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Design and development of lower limb exoskeletons: A survey

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ABSTRACT

Research into the development of the lower limb exoskeleton (LLE) has been on-going since the 1960s. Although this field has long been explored, the technological progress has been very slow. Many exoskeletons were stopped in their tracks toward commercialization at the research stage itself. Therefore, this paper is aimed at systematically reviewing the design and development of multiple joint LLEs. The discussion focuses on the application of LLEs for augmentation, muscle weakness or gait recovery and rehabilitation. Details of aspects such as the control strategy, actuator, safety and design, including compactness, noise, heavy structural weight, cost, mimicking of natural walking, and power sources, will be discussed. Finally, issues concerning the design and development of LLEs will also be presented.

1. Introduction

In the growing field of wearable robotics, prostheses, orthoses and exoskeletons are being designed and developed to support and assist human limbs in the performance of various tasks. Prostheses are artificial devices, such as artificial arms or legs, that are attached to or worn on the body to replace lost limbs [1]. An exoskeleton is described as a device that amplifies or augments the wearer's strength and endurance, whereas an orthosis is traditionally described as a device to assist a person with limb pathology [2]. Orthoses and exoskeletons are mechanical devices that are essentially anthropomorphic in nature. They are worn by an operator to fit closely to the body and to work in concert with the wearer.

The history of the development of exoskeletons began with the first technical concept proposed by Lent in 1956, followed by Mizen in 1966 [3], and which was then continued by General Electric in the United States in the late 1960s [4,5]. The powered exoskeleton project by Hardiman in 1971 [4] was the first practical investigation into the use of a powered exoskeleton for handling materials. It was marketed as a breakthrough in control system designs, analytical techniques and man–machine interface methods. This research was actively pursued by the BLEEX project in 2004 at U.C. Berkeley's Human Engineering and Robotics Laboratory. BLEEX was aimed at amplifying human strength and endurance during locomotion for military purposes [6].

LLEs have been developed since the 1960s to enable spinal cord injury (SCI) patients to walk by regaining their locomotion or recovering their gait [7]. The initial design started with orthoses such as the Hip Guidance Orthosis (HGO) or the ParaWalker, Reciprocating Gait Orthosis (RGO), and the Steeper's Orthosis [8], which required much physical effort on the part of the patient and the loss of a lot of energy in attempting to walk [9,10].

Muscular weakness was among the reasons for designing LLEs. Statistical data from the Department of Statistics, Malaysia show that the life expectancy of 65 years is growing in Malaysia [11]. Increasing age will lead to muscle weakness and will limit the quality of life. Therefore, one solution to muscular weakness is LLEs to aid elderly people in walking. There are a number of examples of LLE devices created for muscular weakness such as WPAL [12], MoonWalker [13], the Walking Assist and Mobility device designed by Honda [14], and the multiple leaf (MLE) and single leaf (SLE) exoskeletons, which are used to reduce the metabolic power required for hopping [15].

It is very critical that rehabilitation therapy be revived. Research trends show that most researchers are still continuing their studies in this field. Based on the literature, LLE devices are currently being developed mostly for military, industrial and medical purposes.

The aim of this paper is to systematically review the issues concerning the design and development of multiple joint LLEs. To achieve this, the characteristics of LLEs in relation to previous development and design strategies are analysed. Finally, conclusions will be made with regard to recent trends from the perspective of the design of LLEs.

The discussion begins with an explanation of the methodology for the literature search in Section 2. Section 3 presents the development of LLEs. The review of multiple joint LLEs is revealed

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in Section 4. In this section, designs for multiple joints in terms of the actuator type, degrees of freedom (DOFs), low level controller and parameters to sense or measure feedback to the controller are explained. Section 5 presents the discussion, while the conclusions are given in Section 6.

2. Methodology for literature search

This paper addressed the use of multiple joint LLEs for augmentation, the powering of muscular weakness, rehabilitation and gait recovery. However, issues related to partial or single joint LLEs, fully passive or quasi-passive LLEs and prostheses, were not included. All the papers in the research and commercialization stages were collected from Scopus, the SCI web and company websites, to which the searches were limited to the period 1999–2016.

3. Exoskeleton design considerations

LLEs are mechatronic devices that combine elements of a mechanical structure, sensor, actuator, and controller. In the design stage, some important considerations have to be made concerning the actuator type, degrees of freedom, control strategy, applied joints, applications domain, power transmission method, human intention detector and design concept.

3.1. Actuator type

LLEs can be actuated by means of three types of actuations, i.e. active actuation, passive or quasi passive assistive actuation, and hybrid actuation. Active actuators comprise electric, pneumatic and hydraulic actuators. Passive assistive actuators comprise non-powered components or elastic components such as springs, which can store energy, and are based on the principles of gravity for balance [16,17]. Quasi-passive actuators are passive devices that work in conjunction with viscosity devices such as clutches, dampers or clutch–damper combinations [18–20]. Passive orthoses depend solely on the physical effort of the patient and allow for very slow walking speeds. Meanwhile, investigations into the effectiveness of the passive components in LLEs have revealed that they reduce the muscle forces and metabolic energy needed for walking [21–23]. Hybrid actuators are a combination of more than one type of active, active–passive or active–quasi-passive actuators in LLE joints.

3.2. Degree of freedom

The complex development of LLEs is entirely dependent on the maximum number of independent displacements or motions at the joint, which is defined as the degrees of freedom (DOFs). Therefore, the minimum collision, maximum safety, comfortable walking and architecture must be exactly the same as the motion and posture of the lower limbs of the human being. Therefore, LLEs are designed with anthropomorphic, ergonomic and human characteristics. The human hip is a ball and socket joint with 3 DOFs, i.e. flexion/extension (f/e), abduction/adduction (ab/ad), and internal/external rotation (i/e). The human knee joint is a combination of rolling and sliding between the femur and tibia, which allows the centre of rotation of the joint to move as the knee flexes. The knee joint consists of 2 DOFs, i.e. flexion/extension (f/e) and internal/external (i/e) rotation. The human ankle joint has 3 DOFs, i.e. dorsiflexion/plantar flexion (d/p), abduction/adduction (ab/ad) and internal/external rotation (i/e) [24].

3.3. Control strategy

The locomotion cycle control framework for animating human walking was introduced by Bruderlin et al. [25]. The latest framework, which is a general control framework for LLEs, was proposed by Tucker et al. [26]. There are 3 levels of hierarchical controllers. First, the high-level controller acts to understand the locomotion intent of subjects through a combination of activity mode detection and direct volitional control. There are many strategies to perceive the locomotion intent of subjects [27], namely, through sensitivity amplification control [28,29], predefined gait trajectory control [30–33], model-based control [34–36,12,37,38], adaptive oscillator-based control [39–42], fuzzy controller [43,44], predefined actions based on gait patterns [45–48], and hybrid assistive strategies [6,49,50].

Second, the middle-level controller acts as an intent-to-state translation layer. It maps the locomotive intent from the high-level controller to the desired device sequence for tracking by a low-level controller. The middle-level controller also manages the controller between multiple actuated joints, whether contained within one device or across multiple devices. The phase-based controllers in [51–53] and non-phase-based controllers in [54,55] are examples of middle-level controllers.

Third, the low-level controller or joint level controller acts as a specific control layer device from which is derived the actuator that tracks the state in the middle layer. This level serves as the force, torque and position or angle of the exoskeleton joint. There are many types of controller strategies for each level, as discussed in [6,56–58,22].

3.4. Applied joints

LLEs can be classified as multiple joint and single or partial joint LLEs. In a multiple joint LLE, more than one of the lower limb joints (hip, knee and ankle) are actuated, while in a single joint LLE, only the hip, knee or ankle joint is actuated.

3.5. Applications domain

The design of the exoskeleton should be focused on its application because this will affect the systems and components required for the development of the LLE. The applications domain includes the rehabilitation treatment [59], regaining of locomotion [60], the augmentation system, which is usually developed for military purposes [61], and the powering of muscular weakness [62].

3.6. Power transmission method

The development of LLEs should take into consideration the method of power transmission that will be used, whether it will be cable-based [63,46], gear-based [64], linkage-based [65,64] or a combination of two or more power transmission methods (hybrid-based) [66].

3.7. Human intention detector

Sensors are used to capture information or intentions from humans to be sent to the exoskeleton controller. The sensors can be categorized into two main groups: cognitive-based sensors and physical-based sensors [20].

Cognitive-based sensors read intentions by measuring the electric signals from the nervous system or musculoskeletal system of humans. For example, muscular activity can be measured by means of electromyography (EMG) and mechano-myography using a muscle stiffness sensor (MSS), muscle tenseness sensor, and ultrasonic muscle activity sensor, while brain activity can be detected by means of an electroencephalogram (EEG).