Mechanism and Machine Theory 74 (2014) 337–353

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

A novel leg orthosis for lower limb rehabilitation robots of the sitting/lying type

Weiqun Wang, Zeng-Guang Hou *, Lina Tong, Feng Zhang, Yixiong Chen, Min Tan

State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China

ARTICLE INFO

Article history:
Received 16 November 2012
Received in revised form 23 December 2013
Accepted 28 December 2013
Available online 23 January 2014

Keywords:
Rehabilitation robot
Leg orthosis
Optimization
Kinematics

ABSTRACT

This paper proposes a novel leg orthosis for lower limb rehabilitation robots of the sitting/lying type. It consists of three joint mechanisms: hip, knee and ankle, and two sets of links: thigh and crus. Each driving motor is located close to the associated joint and the rotational axis of each joint mechanism is unique and stable. These features make it outperform the similar mechanisms in stability and dynamic performance. Different forms of eccentric slider-crank mechanisms are applied in the three joint mechanisms, respectively, such that they can be optimized independently. The optimization problems for the hip and knee joint mechanisms, characterized as strongly nonlinear, are developed respectively. Then, a particle swarm optimization algorithm is used to obtain the optimal solutions, which are subsequently validated by comprehensive comparisons. Moreover, the kinematics necessary for motion control and trajectory tracking are investigated, which denote the relationships between the displacements and velocities of the joint mechanisms, lead screws and the end effector. Finally, this paper illustrates the feasibility of the application of the leg orthosis to actual rehabilitation exercises by a simulation example.

1. Introduction

Stroke is one of the leading causes of death and disability worldwide, and the number of patients with stroke is still increasing [1,2]. For SCI[1], reported incidence lies between 10.4 and 83 per million inhabitants per year in the decade before 2006 [3], and now the annual incidence of traumatic SCI worldwide is estimated to be 35 patients per million [4]. Neurological impairment, frequently caused by stroke, SCI and other neurological disorders, often leads to limb dysfunctions, especially paraplegia and hemiplegia. Although it has been proven that repetitive and intensive rehabilitation exercises with the disabled limbs were effective to neurorehabilitation and motor recovery [5,6], the conventional lower limb rehabilitation exercises are labor intensive and expensive, which limit its clinical application and effects. Therefore, more and more LLRR[2] with novel rehabilitation tools have been designed.

LLRR can be categorized into two types according to the postures of the patients doing exercises with them. One is the sitting/lying type, which is used by patients while sitting or lying, e.g. MotionMaker (Swortec, Switzerland) [7] and Lambda [8]; the other is the standing/walking type, which is used by patients in standing or walking postures and usually incorporated with BWS[3] system, e.g. Lokomat [9], LokoHelp (LokoHelp Group, Germany) [10], and WalkTrainer (Swortec, Switzerland) [11]. Although none of the two types has overwhelming superiority, the sitting/lying type has been less studied presently. However, the sitting and lying postures are closer to those used by physicians or therapists when they are evaluating the motor functions of patients with lower limb dysfunctions, especially those with paraplegia or hemiplegia. Moreover, compared with the standing/walking type, the sitting/lying

* Corresponding author. Tel./fax: +86 10 8254 4531.
E-mail address: hou@compsys.ia.ac.cn (Z.-G. Hou).

[1] SCI: Spinal cord injury.
[2] LLRR: Lower limb rehabilitation robots.
[3] BWS: Body weight support.

0094-114X/$ – see front matter
http://dx.doi.org/10.1016/j.mechmachtheory.2013.12.021

type is easier to use for patients and therapists or nurses from the beginning to the mid of the long term rehabilitation when the patients cannot stand with their weak lower limbs. Therefore, this research focuses on the LLRR of the sitting/lying type.

This kind of robots conventionally consists of one chair and two leg orthoses, which are the most complicated and important parts of these robots and can be synthesized by using different kinds of mechanisms. In [12], mechanical links were used to produce the multi-joint motions. In order to obtain an ideal impedance control system, the device was connected to the patient using elastic components. The disadvantage of this device is, it cannot be used for active exercises that involve the voluntary participation of patients and have been proven more effective for neurorehabilitation and motor recovery [13]. In the design proposed in [14], timing belts were used and the axes of the belt wheels were stable and could exactly match those of human leg joints. Unfortunately, in this design, harmonic speed reducers were used to obtain high transmission ratios for the hip and knee joints, which together with the driving motors were difficult to be located close to associated joints because of the large dimensions. Therefore, the timing belts were long and thus vibration would be caused inevitably when the mechanism was running. In [7], the crank system activated by a lead screw was used to match the motion of each human leg joint. DC motors were located close to associated joints and lead screws could produce high precision; hence, this mechanism was relatively stable. However, the knee joint mechanism could induce a sliding instantaneous center of rotation and a slight movement of the sagittal plane [7]. Moreover, it was shown in Fig. 3 of [15] and Fig. 1 of [23], the torque–angle characteristics of the knee joint mechanism were different from that of human knee joint. Finally, the hip, knee and ankle joints were designed by using the same form of mechanisms in this device [15]. Whereas, angle ranges of the hip and ankle joints are smaller and the torque–angle characteristics of human hip and ankle joints are different from that of knee joint. Therefore, mechanical characteristics of the hip and ankle joint mechanisms proposed in [7] might have been better if they had been designed by using different forms of mechanisms.

Besides, other mechanisms also can be used to replace leg orthoses, such as the mechanisms proposed in [8,16]. However, in these mechanisms, the motion of human foots was limited to a horizontal or sloping plane, thus the exercises they provided were relatively simple.

In this paper, a novel leg orthosis is proposed to overcome the deficiencies of the existing leg orthoses for LLRR of the sitting/lying type. This orthosis consists of three joint mechanisms, corresponding to hip, knee and ankle joints of human leg, respectively, and two sets of links, corresponding to human thigh and crus, respectively. ESCM[4] is used in each joint mechanism to convert the rotation of driving motor, which is with high rotational velocity and lower torque, into the rotation of associated joint, which is with lower rotational velocity and higher torque. A high ratio of the rotational velocity of driving motor to that of the associated joint is obtained by using a lead screw and optimizing the dimensions for each joint mechanism. Hence, there is no need to include additional speed reducing systems. This feature makes it possible to locate the driving motor close to the associated joint, consequently, the transmission system can be simplified to obtain higher stability. The lengths of the thigh and crus of the orthosis can be adjusted, respectively, and each of the hip, knee and ankle joints has unique and stable rotational axis. Therefore, each of the rotational axes of the hip, knee and ankle joints can be adjusted to accurately match that of corresponding human leg joint, which helps to make the process of rehabilitation exercises more comfortable.

For actual application of the leg orthosis proposed in this paper, the following conditions should be satisfied: 1) the dimensions of the leg orthosis should be smaller for the convenience of application; 2) the joint angle and output torque of each joint mechanism should be designed in reasonable ranges; 3) the transmission ratio of each joint mechanism should be higher to obtain greater output torque of associated joint by using a low power DC motor; 4) the relationship between output torque and joint angle for each joint mechanism should be suitable for rehabilitation exercises. Conventionally, mechanisms can be synthesized by trials if the requirements are relatively simple. However, in this design, the first three conditions are contradictory to each other and the last one is difficult to be described in math, and as a result, it is hard to obtain the mechanisms satisfying the above conditions by conventional methods. Therefore, in this paper, the leg orthosis is designed in this way: the first three conditions are applied to develop the optimization problems for associated mechanisms and the last one is used as validation.

The optimization problems developed in this paper are strongly nonlinear, which is shown in Subsections 2.2 and 2.3. Therefore, a PSO[5] method [17], which has been proven effective and easier to use in solving nonlinear optimization problems by plenty of applications [18–20], is used to obtain the optimal solutions. Then, comparisons, including that between the optimized and unoptimized mechanisms and that between the torque–angle characteristics of the knee joint mechanism and of human knee joint, are detailed to validate the optimization results and the suitableness for actual rehabilitation exercises. Moreover, the kinematics, necessary for motion control and trajectory tracking, are obtained by taking the leg orthosis as a linkage with two links. Finally, by using the optimized dimensions and the kinematics obtained in this paper, a simulation example is formulated to demonstrate the feasibility of the application to actual lower limb rehabilitation exercises.

The remainder of the paper is organized as follows: Section 2 describes the mechanism synthesis and optimization in detail. The kinematics are analyzed in Section 3. Section 4 introduces a simulation example and a small discussion is presented. This paper is concluded in Section 5.

2. Synthesis and optimization

The leg orthosis proposed in this paper is designed for people with height from 1500 mm to 1900 mm. According to the respective proportion of thigh and crus lengths and ankle height to body height [21], the length ranges of three parts of the orthosis are given in

[4] ESCM: Eccentric slider-crank mechanism.
[5] PSO: Particle swarm optimization.