Mechatronics 46 (2017) 32–45

Contents lists available at ScienceDirect

Mechatronics

journal homepage: www.elsevier.com/locate/mechatronics

Design and locomotion control of a hydraulic lower extremity exoskeleton for mobility augmentation☆

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ARTICLE INFO

Article history:
Received 27 December 2016
Revised 20 April 2017
Accepted 19 June 2017

Keywords:
Exoskeleton
Wearable robot
Locomotion control
Dual-mode control

ABSTRACT

In this paper, a system design and three locomotion control algorithms are proposed for a hydraulic lower extremity exoskeleton to enhance mobility and reduce muscle fatigue caused by backpack loads. The range of motion of the exoskeleton and the capacity of the hydraulic power unit, which generates the hydraulic flow and pressure, are determined by analysing human walking data obtained using a motion capture device and force plates. For movement comfort, the mechanical structure and the joints of the exoskeleton are designed such that the motion of the wearer coincides with that of the exoskeleton. In addition, locomotion control algorithms for stable normal walking are described; these algorithms enable dual-mode control and transition control. Dual-mode control is comprised of an active mode in the stance phase and a passive mode in the swing phase. In the active mode, the exoskeleton is controlled to track the motion of the wearer, and in the passive mode, its active joints work as passive joints by blocking the hydraulic power supply from the hydraulic power unit. Transition control, which consists of a torque-shaping method and a pre-transition algorithm, is adopted to improve locomotion responses during gait phase transition. Finally, to verify the effectiveness of the locomotion control algorithms and the developed hydraulic lower limb exoskeleton, walking experiments are performed on a treadmill, at a speed of 4 km/h, while carrying 45 kg backpack loads. The assistance effect of the exoskeleton is also validated by comparing the electromyography (EMG) signals of four selected muscles, with and without the exoskeleton, for single stance and level walking while carrying the same 45 kg backpack loads.

1. Introduction

Recently, the development of exoskeletons–mechanical systems that provide additional forces to support or augment the muscle forces of wearers–has been a major area of interest in robotics [1–5]. Exoskeletons are expected to be utilised in various areas such as military, industrial, and medical fields. The ideal goal of exoskeletons is to allow wearers to move comfortably by alleviating muscle activation and to prevent them from feeling any resistive forces, but the performance of currently developed exoskeletons remains unsatisfactory, especially for fast motion.

Initially, exoskeletons were developed to generate large assistive forces and carry heavy loads; examples of such exoskeletons are BLEEX [6,7], HULC [8], and XOS [9]. These robots are effective in offsetting gravitational forces caused by carrying loads but produce some resistive forces on wearers during dynamic movements. These resistive forces are mainly generated from motion misalignment between the wearer and the robot and leads to muscle fatigue.

Several studies have been conducted to reduce the resistive forces. Linkage mechanisms [10,11] were proposed to closely locate the axes of rotation of the exoskeletons ankle and knee joints and those of the corresponding human joints. These mechanisms reduced discomfort kinematically. In other studies [12,13], the load on the muscles of wearers was reduced by designing a lightweight exoskeleton for the leg. Lightweight exoskeletons are effective, but they may not sufficiently reduce resistive forces. The detection of a wearer's movement intention is a key technique that can be used to control the exoskeleton with no resistance, but detecting the intention quickly and accurately is difficult. Bio-signals such as electromyography signals have been adopted to extract movement intention [14–20]. Although such signals can be measured tens of milliseconds before the movements, they are not reliable because of a large amount of signal noise and muscle fatigue. Movement intention can be estimated from the inverse dynamics

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☆ This paper was recommended for publication by Associate Editor Michael Ruderman.

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http://dx.doi.org/10.1016/j.mechatronics.2017.06.009
0957-4158/

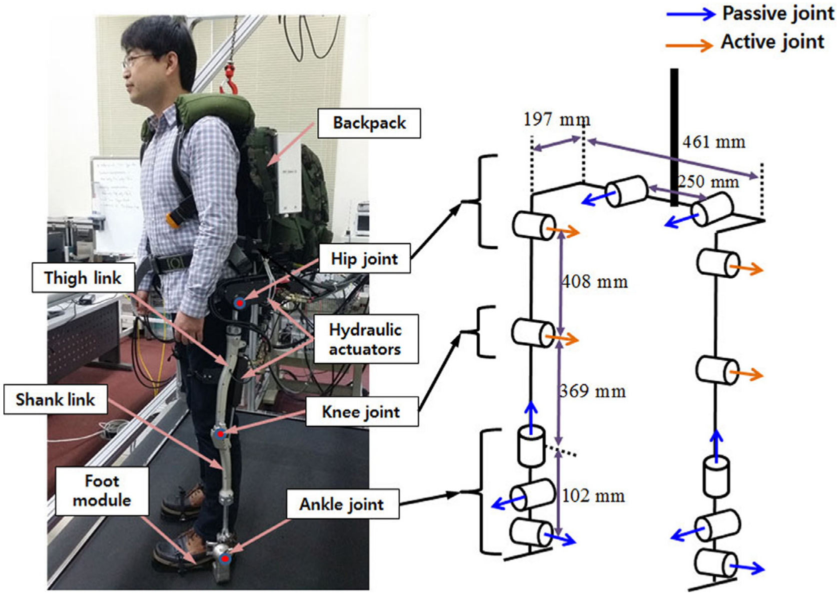

Fig. 1. Exoskeleton system.

of exoskeletons [21,22] and from the interactive forces [23,24] directly measured by force/torque sensors. This estimation includes the inherent time delay compared to the real movement intention. In addition, noise from the force/torque sensors tends to make the exoskeleton system unstable during fast movement. The effectiveness of using cuff sensors fastened to a belt connecting the wearer to the robot has also been investigated to reduce the time delay in detecting movement intention [25–27]. Here, six sensors distributed along the belt length allow the measurement of a large amount of information on interactive forces, but the irregular shape of the wearer's limb prevents reliable measurement. In addition, several approaches employed impedance control strategy [28–32]. Proper impedance of the exoskeleton potentially reduces interactive forces between the wearer and the exoskeleton, but it is hard to estimate an accurate impedance for natural movements.

Despite the numerous approaches described above, the design of exoskeleton robots that can augment the wearers' muscle power while ensuring stable normal walking is still not satisfactory. In response to this design challenge, this paper presents the design of a hydraulic lower extremity exoskeleton system (Fig. 1) and a locomotion control strategy for the exoskeleton to augment human mobility and hence ensure stable normal walking for a long duration. In our system, a quasi-anthropomorphic design is adopted to align the rotation axis of the exoskeleton with that of the human joints; in such a design, the leg is kinematically similar to that of a human but does not include all the degrees of freedom found in human legs. The proposed system has only two active joints–at the hip and knee–powered by hydraulic actuators to reduce the inertia of the swing leg and decrease power consumption. During a gait cycle, the motion of each joint in the swing phase is faster than that in the stance phase, but the required joint torques in the swing phase are considerably smaller than those in the stance phase. Based on the observed human gait characteristics, we propose a dual-mode control algorithm that facilitates stable normal walking while carrying heavy loads. That is, in the stance phase, the hydraulic actuators of the active joints generate joint torques to control the exoskeleton, which is called the active mode. Conversely, the hydraulic forces generated by the actuators are not delivered to the exoskeleton in the swing phase, which is called the passive mode. In addition, transition control is adopted to improve the locomotion responses during gait phase transition; this control consists of a torque-shaping method to prevent sudden and large changes in the torque command and a pre-transition method to classify the gait phase as the swing phase before the start of the actual swing phase. The effectiveness of the proposed locomotion control strategy is verified by performing walking experiments at a 4 km/h speed with 45 kg loads. The assistance effect of the exoskeleton is estimated by comparing the electromyography (EMG) signals of four selected muscles, with and without the system, for single stance and level walking while carrying 45 kg backpack loads. Compared to a previous study [22], the locomotion control for the exoskeleton is more clearly described and the assistance performance of the exoskeleton is also verified by using EMG sensors. The rest of this paper is organised as follows. The design of the hydraulic exoskeleton is explained in Section 2. In Section 3, locomotion control algorithms for the exoskeleton are proposed. The walking experiments performed on the treadmill are described in Section 4. The conclusions and future work are presented in Section 5.

2. System design for hydraulic exoskeleton

In this section, the design of a hydraulic lower extremity exoskeleton is described with respect to its kinematic structure, sensor configuration, and hydraulic power unit (HPU). The design requirements for a 4 km/h walking speed with 45 kg payloads are determined by carrying out gait analysis of the data obtained from a motion capture device with force plates and by using a mock-up of the exoskeleton to measure each joint angle and ground reaction force (GRF).

2.1. Mechanical structure and joints

Fig. 2 shows a 3D CAD model of the exoskeleton system with specific components for each joint and link. Each link of the exoskeleton is designed by considering standard Korean body figures. The lengths of the thigh and shank links can be adjusted to fit normal adults with heights ranging from 170 to 178 cm. As shown in Fig. 2(a), the hip joint module consists of an active pitch joint with a hydraulic actuator and a passive roll joint with a torsional spring. The torsional spring plays the role of supporting a part of the moments generated by hip roll motions, and the width of