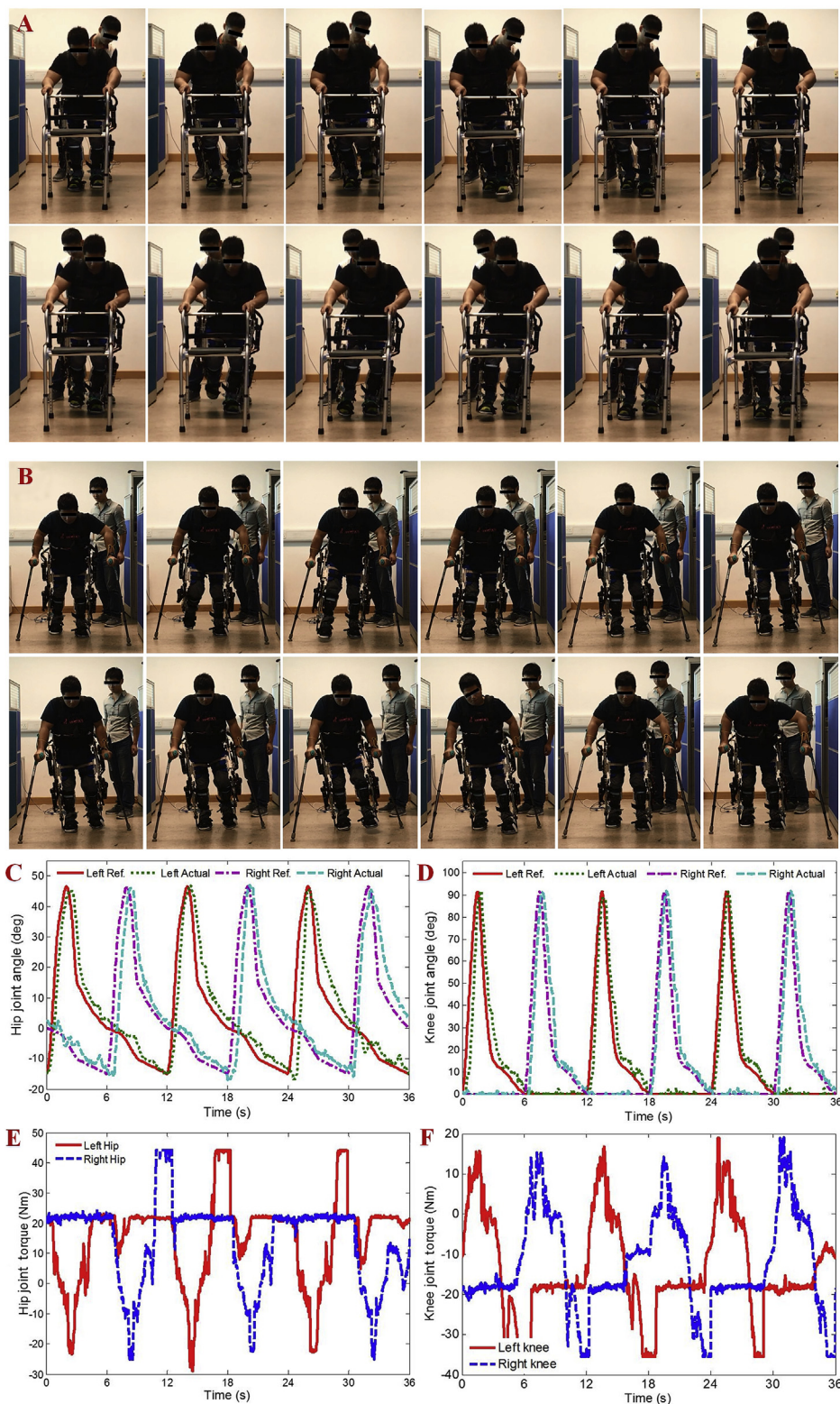
**Figure 7** Pilot clinical trials of the stand-up/sit down assistance. (A) Snapshots of the stand up/sit down test; (B) testing results: reference and actual joint angles of hip and knee joints; (C) testing results: assistive torques generated from hip and knee joint actuators.

balance his body weight. In addition, a hoist was connected to his waist through a slack sling to protect him from falling down in emergencies. After that stage, he was trained to use a walker to keep balance when walking with the motion assistance of CUHK-EXO (Figure 8A). The walker had four legs, and it was easy for him to learn to use it.

After the training to walk with a walker, he was trained to use a pair of crutches to keep balance when walking with the motion assistance provided by CUHK-EXO. Four training sessions were conducted. In each session, the training lasted for 2 hours. Currently, the patient with CUHK-EXO is able to walk smoothly with the support of crutches. It is more convenient to walk with crutches than with a four-leg walker. In addition, the crutches are lighter and they can be moved forward one by one easier by the patient. As for walking with crutches, it is important to place the crutches at suitable positions by the wearer to keep balance; therefore, we have trained the patient to use the crutches to keep balance before conducting the walking trials. Snapshots of the walking test are shown in Figure 8B.

In the testing, the patient swung the crutches forward one by one and transferred his COG from the rear leg to the front leg with the strength from his upper body during the DLSP. Corresponding to different swing legs, the crutches were placed at different positions to achieve better balance. If the patient would swing his left leg, he would place the left crutch closer to his left foot to well balance and support his body weight. Thus, the distance between the left foot and left crutch in the frontal plane was smaller than that between the right foot and right crutch. If the patient would swing his right leg, it was similar, and he would place the right crutch closer to his right foot. During the SLSP, the patient just held the crutches to keep balance and the exoskeleton helped him swing the leg forward.

Testing results of the walking test are shown in Figure 8. Figures 8C and 8D show the desired and actual joint angles of the exoskeleton hip and knee joints in three gait cycles. The assistive torques generated from the exoskeleton actuators are shown in Figures 8E and 8F. We can see that the actual joint angles well track the predefined reference trajectories with the assistance of CUHK-EXO. The testing



**Figure 8** Pilot clinical trials of the walking assistance. (A) Snapshots of the walking test with a walker; (B) snapshots of the walking test with a pair of crutches; (C) testing results: reference and actual joint angles of hip joints; (D) testing results: reference and actual joint angles of knee joints; (E) testing results: assistive torques generated from hip joint actuators; (F) testing results: assistive torques generated from knee joint actuators.

**Table 2** Comparison between CUHK-EXO and other LEEs.

Exoskeleton name	Application	Actuated DOF	Price (HK\$)
MINDWALKER [3]	Human locomotion assistance	Hip ab/adduction, hip flexion/extension, and knee flexion/extension	—
ReWalk [7]	Human locomotion assistance	Hip flexion/extension and knee flexion/extension	600,000
HAL [8]	Human strength augmentation and gait rehabilitation	Hip flexion/extension, knee flexion/extension, and ankle plantar/dorsiflexion	5000/month
Vanderbilt Exoskeleton [9]	Human locomotion assistance	Hip flexion/extension and knee flexion/extension	—
Ekso [19]	Gait rehabilitation and human locomotion assistance	Hip flexion/extension and knee flexion/extension	1,000,000
CUHK-EXO	Human locomotion assistance	Hip flexion/extension and knee flexion/extension	200,000

DOF = degrees of freedom; LEE = lower extremity exoskeletons.

results verify that CUHK-EXO can provide appropriate assistance to support the paralysed patient to walk with a customised gait pattern.

## Discussion

With the increasing number of patients suffering from paralysis, robotic devices that can assist them to regain the ability to stand and walk are expected. In this study, we aim to develop a LEE named CUHK-EXO to help paralysed patients to regain the mobility to STS and walk. The mechanical structure, HMI, reference trajectories, and control of the exoskeleton are designed, and the effectiveness of the whole system design has been validated through the pilot clinical trials with a paralysed patient.

The mechanical structure of CUHK-EXO is designed considering ergonomics and biomechanics of the human movement. The designed hip and ankle angle adjusters (Figures 1D and 1F) make the distance between the two feet smaller than that of the two hip joints; thus, the patient can transfer his/her COG left and right more easily during walking. The three-DOF antiflexion bar (Figure 1E) is able to prevent the wearer's knee joints from bending when the wearer is in the standing posture or in the stance phase when walking. User-friendly HMI, including a smart phone App, a pair of smart crutches, and a multiple sensor system, are developed for CUHK-EXO. In the initial training stages of paralysed patients, it is not safe for the patients to operate the exoskeleton since they are not familiar with the exoskeleton at these stages. The smart phone App enables the physical therapists to help the patients to operate and monitor the working status of the exoskeleton. The smart crutches are equipped with force sensors and IMU sensors; thus, more information of the HES can be obtained for the intelligent control of the exoskeleton.

In our pilot clinical trials, the STS and walking tests were performed with a paralysed patient. The wearer's efforts are needed during the use of the exoskeleton since the exoskeleton is a human-machine cooperative system. Therefore, training is essential for the patient. In the STS tests, the patient is trained to place the crutch at the front or back during different stages of the STS motion. As for the walking tests, the patient is trained to transfer his COG and place the crutches. During the DLSP, the patient is trained to transfer his COG from the rear leg to the front leg with his upper body strength and swing the crutches forward one by one. The

patient is also trained to place the left crutch closer to his left foot in the frontal plane if he would swing his left leg and place the right crutch closer to his right foot if he would swing his right leg. During the SLSP, the patient is trained to hold the crutches for balance and swing the leg forward with the assistance of CUHK-EXO. From the testing results, we can see that CUHK-EXO can provide proper assistance to help the patient perform the STS and walking motions.

To date, four training/clinical sessions have been conducted, and each session lasted 2 hours. There were no adverse events reported by the patient during the training/clinical trials. However, the current pilot study has limitation in the number of patients involved although it took significant time to develop the testing protocols and recruit the very first successful patient to participate into the study. The testing protocols included "assistive standing training" for facilitating cardiovascular preconditioning as well as an important "preconditioning" before starting gain training using CUHK-EXO [17,18]. Future studies involving more patients and comparisons with other commercially available devices are desirable. Herewith, we mainly summarised major similarity and/or differences between CUHK-EXO and other currently available LEEs in Table 2. It can be seen that most of the LEEs developed for the application of human locomotion assistance have the active joints in hip flexion/extension and knee flexion/extension, while the ankle joints are passive. In addition, a walker or a pair of crutches are needed for the motion assistance of paralysed patients with these LEEs. As for the prices, we can see that the commercially available LEEs are very expensive and may be affordable to only few people, while the expected price of CUHK-EXO would be estimated to be HK\$200,000 and more affordable.

The limitation of this study is that the number of patients involved is small. In the near future, we will recruit more patients and conduct more clinical trials to further evaluate the performance of CUHK-EXO. Safety tests for long-term wearing of CUHK-EXO will also be conducted in the future, including any adverse effect in the hip, groin, penis, back, wrist, glutei, and scapula of the wearers. Additionally, further studies will be conducted to compare the effectiveness of CUHK-EXO training and other LEEs.

## Conclusion

In this study, a wearable exoskeleton suit named CUHK-EXO was developed to provide motion assistance for paralysed

patients. The whole system of CUHK-EXO, including the mechanical structure, HMI, reference trajectories, and control, was designed considering ergonomics, safety, and comfort. The performance of CUHK-EXO was evaluated by pilot clinical trials with a paralysed patient. After training the patient to transfer his COG and use a pair of crutches to keep balance with his upper body strength, the patient could STS and walk with the motion assistance provided by CUHK-EXO. Testing results validated the effectiveness of the whole system development of the exoskeleton.

### Conflicts of interest

The authors have no conflicts of interest to declare.

### Funding/support

This work was supported by the Innovation and Technology Commission (Project No. ITS/296/14), Research Grants Council (Project No. CUHK 14201615) of the Hong Kong Special Administrative Region, China, and Vice-Chancellor's Discretionary Fund / CUHK T Stone Robotics Institute (Project ID: 4930762).

### Acknowledgements

The authors would like to thank the physical therapists Mr. Hong-Yin Lau and Mr. Joseph Yu from Prince of Wales Hospital of Hong Kong in helping with the recruitment, scheduling, and clinical evaluations of the paralyzed patient Mr. Li.

### References

- [1] World Health Organization, Media Center, Spinal cord injury. Available at: <http://www.who.int/mediacentre/factsheets/fs384/en/>. [Accessed 15 Nov 2016].
- [2] Murray SA, Ha KH, Hartigan C, Goldfarb M. An assistive control approach for a lower-limb exoskeleton to facilitate recovery of walking following stroke. *IEEE Trans Neural Syst Rehabil Eng* 2015;23:441–9.
- [3] Wang S, Wang L, Meijneke C, Asseldonk EV, Hoellinger T, Cheron G, et al. Design and control of the MINDWALKER exoskeleton. *IEEE Trans Neural Syst Rehabil Eng* 2015;23:277–86.
- [4] Shamaei K, Napolitano PC, Dollar AM. Design and functional evaluation of a quasi-passive compliant stance control knee–ankle–foot orthosis. *IEEE Trans Neural Syst Rehabil Eng* 2014;22:258–68.
- [5] Chen B, Ma H, Qin LY, Gao F, Chan KM, Law SW, et al. Recent developments and challenges of lower extremity exoskeletons. *J Orthop Transl* 2016;5:26–37.
- [6] Cao J, Xie SQ, Das R, Zhu GL. Control strategies for effective robot assisted gait rehabilitation: the state of art and future prospects. *Med Eng Phys* 2014;36:1555–66.
- [7] Talaty M, Esquenazi A, Briceño JE. Differentiating ability in users of the ReWalk™ powered exoskeleton: an analysis of walking kinematics. In: *Proceedings of IEEE International Conference on Rehabilitation Robotics, Seattle, USA; 2013*. p. 1–5.
- [8] Tsukahara A, Hasegawa Y, Eguchi K, Sankai Y. Restoration of gait for spinal cord injury patients using HAL with intention estimator for preferable swing speed. *IEEE Trans Neural Syst Rehabil Eng* 2015;23:308–18.
- [9] Farris RJ, Quintero HA, Goldfarb M. Preliminary evaluation of a powered lower limb orthosis to aid walking in paraplegic individuals. *IEEE Trans Neural Syst Rehabil Eng* 2011;19:652–9.
- [10] Walsh CJ. Biomimetic design of an under-actuated leg exoskeleton for load-carrying augmentation. MS thesis. Cambridge, MA: Department of Mechanical Engineering, MIT; 2006.
- [11] Pons JL. Wearable robots: biomechatronic exoskeletons. New Jersey: John Wiley & Sons Inc; 2008. p. 47–85.
- [12] Önen Ü, Botsalı FM, Kalyoncu M, Tınkır M, Yılmaz N, Sahin Y. Design and actuator selection of a lower extremity exoskeleton. *IEEE/ASME Trans Mechatron* 2014;19:623–32.
- [13] Chen B, Ma H, Qin LY, Guan X, Chan KM, Law SW, et al. Design of a lower extremity exoskeleton for motion assistance in paralyzed individuals. In: *Proceedings of IEEE International Conference on Robotics and Biomimetics, Zhuhai, China; 2015*. p. 144–9.
- [14] Perry J, Burnfield JM. Gait analysis: normal and pathological function. *J Sports Sci Med* 2010;9:353.
- [15] Ma H, Liao WH. Human gait modeling and analysis using a semi-Markov process with ground reaction forces. *IEEE Trans Neural Syst Rehabil Eng* 2016. <http://dx.doi.org/10.1109/TNSRE.2016.2584923>.
- [16] Winter DA. Biomechanics and motor control of human movement. 2nd ed. New Jersey: John Wiley & Sons Inc; 1990. p. 3–5. 45–137.
- [17] Zeilig G, Weingarden H, Zwecker M, Dudkiewicz I, Bloch A, Esquenazi A. Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: a pilot study. *J Spinal Cord Med* 2012;35:96–101.
- [18] Kubota S, Nakata Y, Eguchi K, Kawamoto H, Kamibayashi K, Sakane M, et al. Feasibility of rehabilitation training with a newly developed wearable robot for patients with limited mobility. *Arch of Phys Med Rehabil* 2013;94:1080–7.
- [19] Pransky J. The Pransky interview: Russ Angold, co-founder and president of Ekso™ Labs. *Ind Robot Int J* 2014;41:329–34.