Mechanism and Machine Theory 73 (2014) 103–116

Contents lists available at ScienceDirect

Mechanism and Machine Theory

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

Design and development of a hand exoskeleton for rehabilitation of hand injuries

Fuhai Zhang *, Lei Hua, Yili Fu, Hongwei Chen, Shuguo Wang

State Key Laboratory of Robotics and System, Harbin Institute of Technology, 150001 Harbin, China

ARTICLE INFO

Article history:
Received 13 October 2012
Received in revised form 25 October 2013
Accepted 29 October 2013
Available online 28 November 2013

Keywords:
Rehabilitation
Hand exoskeleton
Circuitous joint
Bowden cable

ABSTRACT

Hand injuries are common problems. In order to adapt to fingers of different sizes and avoid secondary injuries, a hand exoskeleton for rehabilitation is proposed. The exoskeleton is designed as a wearable device and each finger has three joints named the metacarpophalangeal (MCP) joint, the proximal interphalangeal (PIP) joint and the distal interphalangeal (DIP) joint which all employ a novel mechanism called "circuitous joint". Adopting a symmetrical pinion and rack with a parallel sliding mechanism, the circuitous joint can cover a wide workspace of the finger and adapt to fingers of different thicknesses. And the parallel sliding mechanism ensures that the contact force between the exoskeleton and the finger is perpendicular to the finger's bone, which can minimize the secondary injuries. Moreover, the Bowden cable driving method reduces the burden on the fingers by placing the driving and control system on the forearm. Lastly, hand fitness test and contact force experiment are conducted and the results verify the rationality and effectiveness of the exoskeleton.

1. Introduction

Hand is one of the most important organs of human body, and its normal motor capability is crucial for people's daily activities. However, hand injuries are common problems, especially in occupational accidents. These injuries can lead to a loss of sensation and motor functions of the hand. It is essential to perform rehabilitation for the hand to regain previous dexterity. Currently most rehabilitation activities are performed manually by physiotherapists. However, it causes high personnel costs and the lack of motivation of patients to perform exercises.

Recent researches showed that exoskeleton devices based on rehabilitation theory are feasible and effective [1,2]. However, most existing exoskeleton devices were not developed for rehabilitation purposes. Some exoskeleton devices were designed for master–slave systems [3–5], and some were designed as the force feedback devices [6]. They are limited in the number of independently actuated degrees of freedom and may cause secondary injuries easily. Nevertheless, research on hand exoskeletons has already achieved promising results. The exoskeleton designed at the Technical University of Berlin [7,8] has 4 DOFs (degrees of freedom) and can actuate each finger joint by the linkage mechanism, but additional changeable attachments are needed to fit different hand sizes. Worsnopp et al. [9] proposed a virtual prototype with 3 DOFs which can only be assembled on the lateral side of the finger, so it cannot be applied to the middle and ring fingers. Yamaura [10] proposed a hand rehabilitation device that is adjustable to accommodate various hand sizes but only has two DOFs for each finger. An exoskeleton with four DOFs was developed which can realize the passive rehabilitative training [11]. In addition, the exoskeleton designed by Wang for index finger rehabilitation [12,13] can realize multiple rehabilitation motions, but the huge driving system is a

Abbreviations: MCP, metacarpophalangeal; PIP, proximal interphalangeal; DIP, distal interphalaneal; DOF, degrees of freedom; SPRM, symmetrical pinion and rack mechanism

* Corresponding author at: State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, Heilongjiang Province, China. Tel./fax: +86 45186403219.

E-mail address: fuzh_hit@163.com (F. Zhang).

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http://dx.doi.org/10.1016/j.mechmachtheory.2013.10.015

conspicuous problem. Due to the special medical application, there are many unsolved issues and the design of exoskeletons is still an investigation field full of challenges. Most of the devices introduced above can't accommodate a variety of hand sizes. Also contact forces between the exoskeleton and fingers aren't always perpendicular to the bones of the fingers during the rehabilitation process, which causes secondary injuries easily. Fu et al. [14] preliminarily discussed the feasibility to solve the above problems by designing a "circuitous joint" which can stretch and rotate at the same time, and put forward the design scheme of the hand exoskeleton. It is composed of the adaptive dorsal finger exoskeleton, the adaptive dorsal metacarpal base and the Bowden cable driven actuator, and the initial 3D model is established in Pro/E.

In this paper, we design and manufacture a novel hand exoskeleton. Our exoskeleton is designed specifically for the actual requirements of rehabilitation applications for injured fingers. We first finish the fully detailed mechanical design of the device, especially perfect the optimal structure design of the "circuitous joint"; by employing the "circuitous joint", our exoskeleton can cover a wide workspace of a finger and adapt to a variety of fingers with different thicknesses. Second, we introduce the driving method and contact force analysis. Bowden cable driving is recommended and it can actuate each joint bilaterally and reduce the burden on the fingers. Lastly the hand fitness test and contact force experiment are conducted.

2. Mechanical design of the hand exoskeleton

Our novel hand exoskeleton conception for rehabilitation, shown in Fig. 1, is designed as a wearable device. The device is composed of two main parts: the adaptive exoskeleton and the Bowden cable driving actuator. The exoskeleton includes the metacarpophalangeal (MCP) joint, the proximal interphalangeal (PIP) joint and the distal interphalaneal (DIP) joint. The Bowden cable driven actuator with two cables can actuate each joint bilaterally. Next we will introduce the mechanical design of the hand exoskeleton.

2.1. Fundamental design of the circuitous joint

Recently some dexterous robot hands have been developed. These hands can be divided into two categories. One is endoskeleton type. Although it is light-weight and compact, it does not allow complete fist closure because of the placement of the actuators in the palm [15]. The other is exoskeleton type which most of the robot hands adopt. When designing such an exoskeleton, the main theme is focused on the joint mechanisms. The most practical joint is a revolute one that consists of an axis and bearings, and the general way to place it corresponding to an operator's joint is in parallel on backside or in coaxial beside. However, the former tends to narrow the movable range of the operator's joint [4] and the latter cannot find existing space between the operator's fingers [9]. Furthermore, interesting mechanisms [16] are developed, but the problem on how to accommodate to a variety of fingers is still unsolved.

Through observation we discover that the hand exoskeleton should have a stretching displacement along the finger when it actuates a finger in order to solve the issue mentioned above. Therefore this paper proposes a novel joint mechanism named "circuitous joint", which adopts the symmetrical pinion and rack mechanism (hereinafter called "the SPRM"). The fundamental mechanism is shown in Fig. 2. A gear rotates on a rack by relative rotation of two segments, and the shifting of its axis provides stretching of a segment that has the rack. Since the two segments should make same stretching displacement together, two sets of the mechanisms are combined in the opposite direction. Thus two segments have a stretching displacement when a gear has a rotation on the corresponding rack.

However, it is obvious that the stretching displacement S produced by the SPRM is always keeping in proportion to the angular displacement θ. The relationship between the angular displacement θ and the stretching displacement S must be non-linear to cover wide workspace of the finger and the stretching displacement required for different fingers is different. For this reason, a parallel sliding mechanism is adopted. The SPRM is placed in two slots which are fixed on the finger. Segment A and segment B can slide passively along the slots. Thus an extra extension displacement S_1 is obtained by the mechanism itself when stretching

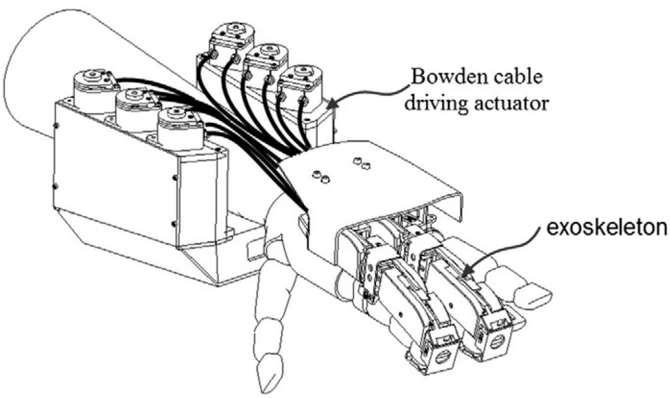

Fig. 1. Appearance of the hand exoskeleton for rehabilitation.