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Review

Ankle-foot orthoses for rehabilitation and reducing metabolic cost of walking: Possibilities and challenges☆

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ABSTRACT

People with diseases such as stroke, spinal cord injury, and trauma usually have paretic ankle involvement because of the plantar flexor and dorsiflexor muscle weakness. Individuals with paretic ankle normally have the drop-foot gait, which has the complications of foot-slap after heel contact and toe-drag during the swing phase of a gait cycle. This could cause slow walking speed, short step-length, high metabolic cost, and high risk of tripping. Ankle-foot orthotic intervention is mostly prescribed to treat paretic ankle impairments. In addition, ankle-foot orthoses (AFOs) have been developed to assist human walking, which can reduce the wearer's metabolic cost of walking. To date, three kinds of AFOs have been developed, including the passive AFOs, semi-active AFOs, and active AFOs. This paper provides a systematic review on these three types of AFOs, where the biomechanics of normal and pathological gaits of human, the design concepts of the AFOs, and motion data collection of the human-machine system in human trials are described. The limitations of the currently developed AFOs and future research and development directions of AFOs are discussed, which would provide useful information for researchers to develop suitable AFOs.

1. Introduction

Human ankle plays an important role in performing activities of daily living. However, stroke, brain injury, spinal cord injury (SCI), trauma, muscular dystrophy, and other neurologic injuries could cause the weakness in ankle muscles, and hence result in ankle disabilities [1]. Ageing population is now a global issue, and nearly three-quarters of all strokes occur in people over the age of 65. According to the report from the World Health Organization, approximately 15 million people have a stroke worldwide each year [2,3]. In addition, there are about 0.25–0.5 million people who suffer a SCI every year all over the world [4]. Thus the number of patients with ankle impairments is increasing. Patients with ankle disabilities usually have plantar flexor and/or dorsiflexor muscle weakness. The weakness of plantar flexor muscle, which is comprised of the gastrocnemius, soleus, and the peroneal and posterior tibial muscles, could reduce the push-off power that is essential to propel the body forward during the stance phase. The weakness of dorsiflexor muscle (including the tibialis anterior, extensor digitorum longus, and extensor hallucius longus) could result in inadequate lifting of the toes during the swing phase, which could cause a drop-foot gait. An individual with a drop-foot would have toe-drag, slow walking speed, short step-length, high metabolic cost, and high risk of tripping [5]. Therefore, patients with paretic ankle usually have reduced walking capacity and then result in a reduced participation in activities of daily living, which could affect the patients' quality of life.

Treatments including surgical, therapeutic, and orthotic have been adopted for individuals with paretic ankle. One approach is the functional-electrical stimulation (FES). FES uses electric current to contract the damaged muscles, and hence to enhance the functionality [6,7]. However, FES should be individually customized by using the trial-and-error method. Generally, a trained professional is needed to evaluate the patient's gait qualitatively and change the device setting accordingly [8]. In addition, the electrodes should be placed at the suitable positions on the affected side carefully.

Nowadays, orthotic treatment has been widely adopted to treat individuals with paretic ankle. An ankle-foot orthosis (AFO) is a wearable medical device that is attached to the wearer and aligned with the wearer's ankle and foot. The functions of an AFO are realized by supporting or by assisting the wearer's neuro-musculo-skeletal system. The AFO can generate assistive force/torque to help the weak and paralyzed

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muscles of the ankle to correct the wearer's orthopedic maladjustment [9]. Most of the AFOs for rehabilitation purpose are designed to treat the drop-foot gait because the dorsiflexor muscles are more frequently affected as compared with the plantar flexor muscles [10].

In addition to the purpose for rehabilitation, AFOs are also developed to reduce the metabolic cost of human walking. The activities of human daily living include stand up/sit down, walking, walking upstairs/downstairs, walking upslope/downslope, running, and so on. Among these motions, walking is the most important and frequent one. AFOs can provide push-off assistance for the wearers to propel the body forward during walking, and hence to reduce their metabolic cost of walking below that of normal walking [11]. In the past few decades, universities and research institutes have been actively carrying out research in the development of AFOs, and enormous progress has been made in this field. Different kinds of AFOs have been developed such as the passive AFOs, semi-active AFOs, and active AFOs.

Some reviews on AFOs have been performed. Wong et al. [12] reviewed the AFOs interventions for patients with stroke, but they were mainly focused on the passive AFOs. In the review of Tyson et al. [13], Zhang et al. [14], and Daryabor et al. [15], the effectiveness of AFOs on gait biomechanics of individuals with musculoskeletal or neurologic ankle injuries were investigated. However, the AFOs used in the human trials were not described and analyzed. Especially, to our knowledge, there is no review on AFOs for healthy individuals to reduce the metabolic cost during normal walking or loaded walking so far. In this paper, we reviewed and analyzed the AFOs for rehabilitation and reducing metabolic cost of walking, and then proposed some possible directions to improve the currently developed AFOs for the researchers.

This paper first presents the normal and pathological gaits of human. Then, the AFOs developed to help individuals with paretic ankle for rehabilitation and healthy people to reduce the metabolic cost of walking are reviewed. Collection of the motion data of the human-machine system (HMS) is presented as well. Finally, this paper discusses the limitations of the existing AFOs and the relevant research and development directions of AFOs.

2. Normal and pathological gait patterns of human

Before introducing the state-of-the-art technologies of AFOs, the normal and pathological gait patterns of human are firstly presented in this section.

2.1. Normal gait pattern

Human gait is generally continuous and periodic, as we move forward our bodies with a repetitive movement of each leg. As a result, the ground reaction forces (GRFs) are applied to the feet to support the body weight. There are two requisites of walking: periodic movement of each foot and continuing GRFs [16]. A human gait cycle is defined as a sequence of movements during walking. It starts when one foot contacts the ground (heel contact) and ends when the same foot contacts the ground (heel contact) again. It is basically comprised of the alternating stance phase and swing phase [17], as shown in Fig. 1(a). The stance phase starts with heel contact (HC) and ends with pre-swing (PS). During the stance phase, the body is decelerated and stabilized, and then is propelled forward. The swing phase starts with initial swing (IS) and ends with the next HC of the same foot. During the swing phase, the swing foot is off the ground, and the hip joint provides large power to raise the leg and swing it forward.

Human ankle has significant effects on normal walking, such as the function of absorbing the shock with the ground, storing the elastic energy, and propelling the body forward. The ankle joint is a hinge-type synovial joint with three degrees of freedom, including the dorsiflexion/ plantarflexion, inversion/ eversion, and pronation/ supination. The dorsiflexion/ plantarflexion occurred in the sagittal plane is the most important for forward progression during the stance phase and ensuring sufficient toe clearance during the swing phase. The dorsiflexion is responsible for bringing the toes closer to the shank, while the plantarflexion is the opposite movement [18]. The stance phase of human ankle during a gait cycle is comprised of three stages: controlled plantarflexion (CP), controlled dorsiflexion (CD), and powered plantarflexion (PP) [19]. The torque of the ankle joint is small in the CP stage, and the ankle joint stores the elastic energy in this stage. In the CD stage, the ankle joint also stores the elastic energy and reaches the maximum dorsiflexion. In the PP stage, the stored energy in the ankle joint is released to help to propel the body forward. The CD and PP stages are the propulsive stage of the stance phase [20], and the ankle joint generates large power and torque for the body forward propulsion during this stage.

2.2. Pathological gait pattern

The dorsiflexor and plantar flexor muscle weakness is the main cause of pathological gait [21]. The weakness of dorsiflexor muscles has significant effects on the HC stage and swing phase of a gait cycle. During the stance phase, weak dorsiflexors could cause audible foot-slap due to the uncontrolled foot deceleration at the HC stage. During the swing phase, the dorsiflexor muscle weakness cannot ensure sufficient toe clearance, which would lead to a drop-foot gait. In this situation, the hip and knee flexion of the affected side would increase to ensure sufficient toe clearance. The plantar flexor muscle weakness could cause a reduction of the push-off power during the single-leg stance phase, which could lead to slow walking speed and short step-length [22,23].

The comparisons between gait patterns of normal people and individuals with paretic ankle is shown in Fig. 1. Due to less support from the plantar flexors on the affected side, the knee extensor has to work much later during the stance phase. Furthermore, more support should be provided by the hip extensor as compared with the unaffected side [24]. The main complications of drop-foot gait are foot-slap during the HC stage and toe-drag during the swing phase of a gait cycle. When walking, individuals with a drop-foot will drag their paretic limb in a semicircle (circumduction) by using exaggerated positive work from the hip flexor to raise the foot. They normally have shorter stance phase and a shorter step-length of the affected side, which results in an asymmetric gait pattern. As compared with the normal gait pattern, the drop-foot gait has the features of decreased joint range of motion (ROM), slow walking speed, elevated metabolic cost, and increased falling risk [24-26].

3. Category of ankle-foot orthoses

To date, three kinds of AFOs have been developed, including the passive AFOs, semi-active AFOs, and active AFOs. The passive AFOs do not include any electrical elements or power sources, except for some mechanical elements such as springs and dampers. Generally, they are designed with articulated or non-articulated joints. During the past decade, robotic technologies have been employed in the research and development of medical devices such as exoskeletons [27–30] for robot-assisted rehabilitation. Semi-active AFOs do not include any actuator to a power supply. They have the ability to modulate the ankle joint compliance or damping. For active AFOs, they are more complex and are normally composed of actuators, power source, sensors, and controllers. According to the applications and users, AFOs can be classified into two groups: one is for rehabilitation for individuals with muscle weakness at the ankle, and the other is for reducing the metabolic cost of walking for healthy people.

3.1. AFOs for rehabilitation

The aim of rehabilitation for individuals with paretic ankle is to recover healthy gait patterns for the ankle [31]. The effectiveness of