Robotica (2018) volume 36, pp. 535–551. © Cambridge University Press 2017
doi:10.1017/S0263574717000546

Sit-to-stand and stand-to-sit assistance for paraplegic patients with CUHK-EXO exoskeleton

Bing Chen†‡, Chun-Hao Zhong§, Hao Ma§, Xiao Guan§, Lai-Yin Qin¶, Kai-Ming Chan‡, Sheung-Wai Law‡, Ling Qin‡*, Wei-Hsin Liao§*

†*School of Mechanical Engineering, Hefei University of Technology, Hefei, P.R. China. E-mail: chbing@ort.cuhk.edu.hk*
‡*Department of Orthopaedics and Traumatology, The Chinese University of Hong Kong, Hong Kong, P.R. China. E-mails: kaimingchan@cuhk.edu.hk, lawsw@ort.cuhk.edu.hk*
§*Department of Mechanical and Automation Engineering, The Chinese University of Hong Kong, Hong Kong, P.R. China. E-mails: chzhong@mae.cuhk.edu.hk, mahao.thume@gmail.com, gx.personal@gmail.com*
¶*Department of Biomedical Engineering, The Chinese University of Hong Kong, Hong Kong, P.R. China. E-mail: annaqin097@gmail.com*

(Accepted October 04, 2017. First published online: November 27, 2017)

SUMMARY

In this paper, we introduce a lower extremity exoskeleton CUHK-EXO that is developed to help paraplegic patients, who have lost the motor and sensory functions of their lower limbs to perform basic daily life motions. Since the sit-to-stand and stand-to-sit (STS) motion is the first step for paraplegic patients toward walking, analysis of the exoskeleton's applicability to the STS motion assistance is performed. First, the human-exoskeleton system (HES) is modeled as a five-link model during the STS motion, and the center of pressure (COP) on the ground and center of gravity of the whole system are calculated. Then, a description of the CUHK-EXO hardware design is presented, including the mechatronics design and actuator selection. The COP position is an important factor indicating system balance and wearer's comfort. Based on the COP position, a trajectory online modification algorithm (TOMA) is proposed for CUHK-EXO to counteract disturbances, stabilize system balance, and improve the wearer's comfort in the STS motion. The results of STS motion tests conducted with a paraplegic patient demonstrate that CUHK-EXO can provide a normal reference pattern and proper assistive torque to support the patient's STS motion. In addition, a pilot study is conducted with a healthy subject to verify the effectiveness of the proposed TOMA under external disturbances before future clinical trials. The testing results verify that CUHK-EXO can counteract disturbances, and help the wearer perform the STS motion safely and comfortably.

KEYWORDS: Lower extremity exoskeleton, Motion assistance, Sit-to-stand, Stand-to-sit, Trajectory generation, Balance control.

1. Introduction

The number of people with mobility disorders caused by spinal cord injury (SCI) is increasing, and around 0.25–0.5 million people suffer a SCI every year around the world.[1] Since SCI happens predominantly in young people, who need to work to support their families, a huge and long-term financial burden is imposed on both families and the society.[2] In addition, these patients are at an increased risk of secondary medical consequences of paralysis, including osteoporosis, obesity, coronary heart disease, diabetes arthritis, and pressure ulcers.[3] In order to improve the physical and

---

* Corresponding authors. E-mails: qin@ort.cuhk.edu.hk, whliao@cuhk.edu.hk

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

mental health of these people, devices that can assist them to stand and walk are desirable.[4] Therefore, it is necessary to develop assistive devices utilizing state-of-the-art technologies to help the people with disabilities regain mobility.

Lower limb orthoses have been developed for paraplegic patients to provide some degree of legged mobility and reduce the occurrences of secondary complications. These passive orthoses (without actuators) are generally composed of long-leg braces and ankle–foot orthoses.[5] With these passive orthoses, wearers need to provide energy using their upper body for movement. Thus, the target users of these orthoses are patients with considerable upper body strength. In addition, high-level physical exertion is needed but the walking speed is very slow. Due to these limitations of passive orthoses, lower extremity exoskeletons (LEEs) that are equipped with powerful actuators have been developed.[6] LEEs are wearable robotic systems that integrate both human intelligence and robot power. With multiple sensors such as angle sensors, force sensors, and orientation sensors, LEEs can acquire the wearer's motion intention and provide motion assistance accordingly. With fine control, it can provide the wearer's lower limbs with external force/torque in order to have user-initiated mobility. Universities and research institutes as well as industrial companies have been actively carrying out research and development in exoskeletons in recent years. Up to now, several LEEs have been developed to help people with impaired mobility, such as ReWalk,[7] Ekso,[8] HAL,[9] and the Vanderbilt Exoskeleton.[10]

According to surveys of paraplegic patients, the most prevalent desires of these people are to regain mobility in their lower limbs, especially the ability to stand and walk.[11,12] With the motion assistance from LEEs, paraplegic patients are able to stand and walk again, and their quality of life will be improved with better independence. The sit-to-stand motion is the first step for paraplegic patients to regain the ability to walk around from their wheelchairs, so it is very important. Since paraplegic patients may rely on wheelchairs for a long time, standing up suddenly could lead to some issues. Thus, sit-to-stand and stand-to-sit (STS) motion training is very important for paraplegic patients. It can activate the circulatory and respiratory system of paraplegic patients, alleviate spasticity, and increase the bone mineral density of their lower body.[13]

Some research has been conducted on the analysis of STS assistance in the field of exoskeletons. For wearers with different physical conditions, different strategies have been adopted in LEEs for STS assistance. Mefoued et al.[14] proposed a second-order sliding mode controller (SoSMC) for a knee exoskeleton to help persons with limited lower limb motor function to perform the STS motion. The SoSMC strategy ensured the system robustness and stability and showed good trajectory tracking. Karavas et al.[15] proposed a tele-impedance-based assistive control scheme for a knee exoskeleton to provide motion augmentation in the STS motion. With this strategy, the knee exoskeleton can provide assistance according to the wearer's muscle activity. Huo et al.[16] proposed an active impedance control (AIC) strategy for LEEs to provide STS assistance for wearers, who have limited lower limb strength. The AIC strategy was able to reduce the impedance of the human-exoskeleton system (HES) and provide "assist-as-needed" power assistance to the wearer. In the research of Tsukahara et al.[13], an analysis of STS assistance for paraplegic patients with the HAL exoskeleton was performed based on an estimation of the wearer's motion intention. In their research, a PD controller was used, and reference hip joint angles were generated based on other joint angles by considering the system balance.

Most of the currently developed LEEs[7–10] can only provide motion assistance in the sagittal plane; thus a pair of crutches is needed to help the wearer to keep balance. The wearers exert themselves during the STS motion by applying supporting forces in their arms. However, most of the current studies do not consider the supporting forces from the wearers' arms in the STS motion. The ground reaction forces (GRFs) applied to crutches can be used to evaluate the supporting forces in the wearer's arms; thus, they are related to the wearer's comfort. In addition, the GRFs applied to crutches are essential to calculate the system center of pressure (COP). The system COP position is an important factor to evaluate system balance. Therefore, it is important to perform a comprehensive analysis of STS assistance by considering the GRFs applied to crutches in the development of LEEs. In this study, a trajectory online modification algorithm (TOMA) is proposed for the CUHK-EXO exoskeleton, which was developed to provide motion assistance for paraplegic patients, who have lost the motor and sensory functions of their lower limbs. The exoskeleton lower limb joint angles have a great influence on the COP position. Based on TOMA, the reference joint trajectories of CUHK-EXO can be modified online according to the system COP position to counteract disturbances. Therefore, STS

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

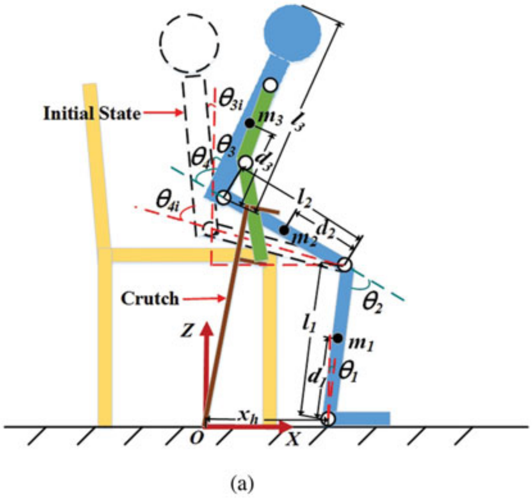


Fig. 1. Model of the human-exoskeleton system (HES) in the sit-to-stand and stand-to-sit (STS) motion. (a) Five-link model. The HES in the initial sitting posture is illustrated by the dashed lines, and the HES shown in blue color is one phase during the STS motion. (b) Ground reaction force support area and force sensing resistor (FSR) sensor locations. The red circles are FSR sensors.

assistance can be provided by the exoskeleton for paraplegic patients considering system balance and wearer comfort.

In this paper, the COP and center of gravity (COG) of the HES are calculated based on a five-link kinematic model, and then the exoskeleton hardware design is introduced. In order to counteract disturbances and ensure system balance and wearer comfort during STS assistance, TOMA is proposed. Finally, trials with a paraplegic patient and a healthy subject are conducted to verify the effectiveness of the system design and the proposed TOMA.

2. STS Kinematics Modeling

Safety has been put on top priority in the development of a LEE. COP and COG positions of the HES are crucial factors that indicate the system balance in the motion assistance of paraplegic patients. Before introducing the hardware design of the exoskeleton, a kinematic model of the HES in STS motion is developed. Then, the HES, COP, and COG positions are calculated based on this model.

2.1. Kinematic model of HES

In general, human daily motions are three-dimensional and can be described in three primary planes of the body, namely, the frontal, transversal, and sagittal planes. Among these planes, the sagittal plane is the most important one because most of our movements take place in this plane. If we only consider human motions in the sagittal plane, all lower limb joints only have one DOF. Some assumptions are made before modeling the HES in the STS motion: (1) the upper body including the head, arms, and trunk (HAT) is assumed as a link with specific weight and moment of inertia; (2) the distance between the waist and hip joints in the vertical direction is ignored; (3) the left and right legs have synchronized movements during the STS motion; (4) the weight of feet is ignored and ankle joints are on the ground. For the HES lower body, two links are assumed for each leg, one for the shank and one for the thigh. Therefore, the HES system is modeled as a five-link system in the STS motion, as shown in Fig. 1(a).

Parameters in Fig. 1(a) are defined as follows. The shanks are links 1 and 5, the thighs are links 2 and 4, and the upper body is link 3. θ_2 and θ_4 are the relative joint angles of knee and hip joints, respectively, and each of them is the angle between the two links connected. As for these joint angles, flexion direction of each joint is positive, and the joint angle is zero when the HES is in the upright posture. θ_1 and θ_3 are the angles of the shank and upper body with respect to the vertical, respectively, and clockwise direction is positive. m_i and l_i $(i = 1, 2, 3)$ are the mass and length of link i, respectively. d_1 is the length from the center of mass (COM) of link 1 to the ankle joint; d_2 is the length from the

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

COM of link 2 to the knee joint; and d_3 is the length from the COM of link 3 to the hip joint. O–XZ is the coordinate system in the sagittal plane, and the original point O is the midpoint of the line connecting the bottoms of two crutches. For convenience, smart crutches are assumed to be placed at both sides of the body, so that the ground projection points of the exoskeleton hip joints lay on the Y axis in the initial posture when the wearer wants to stand up. (x_i, z_i) is the COM position of link i in the coordinate system O–XZ. In this study, θ_2 and θ_4 are measured by potentiometers, and θ_1 and θ_3 are measured by inertial measurement units (IMUs). This is because in some environments or situations, θ_1 or θ_3 is different from the corresponding joint angle between the two links connected. For example, if the exoskeleton stands on a slope, θ_1 is different from the angle between the foot and shank.

2.2. *Calculation of COG position*

Based on the HES kinematic model (Fig. 1(a)), the X coordinate of ankle joints can be obtained as follows:

$$x_h = l_2 \sin(\theta_{4i} - \theta_{3i}) - l_1 \sin\theta_{1i} \tag{1}$$

where θ_{1i} and θ_{3i} are the angles of the shank and upper body with respect to the vertical, and θ_{4i} is the relative joint angle of the hip joint. They are all measured when the wearer is in the initial sitting posture.

COM positions of the shank, thigh, and upper body links in the STS motion can then be calculated as follows:

$$\begin{cases} x_1 = x_h + d_1 \sin\theta_1 \\ z_1 = d_1 \cos\theta_1 \end{cases} \tag{2}$$

$$\begin{cases} x_2 = x_h + l_1 \sin\theta_1 - d_2 \sin(\theta_2 - \theta_1) \\ z_2 = l_1 \cos\theta_1 + d_2 \cos(\theta_2 - \theta_1) \end{cases} \tag{3}$$

$$\begin{cases} x_3 = x_h + l_1 \sin\theta_1 - l_2 \sin(\theta_2 - \theta_1) + d_3 \sin\theta_3 \\ z_3 = l_1 \cos\theta_1 + l_2 \cos(\theta_2 - \theta_1) + d_3 \cos\theta_3 \end{cases} \tag{4}$$

Since the left and right legs have synchronized movements during the STS motion, COM positions of the shank links and thigh links of both legs are the same. Therefore, the COG position of the HES in the sagittal plane can be obtained as follows:

$$\begin{cases} x_{\mathrm{COG}} = \dfrac{2m_1x_1 + 2m_2x_2 + m_3x_3}{2m_1 + 2m_2 + m_3} \\ z_{\mathrm{COG}} = \dfrac{2m_1z_1 + 2m_2z_2 + m_3z_3}{2m_1 + 2m_2 + m_3} \end{cases} \tag{5}$$

2.3. *COP estimation*

GRFs are associated with human gait and can indicate the foot−ground contact conditions, which provide important information for the analysis and evaluation of human motion. In general, GRF has two components: the horizontal and vertical forces. The horizontal force is parallel to the ground, such as the frictional force when a person is walking, and the vertical force is the supporting force perpendicular to the ground. In this study, we only consider the vertical GRF. Vertical GRFs can be used to indicate the foot−ground contact conditions and to calculate the COP position. In the multi-sensor system of CUHK-EXO, four force sensing resistor (FSR) sensors are mounted on each sole of the HES, and one FSR sensor is mounted at the bottom of each crutch. Their locations are shown in Fig. 1(b). The COP position of the HES in the sagittal plane can then be obtained with the following

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

Fig. 2. CUHK-EXO exoskeleton, front view (left) and side view (right).

expression:

$$x_{\text{cop}} = \frac{(f_{lt1} + f_{lt2} + f_{rt1} + f_{rt2})x_t + (f_{lh1} + f_{lh2} + f_{rh1} + f_{rh2})x_h + (f_{rc} + f_{lc})x_c}{f_{lt1} + f_{lt2} + f_{rt1} + f_{rt2} + f_{lh1} + f_{lh2} + f_{rh1} + f_{rh2} + f_{rc} + f_{lc}} \tag{6}$$

where $f_{lt1}, f_{lt2}, f_{rt1}, f_{rt2}, f_{lh1}, f_{lh2}, f_{rh1}$, and f_{rh2} are the GRFs measured by the toe and heel FSR sensors mounted on the right and left soles, respectively; f_{rc} and f_{lc} are the GRFs measured by the FSR sensors mounted in the smart crutches; x_t and x_h are positions of the toe and heel FSR sensors, respectively; and x_c is the position of the FSR sensors in the crutches. In this study, x_c is always zero during the STS motion since the crutch bottoms are fixed on the Y axis of the coordinate system.

3. Hardware Design of CUHK-EXO

The targeted wearers of CUHK-EXO are patients with paraplegia caused by SCI or other related diseases. We have the following inclusion and exclusion criteria for the wearers. The inclusion criteria are male or female aged 16–60 years, with a weight of less than 90 kg and a height 1.55–1.85 m. The level of involvement is T5 or lower with a power equal or less than grade 1 out of 5 (MRC grading). In addition, the wearers shall have sufficient upper body strength to balance their body weight with the support of a pair of crutches. They shall also have the ability to manage weight transfer and trunk balance. The exclusion criteria include significant complications, pressure sores, spinal instability, limited upper extremity power, i.e., Grade 2/5, fixed joint contracture, uncontrolled spasticity, intellectual, or cognitive impairments that may prevent smooth running of the tests or trials.

The exoskeleton CUHK-EXO developed for paraplegic motion assistance is presented in Fig. 2. It is designed with considerations of ergonomics, user-friendly interface, and safety. It weighs about 22 kg and can work continuously for approximately three hours. The dimensions of CUHK-EXO are adjustable so as to accommodate wearers with a height of 1.55–1.85 m.

3.1. Mechanical structure

The mechanical structure of the exoskeleton supports the wearer's body weight and transfers the assistive force/torque from the actuators to the wearer. CUHK-EXO is designed with active joints to assist human lower limb motions in the sagittal plane where most daily movements take place. It has in total seven degrees of freedom (DOFs), with three for the right leg (hip and knee flexion/extension, ankle dorsiflexion/plantarflexion) and four for the left (hip and knee flexion/extension, hip external rotation, and ankle dorsiflexion/plantarflexion). Among these DOFs, hip, and knee flexion/extension are active since these DOFs are essential for daily life movements, while the others are passive. The

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

Table I. Design requirements of CUHK-EXO.

Joint	Peak torque (Nm)	Peak power (W)
Human hip	86	76
Human knee	41	91
CUHK-EXO hip	45	76
CUHK-EXO knee	31	91

hip external rotation DOF is designed to allow the wearer to transfer into the exoskeleton easily and is locked after the wearer has put the exoskeleton on. Structures of the exoskeleton waist, thighs, and shanks are designed to be adjustable. On the extreme ends of the allowed range of motion of each DOF, mechanical stops are designed to ensure safety. The weight of the exoskeleton and wearer are transferred to the ground through the mechanical structure.

3.2. Actuator selection

Actuators play a crucial role in LEEs since they generally determine output speed, force/torque, efficiency, and other performances.[17] Due to the weight and space limitation, actuators with high power-to-weight and torque-to-weight ratios are expected in LEEs. During the development of LEEs, the actuators used include hydraulic actuators, pneumatic actuators, and electric motors. In this study, electric motors were selected for CUHK-EXO owing to their ease of supplying power, control precision and high power-to-weight ratio.

In order to select suitable actuators for CUHK-EXO, the power and torque specifications for the exoskeleton active joints should be known. Clinical gait analysis (CGA) is usually used to determine the joint torque and power of LEEs.[18,19] Human joint angles and torques can be obtained through CGA with a motion capture system. Using the CGA normative gait database of Hong Kong Polytechnic University,[20] the power and torque of hip and knee joints for a 112-kg individual during walking were obtained, as shown in Table I. During the use of CUHK-EXO, the wearers need to use a pair of crutches to support and balance their body weight with the upper limbs. Thus, the exoskeleton just needs to support a certain amount of the HES weight because the crutches help to transfer part of the HES weight to the ground. In the research conducted by Onen et al.[18] the subjects' legs only carry about 52% of their body weight by using the crutches in the stance phase of walking. The power and torque specifications of CUHK-EXO hip and knee joints are then shown in Table I.

In this study, Maxon DC motors (RE40, 150 W) were selected to actuate the active joints (hip and knee flexion/extension) of CUHK-EXO through the planetary gearboxes (Maxon GP 42 C, with a 113:1 reduction ratio for the hip joint and 91:1 for the knee joint) and bevel gears (with a 2:1 reduction ratio). The motor has a rated voltage of 24 V with a nominal torque (maximal continuous torque) of 0.177 Nm and a torque constant of 0.0302 Nm/A. The efficiencies of the planetary gearbox and bevel gears are 72% and 90%, respectively. Thus, the output torque of the motors through the drivetrain can be calculated with Eq. (7).

$$T = T_n k_s k_e \tag{7}$$

where T_n is the nominal torque of the motor, k_s is the speed reduction ratio, and k_e is the drivetrain efficiency.

Thus, CUHK-EXO can provide a maximum continuous assistance torque of 25.9 Nm for the hip joint and 20.8 Nm for the knee joint. Maxon motors have the characteristic of overload for short term, and short-term peak torques of approximately 52 Nm and 42 Nm can be provided for the hip and knee joints, respectively. According to the technical specifications of the selected motors, Maxon motor drivers (ESCON 50/5) are used to drive the motors, which can be used for speed control and current control. The power supply for the actuators is four 7.4 V/6000 mAh lithium polymer (LiPo) batteries connected in series.

3.3. Electronics system

The CUHK-EXO electronics system mainly includes the actuators, a backpack with controllers and batteries, multiple sensors and a pair of smart crutches,[21] as shown in Fig. 3. As for the data processing

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

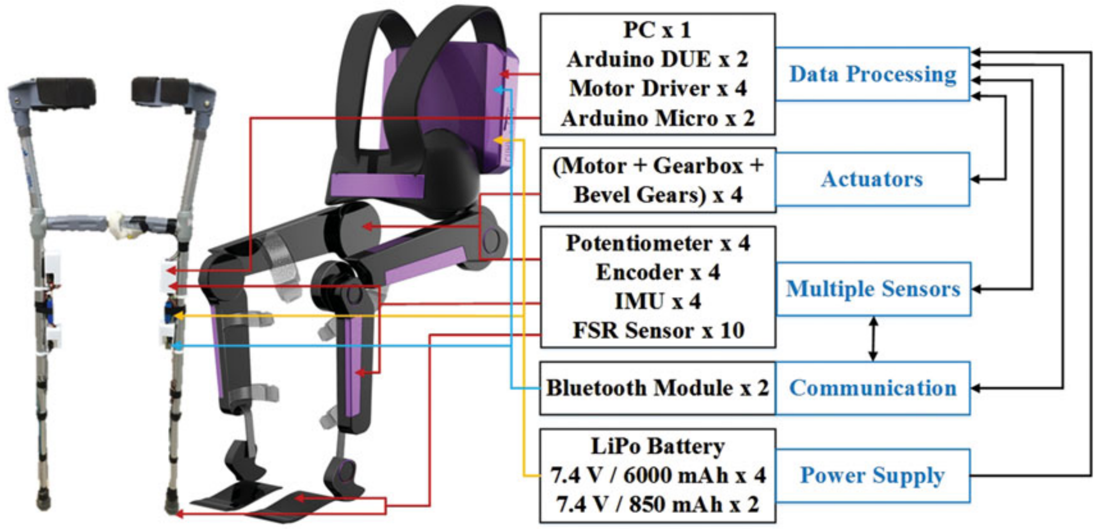


Fig. 3. Overall layout of CUHK-EXO whole system.

module, the high-level controller is a PC and the lower-level controller consists of two 84 MHz Arduino DUE microcontrollers for exoskeleton control and two 16 MHz Arduino Micro microcontrollers for the smart crutches. The embedded controllers, motor drivers, and main batteries are placed in the backpack. Bluetooth modules are used for wireless communication among embedded controllers, smart crutches, and the PC. The multi-sensor system is designed to measure the motion data and recognize the wearer's motion intention. Encoders and potentiometers are mounted on the exoskeleton hip and knee joints to obtain the joint angles and angular velocities. IMUs are mounted on the exoskeleton trunk, shank, and crutches to get their orientation information. FSR sensors are placed on the sole of CUHK-EXO and bottom of the crutches to measure the GRFs applied to the feet and crutches.

4. Capture of Reference Trajectories

To provide effective and comfortable STS assistance for paraplegic patients, a reference STS motion pattern is designed as shown in Fig. 4. It was obtained based on discussion with clinical doctors considering balance and comfort. The sit-to-stand motion is composed of the sitting posture, trunk flexion, hip flexion, hip and knee extension, and standing posture; the stand-to-sit motion is composed of the standing posture, trunk flexion, hip flexion, hip and knee flexion, hip extension, and sitting posture. In different phases of the STS motion, the wearer has different trunk orientations and foot−ground contact conditions, and the crutches are placed at different positions (front or back).

According to the designed STS motion scenarios and logics, a preliminary test was conducted with a healthy subject to obtain reference trajectories of hip and knee joints of CUHK-EXO. In the test, an optical motion capture system (Vicon Motion Systems Ltd, Oxford, United Kingdom) was used, and it was synchronized with a force platform (AMTI, Watertown, USA) that can indicate the foot−ground contact conditions based on the measured six-dimensional force/torque, as shown in Fig. 5(a). Sixteen skin reflective markers were attached at anatomical landmarks of the subject's lower body, according to the Vicon Plug-in Gait model. The subject wore CUHK-EXO without turning on motors and imitated the paraplegic patient's STS motion. Three-dimensional kinematic data of the subject lower body were collected. Finally, normalized trajectories of hip and knee joints in the sagittal plane were obtained, as shown in Fig. 5(b). To make the trajectories suitable for different wearers, the features of the trajectories such as the time period will be modified according to the wearers' physical conditions.

5. Trajectory Online Modification Considering Balance and Comfort

In this study, the exoskeleton is controlled to follow the predefined reference trajectories as shown in Fig. 5(b). In using the CUHK-EXO for motion assistance, the wearer uses a pair of smart crutches to

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

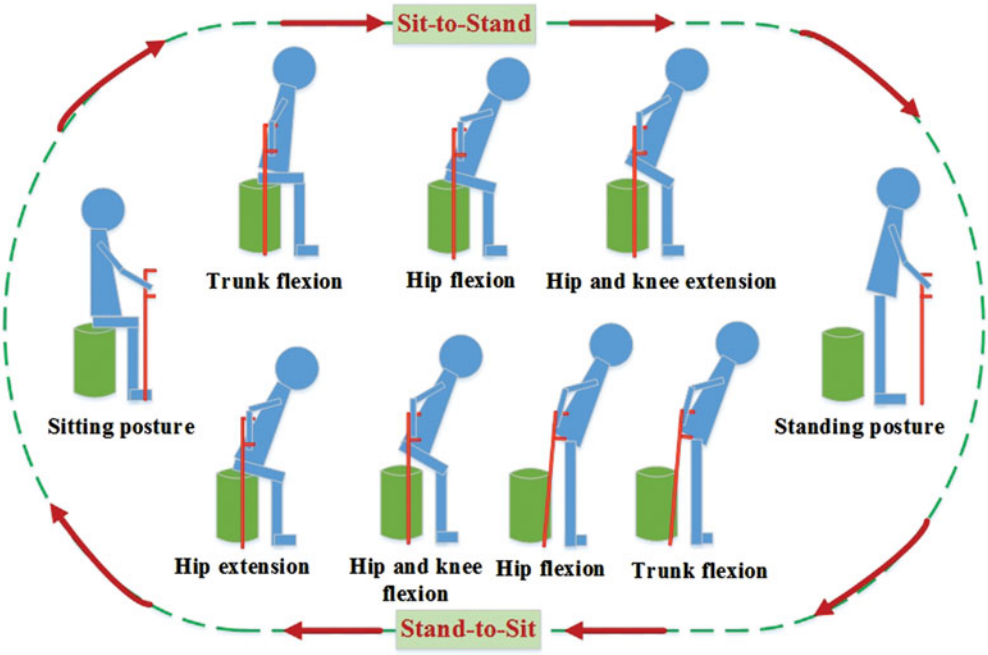
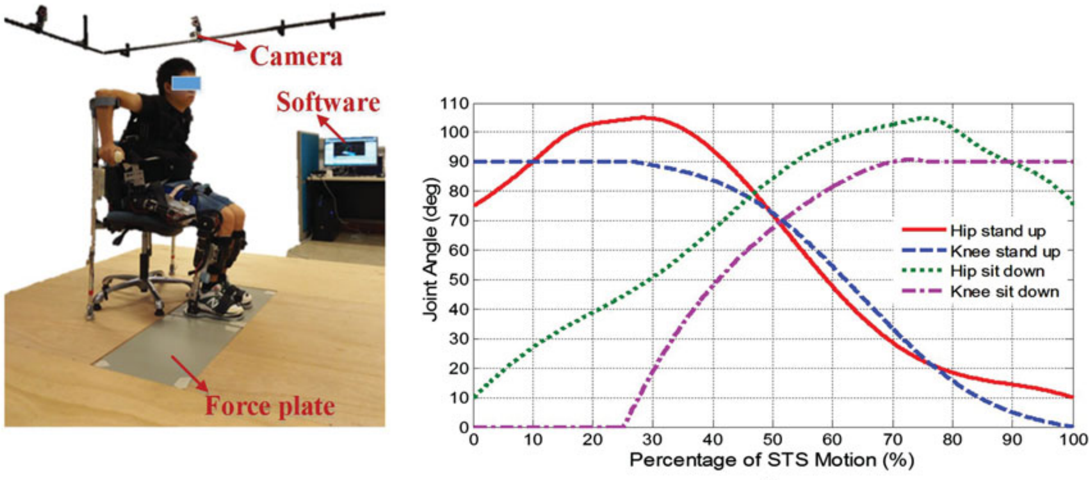


Fig. 4. Illustration of the STS motion scenarios and logics.



(a) (b)

Fig. 5. Reference trajectories capture. (a) Optical motion capture system. (b) Hip and knee joint trajectories in the STS motion.

help support and balance his/her body weight. Thus, the system COP position is obtained by measuring the GRFs applied to both feet and crutches, and it is always located in the trapezoidal area indicated by the dashed lines in Fig. 1(b). If the COP is near the center of the convex polygon, the system will have a large stability margin. On the other hand, if the COP is near the edge of the convex polygon, the system would lose balance. Thus, the relative position of system COP is important for system balance evaluation. In addition, the magnitude of supporting forces from the wearer's arms is related to the wearer's comfort during the STS motion. Less effort makes the wearer more comfortable. Therefore, in order to provide paraplegic patients with safe and comfortable STS assistance, the predefined reference trajectories of CUHK-EXO should be online adjusted according to the system posture and actual COP estimation.

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

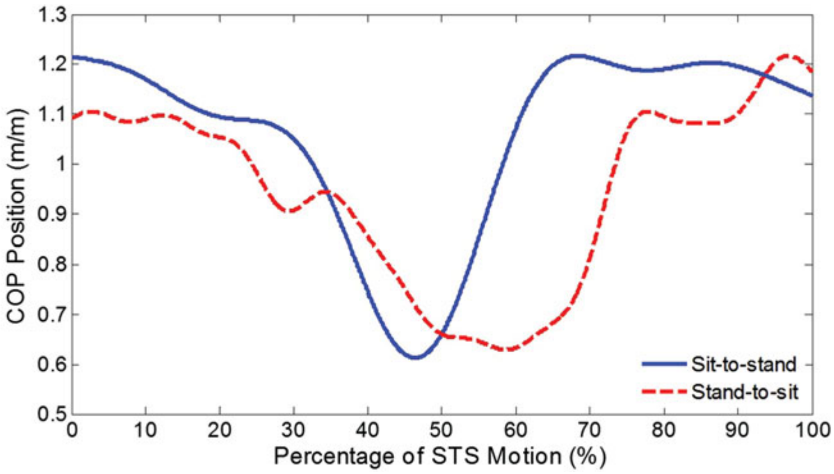


Fig. 6. Normalized reference trajectory of COP in the sagittal plane.

5.1. *Capture of COP desired area*

Normally, the COP position of a healthy person in the STS motion is located around the ankle joints.[22] However, the COP position of the HES is different due to the use of crutches. To obtain the COP desired area in the STS motion, preliminary tests were conducted. In the test, the subject wore CUHK-EXO, imitated paraplegic patients and performed the STS motion with assistance provided by the exoskeleton. With the measured GRFs applied to feet and crutches, COP position of the HES can be obtained with Eq. (6). From the testing, it is found that if the X coordinate of COP (x_{cop}) is smaller than that of point A (shown in Fig. 1(b)), which is about 45% of the distance between the crutch bottom and toe FSR sensor (x_t), the wearer will feel uncomfortable due to a large supporting force requirement on the crutches. On the other hand, if the COP exceeds point B (shown in Fig. 1(b)), which is about 83% of x_t, the HES will have the possibility of losing balance due to the small stability margin. Thus, we conclude that COP position of the HES in the STS motion should be located in the trapezoidal area indicated by the solid lines in Fig. 1(b) to ensure the system balance and wearer's comfort.

From the preliminary tests, we also found that the COP is located in different regions of the COP desired area during different phases of the STS motion. For a specific phase of the STS motion, the COP position varies in the COP desired area with different wearers, but the variation is small. Thus, the reference trajectory of the COP in the STS motion was obtained in the preliminary tests. For different wearers, the HES has different body dimensions. In order to make the COP reference trajectory suitable for different wearers, it is normalized based on x_h, as shown in Fig. 6. Thus, if the wearer wants to perform the sit-to-stand motion, based on Eq. (1), x_h will be calculated first according to the wearer's initial sitting posture in the controller initialization. Then, the COP desired area and reference trajectory in the STS motion can be determined and used for the control of the STS motion. TOMA, which will be introduced in the following section, is based on the COP desired area and reference trajectory.

5.2. *Trajectory online modification algorithm*

With the exoskeleton for STS assistance, if the supporting forces from the wearer's arms do not change dramatically, the deviation between the actual and reference COP positions will be small, and the COP will stay in the desired area. Otherwise, if the deviation is large enough to affect the system balance and wearer's comfort, reference trajectories of the exoskeleton need to be modified to drive the system COP back into the desired area. In general, the ground projection of a system COG is close to its COP if the system is in quasi-static mode.[23–25] In this study, the COG position of the HES is determined by the joint angles, and COP is calculated based on the GRF measurements in the wearer's feet and crutches. Although the STS motion of the HES is not static, most of the movement occurs in the vertical direction. Thus, it can be assumed that the HES COG is strongly related to its COP, and that a change in the COG position will significantly affect the system's COP position on the

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

ground. In this study, we propose a feedback control algorithm for the trajectory online modification based on the observation of COP position to stabilize system balance and ensure the wearer's comfort. The general algorithm is given in Eq. (8). Here, Δx_{COP} is the deviation between the measured and desired COP position, and Δx_{COG} is the COG deviation between the predefined and modified joint trajectories. Parameter k_j $(j = 1, 2)$ is set as constant and was determined in preliminary experiments.

$$\Delta x_{\mathrm{COG}} = k_j \Delta x_{\mathrm{COP}} \tag{8}$$

As for the parameter k_j, k_1 is for the situation where the COP is located in the COP desired area, and k_2 is for the situation where the COP gets out of the desired area. With Eq. (5), the COP deviation Δx_{cop} on the ground can be expressed as follows:

$$\begin{aligned} k_j \Delta x_{\mathrm{COP}} &= k_j \left(x_{\mathrm{act}_{\mathrm{cop}}} - x_{\mathrm{ref}_{\mathrm{cop}}} \right) = \Delta x_{\mathrm{COG}} \\ &= x_{\mathrm{modified}_{\mathrm{COG}}} - x_{\mathrm{predefined}_{\mathrm{COG}}} = \frac{2m_1 x_{12} + 2m_2 x_{22} + m_3 x_{32}}{2m_1 + 2m_2 + m_3} - \frac{2m_1 x_{11} + 2m_2 x_{21} + m_3 x_{31}}{2m_1 + 2m_2 + m_3} \end{aligned} \tag{9}$$

Here, x_{i1} ($i = 1, 2, 3$) and x_{i2} are the COM positions of each segment (shank, thigh and upper body) in the sagittal plane before and after the modification of lower limb joint trajectories, respectively.

As compared with hip joint angles, knee joint angles have more influence on the COG position of the HES,[13] as well as the HES COP position. Therefore, in this study, we only adjust the reference trajectory of CUHK-EXO knee joints in real-time. Then, Eq. (9) can be rearranged as follows:

$$k_j \Delta x_{\mathrm{cop}} = \frac{p(\sin\alpha - \sin(\alpha + \varphi))}{q} \tag{10}$$

where φ is the modification angle, and the other terms are expressed by Eqs. (11)–(13):

$$\alpha = \theta_2 - \theta_1 \tag{11}$$

$$p = 2m_2 d_2 + m_3 l_2 \tag{12}$$

$$q = 2m_1 + 2m_2 + m_3 \tag{13}$$

Rearranging Eq. (10), we obtain the modification angle φ as follows:

$$|\varphi| = \arcsin\left(\sin\alpha - \frac{q}{p} k_j \left| \Delta x_{\mathrm{cop}} \right| \right) - \alpha \tag{14}$$

The sign of φ is determined by the sign of Δx_{cop}. We know that the COP position has a small variation in the COP desired area with different wearers for a specific phase of the STS motion. In addition, a small deviation between the actual and reference COP positions has little effect on the system balance and wearer's comfort. Thus, there is no need to make the system COP follow the predefined reference COP rigidly. We define a threshold, which was obtained through preliminary experiments, for the COP deviation. At each control cycle of the STS motion, the modification angle φ is calculated. If the COP deviation exceeds the predefined threshold, the modification angle φ is added to the predefined reference trajectory of knee joints. Otherwise, the exoskeleton is controlled to follow the predefined reference trajectories.

5.3. Applicability of TOMA

The capability to counteract disturbances of CUHK-EXO with the proposed TOMA is limited. If the external disturbances are too large and the bottoms of crutches almost leave the ground in the STS motion, the HES COP would be near the edge of the convex polygon (trapezoidal area indicated by the dashed lines in Fig. 1(b)). In this situation, the HES would be like an inverted pendulum due to the passive ankle joints. In addition, the calculated modification angle would be very large due to the large COP deviation, and a large discontinuity in motion would occur. Thus, the HES would be very

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

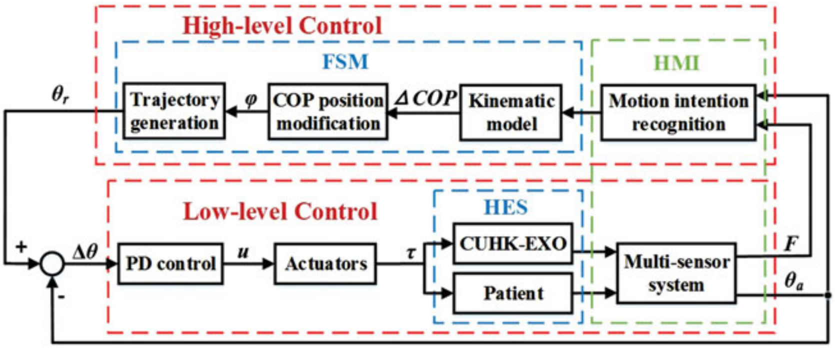


Fig. 7. Controller architecture of CUHK-EXO.

easy to tip over in this situation. It is similar if the toes of the HES leave the ground and the system COP is close to the bottoms of the crutches under large disturbances.

6. Materials and Methods

To validate the effectiveness of our system design and proposed TOMA, STS tests were conducted with CUHK-EXO. By adding the modification angle to the predefined reference trajectory, a discontinuity in motion will occur because of the threshold in the proposed TOMA.

6.1. Controller architecture

The exoskeleton is attached to the wearer, and they form a closed loop as a human–exoskeleton cooperative system. For gait rehabilitation purposes, impedance control has been widely used for LEEs;[15,16] thus, the exoskeleton can provide "assist-as-needed" assistance to the wearer according to the wearer's voluntary muscle activity. In this study, the exoskeleton CUHK-EXO is developed to provide motion assistance for paraplegic patients, who have lost the motor and sensory functions of their lower limbs; thus, there is no voluntary force/torque from the wearer's lower limbs applied to the exoskeleton. Position control is used for CUHK-EXO. As compared with other control strategies such as impedance control, position control also has the advantages of reduced hardware complexity, sensor need, and computational complexity. In addition, with the proposed TOMA, the disadvantages of tracking predefined references, such as limited capability to counteract external disturbances and keep system balance, can also be solved.

The exoskeleton controller architecture is composed of a high-level control and a low-level control, as shown in Fig. 7. The high-level control mainly includes a human–machine interface (HMI) and a finite state machine (FSM). The function of high-level control is to estimate the wearer's motion intention based on the multi-sensor system, analyze and evaluate his/her motion conditions based on the kinematic model, and finally generate reference trajectories for the exoskeleton according to the TOMA. The low-level control is to regulate actuators to output desired motions. Finally, assistive torques in lower limb joints are generated from actuators to assist the wearer to perform daily life motions. The wearer's lower limbs and exoskeleton are well connected through braces; as a result, the wearer and exoskeleton share the same motions.

The HMI of CUHK-EXO consists of a smart phone application (App), a pair of smart crutches and the multi-sensor system. The smart phone app includes several interfaces, such as the Operation Interface, which is composed of several command buttons, and the Motion Monitoring Interface, which can illustrate the exoskeleton feedback information in real-time. The smart crutches are designed with FSR sensors and IMUs to obtain more information from the HES. In addition, the right crutch is designed with several buttons to control the motion assistance. The wearer's motion intention can also be recognized with the multi-sensor system, which is not introduced herein in detail due to space limitation. Corresponding to the different training stages of paraplegic patients, three operation modes are developed for CUHK-EXO. In the initial stage, since the wearer is not familiar with the exoskeleton, the therapist will operate CUHK-EXO through the smart phone app. In the second stage, when the wearer gets familiar with CUHK-EXO, he/she can operate it through buttons on the right

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

smart crutch. In the final stage, when the wearer has become familiar with CUHK-EXO, he/she can operate it based on automatic motion intention recognition algorithms through the multi-sensor system.

The FSM defines different motion scenarios of CUHK-EXO. It is composed of a finite number of states, and each state is defined by the combination of a set of trajectories. In different states, the HES has different body postures and foot−ground contact conditions. The FSM is designed to be hierarchical for CUHK-EXO, i.e., the high-level FSM and lower-level FSM. The high-level FSM governs two types of postures (sitting posture and standing posture) and three types of motions (stand up, sit down, and walk). With the FSM, desired motion assistance can be provided for paraplegic patients by CUHK-EXO.

In the low-level control, motion data of the HES including the kinematic and kinetic data are obtained with the established multi-sensor system. The measured motion data, such as the wearer's trunk posture, GRF applied to feet, and joint angles, can be used to estimate the wearer's motion intention and analyze the motion status and gait pattern of the HES. Maxon ESCON 50/5 controllers are used to control the joint actuators. In this study, the references of CUHK-EXO are predefined and online modified. The instantaneous errors of joint motion are obtained by comparing the actual joint angles and online-generated reference joint angles. PD control is adopted to regulate the actuators to minimize the joint motion errors, track the references and output the desired motions.

6.2. Evaluation of STS assistance

STS tests were conducted with a paraplegic patient to verify the effectiveness of the basic STS assistance of CUHK-EXO. The subject was a 51-year-old male (1.80 m, 85 kg) with a T6 SCI, eight-years post injury. He lost the sensory and motor function of his lower limbs completely, and he was dependent on a wheelchair for mobility in his daily life. The tests were conducted under clinical and ethical approval, which 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). Before the subject participated in the tests, he was informed of the testing protocol, and informed consent was obtained from him.

The STS tests were performed in a rehabilitation center of Prince of Wales Hospital in Hong Kong. Two certified physiotherapists were engaged in all tests. CUHK-EXO was a medical device that the subject was not familiar with beforehand. In addition, the exoskeleton was a human−machine cooperative system, and the wearer's efforts were needed during the use of the exoskeleton. Thus, it was necessary to train the subject before performing the STS tests. In the initial training section, the subject was instructed to move his trunk back and front, while in the sitting posture. After he stood up in a standard set of parallel bars with the assistance of CUHK-EXO and a therapist, he was trained to transfer his COG front and back in the standing posture. For safety consideration, two physical therapists stood on both sides of the subject to protect him from potential fall.

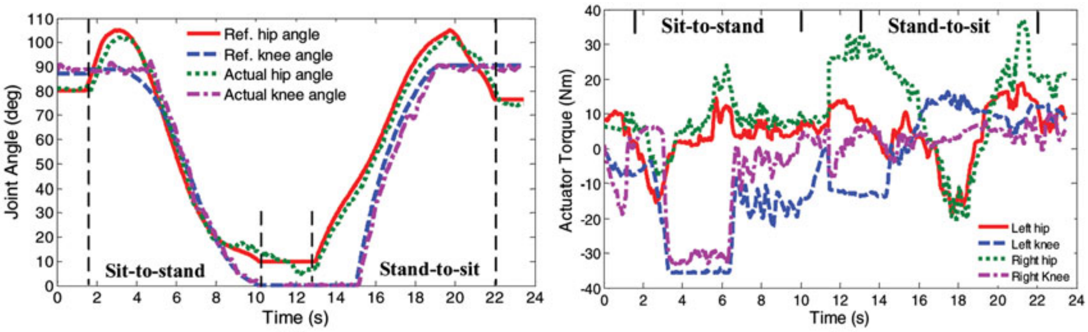
According to CGA data,[20] the power and torque of human lower limbs of different individuals are different due to different weight. However, the joint angles of individuals with different weight and body dimension are similar. Thus, the reference joint trajectories captured from normal people were applied during STS assistance, but the time period of the STS motion was modified according to the patient's feedback. In different training stages, different devices such as the parallel bars, a walker and a pair of crutches were used to assist the paraplegic patients to keep their balance.

In the STS tests, the subject held a standard set of parallel bars to help support and balance his body weight (Fig. 8). The subject was initially in a sitting position. After receiving instructions from a physical therapist, the subject held the parallel bars. Then, the physical therapist pressed the button that corresponded to the sit-to-stand motion through the smart phone app. After that, hip joints of the exoskeleton started to flex to incline the subject's trunk forward, and then both the exoskeleton hip and knee joints extended to help the subject stand up. Finally, the subject reached the standing posture with the assistance of CUHK-EXO. It was similar for the stand-to-sit motion. First, the physical therapist pressed the relevant button for triggering the exoskeleton hip joints to start flexion to incline the subject trunk forward, and then both the exoskeleton hip and knee joints flexed to help the subject sit down. Finally, the subject moved to the sitting posture.

As for the results, joint angles and assistive torques generated from CUHK-EXO are presented in Fig. 9. The assistive torque is the actuator output torque that is calculated by multiplying the motor current, motor torque constant, actuator speed reduction, and drivetrain efficiency. The motor

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

Fig. 8. STS tests with a paraplegic patient.



(a) (b)

Fig. 9. Testing results of the STS tests. (a) Reference and actual joint angles of hip and knee joints. (b) Assistive torques generated from CUHK-EXO.

current is outputted from the motor driver. It can be seen that the actual joint angles closely follow the reference trajectories. The testing results demonstrated that CUHK-EXO can provide a normal reference pattern and proper assistive torque to support the patient's STS motion.

6.3. *Evaluation of TOMA*

To evaluate the effectiveness of the proposed TOMA, STS experiments with disturbances were conducted. For safety consideration, a healthy subject simulating paraplegic patients participated in the experiments. The experiments were also conducted after obtaining Human Ethical Approval granted by the Joint CUHK-NTEC CREC (Ref. No.: 2015.262). Before participating in the experiments, the subject was informed of the experimental protocol and gave consent. The subject was a 27-year-old male, with a height of 1.65 m and weight of 53 kg. The HES weighs about 75 kg. According to the literature,[26,27] the HES parameters in the kinematic model (Fig. 1(a)) are identified, as given in Table II. In addition, the parameters k_1 and k_2 are set as 0.1 and 0.3, respectively.

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

Table II. HES parameters in the kinematic model.

Body segment	Segment weight m (kg)	Segment length *l* (m)	COM position d (m)
HAT	50.85	0.8	0.5008
Thigh	7.5	0.38	0.2155
Shank	3.49	0.38	0.2155

Fig. 10. Snapshots of the STS experiment.

The experiments were conducted in a laboratory environment at The Chinese University of Hong Kong. In the experiment, the subject wore the CUHK-EXO and used the smart crutches for balance and support. He tried not to use his lower body strength to simulate a paraplegic patient and operated the exoskeleton through the buttons mounted on the right crutch. The subject performed the STS motion with assistance provided by the exoskeleton. GRFs applied to the wearer's feet and crutches were obtained in real-time during the experiment. Since the TOMA was developed to stabilize system balance in the STS assistance, the experiment was designed with disturbances, such as external pushes or uncontrolled trunk inclination, during the STS motion to verify the algorithm effectiveness. Snapshots of the STS experiment are shown in Fig. 10.

Experimental results of the STS motion are shown in Fig. 11. The GRFs applied to crutches are shown in Fig. 11(a). The reference and actual trajectories of the HES, COP and the COP deviation between the reference and actual COP position are given in Fig. 11(b). The horizontal dashed lines indicate the threshold of COP deviation. When the deviation exceeds the threshold, the reference trajectory of knee joints will be modified accordingly. The modification angle φ generated in real-time is shown in Fig. 11(c). The predefined reference trajectory, online generated reference trajectory and actual joint angles for the exoskeleton knee joints are shown in Fig. 11(d).

The sit-to-stand motion is from 2.5 s to 11.5 s. During this motion, a push on the wearer's back was applied by another person at about 6.2 s to simulate an external disturbance. Due to additional forward momentum, GRFs (Fig. 11(a)) applied to the crutches become small suddenly, and the COP deviation exceeds the threshold (Fig. 11(b)), getting into an area where the system has the possibility of losing balance. Thus, the modification angle φ (Fig. 11(c)) is calculated and added to the predefined reference trajectory of the knee joints. Finally, the knee joint trajectory is modified (Fig. 11(d)) to drive the COP deviation back into the normal range (Fig. 11(b)), which ensures the system balance during the STS assistance. The stand-to-sit motion is from 14.5 s to 23.5 s. During the stand-to-sit

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

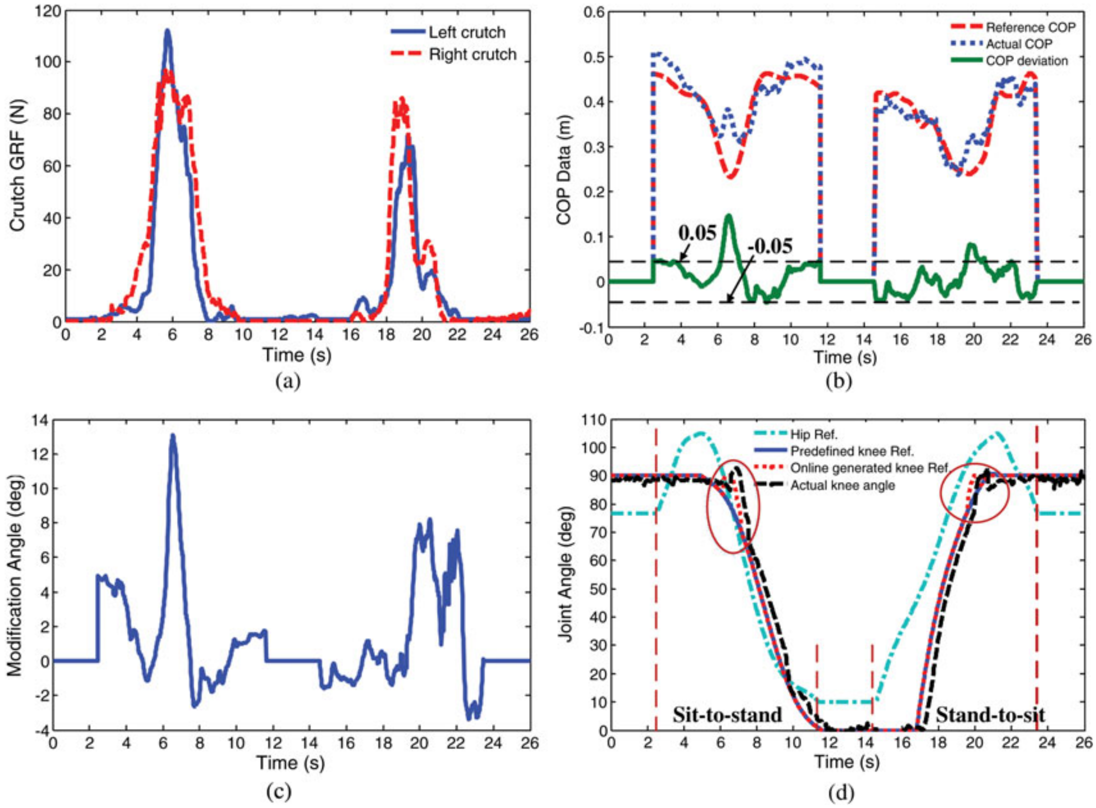


Fig. 11. Experimental results of the STS motion. (a) Crutches GRFs. (b) The HES COP positions. The horizontal dashed lines indicate that the threshold of COP deviation is 0.05 m. (c) Online generated modification angles for knee joints. (d) Reference trajectories of hip and knee joints. Reference trajectory of the hip joint is used to illustrate the start time and end time of the STS motion. The circles in dark red color illustrate that the trajectory online modification occurs.

motion, the wearer leaned his trunk forward suddenly at about 19.5 s. Similarly, we can also see that the GRFs (Fig. 11(a)) applied to crutches become small suddenly, and the COP deviation also exceeds the threshold (Fig. 11(b)). Thus, the knee joint trajectory is modified accordingly to drive the COP deviation back into the normal range. During the time when the COP deviation is within the normal range, the exoskeleton just follows the predefined reference joint angle trajectories.

7. Discussion

In order for paraplegic patients to regain their mobility, STS motion is the first step for them to walk and perform other daily life motions. In this study, we aimed to develop a LEE named CUHK-EXO, for paraplegic patients who have lost the motor and sensory functions of their lower limbs, allowing them to regain mobility. TOMA was proposed for the CUHK-EXO exoskeleton in the STS motion. Based on TOMA, STS assistance can be provided for the wearers by the exoskeleton considering system balance and the wearer's comfort.

To verify the effectiveness of the system design of the exoskeleton, STS tests were conducted with a paraplegic patient. In the test, the subject held a standard set of parallel bars to help support and balance his body weight. Based on the testing results (Fig. 9), it can be seen that CUHK-EXO can effectively assist the patient to perform the STS motion with proper assistive torque in the predefined reference pattern. In addition, STS experiments with disturbances were conducted to evaluate the effectiveness of the proposed TOMA. For safety consideration, a healthy subject, who was recruited to simulate paraplegic patients without using his lower limb strength, participated in our pilot study before future clinical trials. From the experimental results (Fig. 11), it can be seen that when the COP deviation exceeded the threshold, the modification angle was calculated and the knee joint trajectory was modified to drive the COP deviation back into the normal range, which ensured system balance.

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

There are some limitations in our present study. The low-level controllers are Arduino devices that were preliminary selections at the current stage in our research and development. We will further improve the control hardware of the exoskeleton for more powerful computational capability in future studies. The number of subjects is small and in the near future, we will recruit more subjects and conduct more tests to further evaluate the effectiveness of CUHK-EXO and the algorithm TOMA. Further studies will also be performed to compare the effectiveness of CUHK-EXO and other LEEs. With the approval of the ethical commission, clinical trials with a suitable number of subjects will be conducted in further studies as well.

8. Conclusions

In this paper, analysis of CUHK-EXO STS assistance was performed. A kinematic model of the HES in the STS motion was first established, and the system COP and COG positions were calculated. Hardware design of CUHK-EXO was also presented. Then, reference joint trajectories of the exoskeleton in the STS motion were obtained with an optical motion capture system. Since the relative position of the HES COP is important to evaluate system balance and the wearer's comfort, the TOMA was proposed based on the COP position. With TOMA, the offline designed reference joint trajectories can be modified online considering the system balance and wearer's comfort. Position control was used in CUHK-EXO, and the exoskeleton was controlled to follow reference trajectories. STS tests with a paraplegic patient were conducted, and the results validated the effectiveness of the system design and control. For planning our future clinical trial, a pilot study with a healthy subject was conducted to verify the effectiveness of the proposed TOMA. These results demonstrated that CUHK-EXO can counteract disturbances, stabilize system balance, and provide safe and comfortable STS assistance for the wearer.

Acknowledgments

The work described in this paper 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). The authors would also 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 paraplegic patient.

References

1. World Health Organization, Media Center, Spinal cord injury. Available at http://www.who.int/mediacentre/factsheets/fs384/en/ (Accessed May 25, 2016).
2. D. M. Dryden, L. D. Saunders, B. H. Rowe, L. A. May, N. Yiannakoulias, L. W. Svenson, D. P. Schopflocher and D. C. Voaklander, "Utilization of health services following spinal cord injury: A 6-year follow-up study," *Spinal Cord* **42**(9), 513–525 (2004).
3. W. O. McKinley, A. B. Jackson, D. D. Cardenas and M. J. DeVivo, "Long-term medical complications after traumatic spinal cord injury: A regional model systems analysis," *Arch. Phys. Med. Rehab.* **80**(11), 1402–1410 (1999).
4. B. Chen, H. Ma, L. Y. Qin, F. Gao, K. M. Chan, S. W. Law, L. Qin and W. H. Liao, "Recent developments and challenges of lower extremity exoskeletons," *J. Orthopaed. Trans.* **5**, 26–37 (2016).
5. G. Scivoletto, M. Mancini, E. Fiorelli, B. Morganti1 and M. Molinari, "A prototype of an adjustable advanced reciprocating gait orthosis (ARGO) for spinal cord injury (SCI)," *Spinal Cord* **41**(3), 187–191 (2003).
6. C. Copilusi, M. Ceccarelli and G. Carbone, "Design and numerical characterization of a new leg exoskeleton for motion assistance," *Robotica* **33**(05), 1147–1162 (2015).
7. M. Talaty, A. Esquenazi and J. E. Briceño, "Differentiating Ability In Users Of The Rewalk^{tm} Powered Exoskeleton: An Analysis Of Walking Kinematics," *Proceedings of the 2013 IEEE International Conference on Rehabilitation Robotics (ICORR)*, Seattle, USA, IEEE (2013) pp. 1–5.
8. L. Mertz, "The next generation of exoskeletons: Lighter, cheaper devices are in the works," *IEEE Pulse* **3**(4), 56–61 (2012).
9. A. Tsukahara, Y. Hasegawa, K. Eguchi and Y. Sankai, "Restoration of gait for spinal cord injury patients using HAL with intention estimator for preferable swing speed," *IEEE Trans. Neural Syst. Rehab. Eng.* **23**(2), 308–318 (2015).

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press

10. S. A. Murray, K. H. Ha, C. Hartigan and M. Goldfarb, “An assistive control approach for a lower-Limb exoskeleton to facilitate recovery of walking following stroke,” *IEEE Trans. Neural Syst. Rehab. Eng.* **23**(3), 441–449 (2015).
11. J. L. Collinger, M. L. Boninger, T. M. Bruns, K. Curley, W. Wang and D. J. Weber, “Functional priorities, assistive technology, and brain-computer interfaces after spinal cord injury,” *J. Rehab. Res. Dev.* **50**(2), 145 (2013).
12. D. L. Brown-Triolo *et al.*, “Consumer perspectives on mobility: Implications for neuroprosthesis design,” *J. Rehab. Res. Dev.* **39**(6), 659–670 (2002).
13. A. Tsukahara, R. Kawanishi, Y. Hasegawa and Y. Sankai, “Sit-to-stand and stand-to-sit transfer support for complete paraplegic patients with robot suit HAL,” *Adv. Robot.* **24**(11), 1615–1638 (2010).
14. S. Mefoued, S. Mohammed, Y. Amirat and G. Fried, “Sit-to-Stand Movement Assistance Using An Actuated Knee Joint Orthosis,” Proceedings of the 2012 IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), Roma, Italy, IEEE (2012) pp. 1753–1758.
15. N. Karavas, A. Ajoudani, N. Tsagarakis, J. Saglia, A. Bicchi and D. Caldwell, “Tele-Impedance Based Stiffness And Motion Augmentation For A Knee Exoskeleton Device,” Proceedings of the 2013 IEEE International Conference on Robotics and Automation (ICRA), Karlsruhe, Germany, IEEE (2013) pp. 2194–2200.
16. W. Huo, S. Mohammed, Y. Amirat and K. Kong, “Active Impedance Control of A Lower Limb Exoskeleton to Assist Sit-to-Stand Movement,” Proceedings of the 2016 IEEE International Conference on Robotics and Automation (ICRA), *Stockholm*, Sweden, IEEE (2016) pp. 3530–3536.
17. Y. Han, S. Q. Zhu, Z. Zhou, Y. Shi and D. B. Hao, “Research on a multimodal actuator-oriented power-assisted knee exoskeleton,” *Robotica* **35**(9), 1906–1922 (2017).
18. U. Onen, F. M. Botsali, M. Kalyoncu, M. Tınkır, N. Yılmaz and Y. Sahin, “Design and actuator selection of a lower extremity exoskeleton,” *IEEE/ASME Trans. Mechatr.* **19**(2), 623–632 (2014).
19. O. Unluhisarcikli, M. Pietrusinski, B. Weinberg, P. Bonato and C. Mavroidis, “Design and Control of A Robotic Lower Extremity Exoskeleton for Gait Rehabilitation,” Proceedings of the 2011 IEEE International Conference on Intelligent Robots and Systems (IROS), San Francisco, CA, USA, IEEE (2012) pp. 4893–4898.
20. C. Kirtley, CGA Normative Gait Database, Hong Kong Polytechnic University. Available at: http://www.clinicalgaitanalysis.com/data/ (Accessed February 15, 2017).
21. B. Chen, H. Ma, L. Y. Qin, X. Guan, K. M. Chan, S. W. Law, L. Qin and W. H. Liao, “Design of A Lower Extremity Exoskeleton for Motion Assistance in Paralyzed Individuals,” Proceedings of the 2015 IEEE International Conference on Robotics and Biomimetics (ROBIO), Zhuhai, China, IEEE (2015) pp. 144–149.
22. V. S. Gurfinkel, Y. P. Ivanenko, Y. S. Levik and I. A. Babakova, “Kinesthetic reference for human orthograde posture,” *Neuroscience* **68**(1), 229–243 (1995).
23. A. Goswami, “Postural stability of biped robots and the foot-rotation indicator (FRI) point,” *Int. J. Robot. Res.* **18**(6), 523–533 (1999).
24. S. Ito and H. Kawasaki, “A Standing Posture Control Based on Ground Reaction Force,” Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, (2000) pp. 1340–1345.
25. V. Rajasekaran, J. Aranda, A. Casals and J. L. Pons, “An adaptive control strategy for postural stability using a wearable robot,” *Robot. Auton. Syst.* **73**, 16–23 (2015).
26. D. A. Winter, *Biomechanics and Motor Control of Human Movement*, 4th ed. (Hoboken, NJ, USA: Wiley, 2009).
27. S. Mefoued, S. Mohammed and Y. Amirat, “Knee Joint Movement Assistance Through Robust Control of An Actuated Orthosis,” Proceedings of the 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems, San Francisco, USA, IEEE (2011) pp. 1749–1754.

https://doi.org/10.1017/S0263574717000546 Published online by Cambridge University Press