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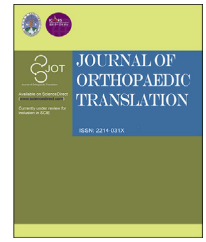

ORIGINAL ARTICLE

A wearable exoskeleton suit for motion assistance to paralysed patients

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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.

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The translational potential of this article

In recent years, wearable exoskeleton suits have been developed and utilised for rehabilitation and healthcare 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.