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ScienceDirect
Journal of Bionic Engineering 14 (2017) 272–283

# Development and Analysis of an Electrically Actuated Lower Extremity Assistive Exoskeleton

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**Abstract**

An electrically actuated lower extremity exoskeleton is developed, in which only the knee joint is actuated actively while other joints linked by elastic elements are actuated passively. This paper describes the critical design criteria and presents the process of design and calculation of the actuation system. A flexible physical Human-Robot-Interaction (pHRI) measurement device is designed and applied to detect the human movement, which comprises two force sensors and two gasbags attached to the inner surface of the connection cuff. An online adaptive pHRI minimization control strategy is proposed and implemented to drive the robotic exoskeleton system to follow the motion trajectory of human limb. The measured pHRI information is fused by the Variance Weighted Average (VWA) method. The Mean Square Values (*MSV*) of pHRI and control torque are utilized to evaluate the performance of the exoskeleton. To improve the comfort level and reduce energy consumption, the gravity compensation is taken into consideration when the control law is designed. Finally, practical experiments are performed on healthy users. Experimental results show that the proposed system can assist people to walk and the outlined control strategy is valid and effective.

**Keywords:** exoskeleton, pHRI measurement, data fusion, pHRI minimization, adaptive control


doi: 10.1016/S1672-6529(16)60397-9

## 1 Introduction

A lower extremity exoskeleton is an automatic device worn by human users to improve strength and endurance. In recent decades, many advances and progress have been made in the development of wearable exoskeletons. The Berkeley Lower Extremity Exoskeleton (BLEEX) was designed to assist people to carry heavy loads, which could walk at the speed of 0.9 $m \cdot s^{-1}$ while carrying 34 kg payload[1]. A single robot leg has four actuators which leads to the complexity and heaviness of the whole system[2]. The developed exoskeletons latter, *i.e.*, ExoHiker, ExoClimber and HULC, simplify the mechanical structure and reduce the number of active Degrees of Freedoms (DoFs). Those DoFs of joints with the highest power consumption during gait cycles should be actuated while the rest DoFs are passively connected with elastic elements to simplify the system[3]. Generally, the lower extremity exoskeleton leg is composed of serial or serial-parallel leg segment. A cam-mechanism is implemented in the design of ankle joint of the exoskeleton[4]. A novel serial-parallel mechanism is designed in a lower extremity exoskeleton to augment load-carrying for walking[5,6]. However, parallel mechanism will increase the complexity of mechanism and decrease its portability. Compact serial-link mechanisms are utilized in many advanced exoskeletons, *e.g.*, Ekso[7] and ReWalk[8].

The actuation system design and development is a significant aspect for the exoskeleton. There are several popular actuation system modes that have been applied in lower extremity exoskeleton, including hydraulic actuators, electrical motors, serial elastic actuators and pneumatic muscle actuators. Torque-mass ratio, velocity, range of motion and controllability are significant specifications when choosing actuators for exoskeletons[9]. Hydraulic actuators and electrical motors are utilized frequently due to their high torque-mass rates[10].

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Comprehensively, electrical motors are suitable for exoskeletons due to its wide range of motion, ease of control and maintenance, and simplicity of the system. Normally, the electrical motors are placed parallel with the joint of mechanical legs, which causes increment of structure complexity. Different from the traditional electrical actuators, a novel electrical actuator consisting of DC motor, gear pair and ballscrew is developed, which has a more compact mechanical structure compared with the traditional actuator.

pHRI-based human motion intent estimation is a critical step for the exoskeleton control. It is essential to get an accurate measurement of the pHRI for the robotic exoskeleton control and the assessment of the assistance grade[11]. The connection cuff is a widely-used device to fasten the human limb to the exoskeleton, which affects the wearing comfort and the walking performance. A flexible connection cuff is a suitable device to interact with the human user. A flexible sensor technique is developed to measure the pHRI pressure, where the sensory system is composed of several optical-electronic sensors[12]. The system has at least six sensors on the surface of the cuff. The pHRI force can be measured by a strain gauge, where a circle sensor is utilized[13]. However, the structure of the interaction cuff is complex and has multiple sensors. In this work, a flexible pHRI measurement device is designed and applied in the robotic exoskeleton control, which is composed of two gasbags and one force sensor connected to each gasbag. The gasbag can enlarge the interaction area and guarantee that the pHRI can be measured easily. In addition, the usage of gasbag can increase the wearing comfort and adapt to different human users.

The control strategy design is the core issue for the exoskeleton. Control strategies can be divided into three categories according to methods of estimating human motion intent, *i.e.*, approaches based on signals measured from the human body, approaches based on interaction force measurement and approaches based on signals measured from exoskeletons[14]. In order to guarantee the natural gait of human users, sensitivity amplification control, model-based control and hybrid assistive strategy are suitable for load-carrying task[15]. However, sensitivity amplification control is sensitive to external disturbances and model-based control is dependent on the accurate dynamic model. Compared with other assistive strategies, hybrid control strategy is applied successfully in exoskeletons for load-carrying and shows an increased performance. The pHRI-based control strategy is an effective approach for exoskeleton. To minimize the pHRI force, a RBF neural network was proposed to compensate the dynamic uncertainties, where there is no force sensor in the interaction cuff[16]. However, there are some sensors on the human limbs. The goal of human exoskeleton collaboration is to reduce or eliminate the misalignment between the human user and the exoskeleton. In this work, we propose an online adaptive strategy to drive the robotic exoskeleton. With the discussion above, we highlight contributions of this paper: 1) A lightweight and compact electrically actuated robotic exoskeleton system is designed and implemented for walking assistance. 2) A pHRI measurement device is designed, which consists of a force sensor and a gasbag embedded in the connection cuff. 3) A control strategy called model-free adaptive pHRI minimization is proposed to drive the exoskeleton to follow the human limbs.

The remainder of this paper is organized as follows. The specific mechanical design of exoskeleton and the details of actuator are given in the second section. The sensory system is illustrated in the third section. In the fourth section, the adaptive pHRI minimization control strategy is proposed. Experiments are performed and experimental results are presented in the fifth section. Discussion and conclusion are presented in the final section.

## 2 System architecture description

### 2.1 Mechanical structure

Exoskeletons are anthropomorphic devices that work in parallel with the human body. In the design of lower extremity exoskeletons, the number of DoF is required to be close to the number of human lower limbs' DoFs in order to achieve a comfortable walking[17]. The lower extremity assistive exoskeleton has two mechanical segments attached to human limbs, in which there are seven DoFs on the thigh, the knee and the ankle joints in total. Fig. 1 shows the architecture of the lower extremity exoskeleton, which includes three main components as below[18]:

(1) The leg segment including a shank and a thigh is attached to the human user leg by the interaction cuffs. The knee joint is activated by an actuator while the hip joint is passive. The actuator of the knee joint consists of