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A novel exoskeleton robotic system for hand rehabilitation – Conceptualization to prototyping

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ABSTRACT

This research presents a novel hand exoskeleton rehabilitation device to facilitate tendon therapy exercises. The exoskeleton is designed to assist fingers flexion and extension motions in a natural manner. The proposed multi-Degree Of Freedom (DOF) system consists of a direct-driven, optimized and underactuated serial linkage mechanism having capability to exert extremely high force levels perpendicularly on the finger phalanges. Kinematic and dynamic models of the proposed device have been derived. The device design is based on the results of multi-objective optimization algorithm and series of experiments conducted to study capabilities of the human hand. To permit a user-friendly interaction with the device, the control is based on minimum jerk trajectory generation. Using this control system, the transient response and steady state behavior of the proposed device are analyzed after designing and fabricating a two-fingered prototype. The pilot study shows that the proposed rehabilitation system is capable of flexing and extending the fingers with accurate trajectories.

1. Introduction

Hands offer autonomy in a human life by offering physical interaction and grasping capabilities. Motivated by the central role of hands in our daily life, researchers have been targeting its imitation using robotic systems. Thanks to technological advancements in mechatronics, such robotic systems greatly improve both the sensing and manipulation strengths of a human. It has been predicted that by 2024, people will use fashionable and portable exoskeleton based robotic systems for interaction in social life [1].

Hands are the most vulnerable limbs having high chances of suffering from disabilities like injuries or strokes especially in elder persons. The most commonly influenced neurological domain of stroke is the motor system [2]. The disabled motor deficit usually is the impaired hand function [3]. Results of a study [4] carried out to evaluate the needs of stroke patients showed that the most desired function in recovery of an impaired hand is its ability to regain strength to perform Activities of Daily Living (ADL). Rehabilitation therapy during post-stroke activities can significantly facilitate the recovery process. Physiotherapists usually conduct these therapy exercises manually or occasionally use simple devices offering passive assistance. Results of therapeutic treatment indicate that the chances of impaired hand recovery are low [5]. Studies report that weakness in both finger flexor and extensor muscles is one of the factors for hand impairment [6].

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Repetitive active training schemes based on activities requiring finger flexion and extension motion could restore the grasping and object manipulation capabilities of an impaired hand [7]. There is an increasing belief that novel therapy procedures using active exoskeleton based exercisers or assistive devices can be potentially helpful in reducing the recovery times and the treatment cost.

The primitive functions of a hand exoskeleton are to monitor the human hand/fingers motions and to apply forces at the fingers. Such devices are aimed at emulating the grasping constraints by transmitting the kinesthetic feedback at finger level. Studies have shown that rehabilitative training of hand using mechatronic systems has enhanced the outcomes of rehabilitation [8]. Robot-based rehabilitation offers precise execution of therapy procedures and enhances exercises repeatability. Autonomous robots can share the workload of therapists conducting the rehabilitation paradigms. Moreover, integration of robotics with Virtual Reality (VR) and acquisition of quantitative data can facilitate hand rehabilitation by optimization of therapy procedures and analysis of patients' response.

This paper is organized as follows: Section 2 presents details of the existing hand rehabilitation devices based on exoskeletons. It also highlights the novelty of the proposed rehabilitation system. The concept and model of the system is presented in Section 3. Section 4 introduces the design requirements and optimization of the device while Section 5 deals with its control part. The fabricated prototype and results are reported in Section 6. Finally Section 7 comments on conclusion.

2. Literature review and novelty of the proposed system

The complex structure and intricateness of human hands offer high dexterity and precise manipulation capability. These, however, impose great difficulties on the development of a hand exoskeleton system. Multi-Degree Of Freedom (DOF) in our hands with small moving parts and availability of limited space for mechatronic placement make the development task further challenging. Compared to exoskeleton systems for lower extremity and arm rehabilitation, the devices for hand or fingers are few, but are receiving growing attention. The reported devices for the hand vary widely in terms of Range Of Motion (ROM), no. of actuated DOFs, design strategy and nature of intended movements.

Therapy procedures for rehabilitation can be based either on passive or active movements. Passive devices offer limited rehabilitation features and have the capability to support few DOFs. No sensory feedback data is available to therapists. Many of these devices apply a simple continuous motion and cannot exert forces perpendicular to the finger digits. Jace H440 [9] is a commercially available Continuous Passive Machine (CPM) that operates in two modes: warm-up mode and dynamic tension mode. On-board microprocessor senses the resistance of the tissues and adjusts ROM automatically. Researchers of Harbin Institute of Technology (HIT) developed a passive rehabilitation device that provides bidirectional force feedback with 4 DOF/finger [10]. The proposed CPM is actuated by two motors and provides both position and force feedbacks to therapist. Another passive rehabilitation device, HandSOME (Hand Spring Operated Movement Enhancer) [11] is aimed at coordination of natural grasping motion. The device, consisting of four bar linkage mechanism, compensates for flexor hypertonia by extension of the finger joints.

A rehabilitation device essentially demands capability of bidirectional assistance i.e. finger flexion as well as its extension. Primarily, due to this reason, most of the hand exoskeleton systems used in VR applications e.g. [12–17] do not find significant potential in rehabilitation.

Due to the restricted space at the hand, most of the hand exoskeleton systems with only few exceptions [18,19], are remotely actuated. The torque/force is transmitted to the exoskeleton mechanism through Bowden cables or tendons. Researchers of Salford University have proposed a four finger novel hand exoskeleton based exerciser [20] with 7 active DOF. The actuators are placed on ground and tendons having low friction transmit the bidirectional forces. The major milestone during the device design was to offer dexterity with adequate ROM. Introducing interactive VR in rehabilitation, the device has been integrated within a hand therapy system to permit a physiotherapist to conduct hand exercises and to analyze motion data. Wege et al. developed another tendon driven hand rehabilitation system having 4 DOF/finger [21]. Actuated with a single DC motor, the device can exert bidirectional forces on the finger phalanges based on torque control. Link lengths have been designed to allow nearly full ROM. HANDEXOS proposed by the researchers at SSSA, Italy has been aimed at simplifying complexity of the exoskeleton in terms of its actuation, mechanism and structure while ensuring full hand mobility [22]. Each finger incorporates one passive and three active rotational joints while the only translational joint is passive. The active joints provide flexion and extension of finger joints while abduction and adduction is permitted by passive rotational joint. With an under-actuated mechanism and tendon transmission, an index finger prototype has been realized. Other examples of systems using cable as transmission media include HEXORR (Hand EXOskeleton Rehabilitation Robot) [23] and Beihang University device [24]. Cable based systems suffer from inherent friction and associated issues when compared with their direct-driven counterparts.

A rehabilitation device should offer free palm so that patients can have natural interaction with the objects. Few reported devices e.g. Rutgers Hand Master II [18] is a pneumatically actuated device having pistons in the inner side of the palm. The device provides force feedback and has been used for stroke rehabilitation [25]. In addition to palm, a rehabilitation device should also let each fingertip of a patient's hand free for exploiting tactile cues. HandCARE [26] is a Cable-Actuated REhabilitation device which uses cable loops fixed at the end of each finger. Promising attribute of the device is a clutch system that can actuate all the five fingers with a single actuator. Amadeo by Tyromotion Inc. [27] is a commercial rehabilitation device that offers fingertips control of each hand digit. The system offers a therapist to select among three modes: active, completely passive or assistive. Rehabilitation devices exerting forces on the distal finger phalanges of the hand provide limited control over proximal