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REVIEW ARTICLE

Recent developments and challenges of lower extremity exoskeletons

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Summary The number of people with a mobility disorder caused by stroke, spinal cord injury, or other related diseases is increasing rapidly. To improve the quality of life of these people, devices that can assist them to regain the ability to walk are of great demand. Robotic devices that can release the burden of therapists and provide effective and repetitive gait training have been widely studied recently. By contrast, devices that can augment the physical abilities of able-bodied humans to enhance their performances in industrial and military work are needed as well. In the past decade, robotic assistive devices such as exoskeletons have undergone enormous progress, and some products have recently been commercialized. Exoskeletons are wearable robotic systems that integrate human intelligence and robot power. This paper first introduces the general concept of exoskeletons and reviews several typical lower extremity exoskeletons (LEEs) in three main applications (i.e. gait rehabilitation, human locomotion assistance, and human strength augmentation), and provides a systemic review on the acquisition of a wearer's motion intention and control strategies for LEEs. The limitations of the currently developed LEEs and future research and development directions of LEEs for wider applications are discussed.

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Introduction

The ageing population is a global issue, and physical deterioration and frailty in elderly people has become a socioeconomic problem in many countries. A survey from the United Nations reveals that people older than 60 years represented ~11.5% of the global population in 2012, and this percentage will be nearly doubled by 2050 [1]. By the year 2050, the ageing problem will be even worse in China and European countries where >30% of the population will consist of elderly people. The frailty of elderly people is reflected by reduced daily physical activities such as walking less frequently because of significantly reduced muscle mass and strength. In the worse instances, their muscles could further deteriorate and they may become bedridden or immobilized, which may accelerate the deterioration of the neuromusculoskeletal systems and their interactions [2—4]. Stroke is a major disease that may lead to a mobility disorder, and nearly three-quarters of all strokes occur in people older than the age of 65 years. The increased number of stroke patients in an ageing society will also result in many health care issues [5,6].

In addition to age-related pathologies, the number of patients experiencing mobility impairment caused by spinal cord injury (SCI) is also increasing because of accidents and diseases [7,8]. Spinal cord injury predominantly occurs in people under the age of 30 years [9]; therefore, the financial burden imposed on family and society is long-term and high. Patients who have a complete SCI lose motor and sensory functions in their lower limbs. In addition, they are at increased risk for several secondary medical consequences of paralysis such as osteoporosis, muscle atrophy, obesity, coronary heart disease, diabetes, insulin resistance, impaired bowel and/or bladder function, and pressure ulcers [10,11]. In addition, patients who have various diseases and injuries such as cerebral paralysis and orthopaedic injuries have a dysfunction in the lower extremities. Impaired mobility would significantly reduce life expectancy, and thus rehabilitation training is needed to help these patients recover and regain mobility. Therefore, it is necessary and impactful to develop assistive devices that utilize state-of-the-art technologies to help disabled people regain the ability to stand and walk, and release therapists from the heavy work of rehabilitation training [12].

Apart from the demands in health care, the applications of robotic assistive devices for human strength augmentation are also in great need. Heavy objects are usually transported by wheeled vehicles. However, many environments such as rocky slopes and staircases cause significant challenges to wheeled vehicles. Legs can adapt to a wide range of extreme terrains, and therefore legged locomotion is a desired method of transportation in these circumstances. Therefore, a leg exoskeleton can free people from much of the labour and burden of many types of manual work, lessen the likelihood of injury, and improve the efficiency of work.

An exoskeleton is a wearable bionic device that is equipped with powerful actuators at human joints, and integrates human intelligence and robot power [13—17]. With a built-in multisensor system, an exoskeleton can acquire wearer's motion intensions and accordingly assist the wearer's motion. It can apply external force/torque to the wearer's limbs under control, and hence provide user-initiated mobility. The exoskeleton enhances the strength of the wearer's joints. For example, an exoskeleton allows people with mobility disorders to regain the ability to stand and to walk over the ground, upstairs, and downstairs. Compared to traditional physical therapy, exoskeleton assistive rehabilitation has the advantages of reducing the work of therapists, allowing intensive and repetitive training, and it is more convenient to use for quantitatively assessing the recovery level by measuring force and movement patterns. In other applications, it can also help an able-bodied person carry heavy loads. Therefore, with the help of an exoskeleton, wearers can achieve a high level of performance.

In the past several decades, the progress in the development of exoskeletons has been remarkable. Universities, research institutes, and industrial companies have been actively performing research in this field, especially in recent years. Several exoskeleton systems have been developed and tested. Based on the part of the human body the exoskeleton supports, exoskeletons can be classified as upper extremity exoskeletons, lower extremity exoskeletons (LEEs), full body exoskeletons, and specific joint support exoskeletons [18—24].

This paper primarily focuses on the LEE and discusses some typical LEEs that have been developed worldwide. These exoskeleton systems are classified into three categories (discussed in the section "Classification of LEEs"), according their different applications and target users. The human—exoskeleton motion data acquisition and analysis and control strategies for LEEs are then reviewed. The limitations of current LEEs and relevant research and development directions are also discussed.

Classification of LEEs

LEEs are primarily developed for three types of applications. The first application focuses on gait rehabilitation (i.e. helping patients with mobility disorders in the rehabilitation of musculoskeletal strength, motor control, and gait). Exoskeleton-based rehabilitation also releases the heavy burden of therapists in traditional physical therapy [13]. The second application is human locomotion assistance, which is targeted at paralyzed patients who have lost motor and sensor function in their lower limbs. Assistance from exoskeletons enable these patients to regain the ability to stand up, sit down, and walk, just as an able-bodied person [14,15]. The third application of exoskeletons is aimed at enhancing the physical abilities of able-bodied humans (i.e. human strength augmentation) [20].

Lower extremity exoskeletons for gait rehabilitation

Elderly people with weakened muscle strength may not be able to walk as frequently as before, and may also lose their stability during walking. Loss of motor control can occur because of many other medical conditions.