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Stroke rehabilitation using exoskeleton-based robotic exercisers: Mini Review.

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Abstract

Stroke is a debilitating disease that has afflicted millions of people throughout the world. Assisting physiotherapists in post-stroke activities to conduct rehabilitation therapies, scientific community has presented a new type of man-machine intelligent systems i.e. exoskeleton based exercisers. These devices help the patients having neurological disabilities to partially or fully regain their motor performance by applying forces to the affected finger phalanx and preventing unsuitable motion patterns. The exoskeletons because of their wide range of sensory capabilities have replaced traditional assessment of stroke patients. This article reviews developments in robotic prosthetics and exoskeletons. The primary design requirements of these devices are identified. Highlighting the authors' research achievements in this domain, a collection of exoskeleton-based hand rehabilitation devices has been then presented with a brief description about their mechanical designs. Finally, an overall view of research in this domain is commented.

Keywords: Rehabilitation, stroke, hand function, hand exercisers, robotic exoskeletons

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Introduction

Hands being intricate and multi-fingered body part are the chief organs for physically manipulating objects in an environment including grasping. It is one of the primary elements to have an independent life. Due to their complex hand structure, humans are capable of making more precise and finer movements than other creatures. The high level of dexterity is achieved through complex sensorimotor mechanisms utilizing visual information and the physical structure of the hand. So, humans can modulate grasp forces and precisely position objects.

The major reason of hand disability round the globe is stroke [1]. Rehabilitation therapy may be necessary in post-stroke treatment so as the hand to regain its usual capabilities and normal functions [2]. Physiotherapists usually conduct these therapy exercises in manual mode or sometimes employ passive devices to facilitate rehabilitation. Recent trend is to execute alternative therapies using assistive devices or active robotic hand exoskeletons to considerably improve the medical outcomes [3]. The primary objective of such a hand exoskeleton device is to impart superhuman strengths to the wearer [4]. These devices apply kinaesthetic feedback at the finger level to imitate the grasping constrains with reference to real or virtual objects. From physical design perspective, these devices are composed up of external mechanical linkages and are attached to the patient's hand at single/multiple contact points. As predicted by rehabilitation experts that around 2024, people will use fashionable and portable exoskeleton robots to interact with objects in society [5].

This mini review is arranged as follows: Important requirements to design a rehabilitation device based on exoskeleton are explained. Author's contribution in rehabilitation community is then briefly mentioned followed by state-of-the-art survey of the existing rehabilitation devices. Finally, the conclusions are drawn.

Design requirements of a rehabilitation exoskeleton device

The overall research problem is to address the need of having a system that combines performance with ergonomics and comfort-ability with the provision of the kinaesthetic force feedback for a wearer [6]. These three inter-related factors that are performance, ergonomics and comfort-ability can be mapped to force levels, device mass/inertia and its range of motion (ROM), mechanism complexity and easiness in removal/donning.

Force levels

An effective rehabilitation device must be capable of exerting adequate force levels on the amputee’s fingers. A Study on human hands of various sizes and aged-group conducted by Iqbal *et al.* [7] reported that maximum force exerted by a human finger can be in the order of 45N.

Mass/Inertia

The mass of the rehabilitation exoskeleton must be minimized so as to enhance portability, comfort-ability and energy optimization. Low mass/inertia also offers advantage in terms of safety, which is the primary requirement for any device directly attached to the human wearer. This requirement dictates careful selection of actuators with optimum power/weight ratio.

Complexity

A less complicated design essentially improves reliability and lessens cost. The complexity of the mechanism is a function of number and arrangements of joints, proper choice of number of degree of freedom (DOF), type of sensors and actuators selected and link lengths.

Comfort-ability

A rehabilitation device may have to be used for couple of hours of continuous operation. This probable fact necessitates having a comfortable device thus causing no fatigue and offering ease in device donning and removal.

ROM

Typically, workspace of a healthy human hand can be considered as a reference for ROM of an exoskeleton-based rehabilitation device.

To derive the design requirements in a more analytical way, Iqbal [8] conducted series of experiments using appropriate sensory equipments to evaluate human hand strength in terms of maximum and average force levels, natural ROM and stiffness range. Results of these experiments constituting design requirements of a rehabilitation exoskeleton device are detailed. With these features as target research objectives, Iqbal *et al.* [9-15] proposed various novel rehabilitation devices for the hand. The two most popular devices in rehabilitation community, the hand exoskeleton system (HEXOSYS)-I and HEXOSYS-II are discussed below.

Hexosys-I and hexosys-II

While both of these devices are portable, direct-driven and underactuated, their underlying mechanism, optimization criteria, physical features and mechanical parameters are different.

Hexosys-I [9] is a novel device for rehabilitation of thumb and index finger. The device can exert perpendicular forces on finger phalanges with extremely higher force levels going beyond any existing hand exoskeleton rehabilitation device. The actuators of the device have been selected as a result of maximum force levels exertion capabilities of a human hand while link lengths have been chosen based on multi-objective optimization criteria [10]. Kinematics, collision avoidance and factors like perpendicular impact force (PIF) and global isotropy index (GII) form the basis of device optimization. Experimental results to demonstrate the efficacy of the device are reported in [11,12]. In addition to rehabilitation, the device also finds potential in motion assistance [13]. Figure 1 illustrates the fabricated prototype.

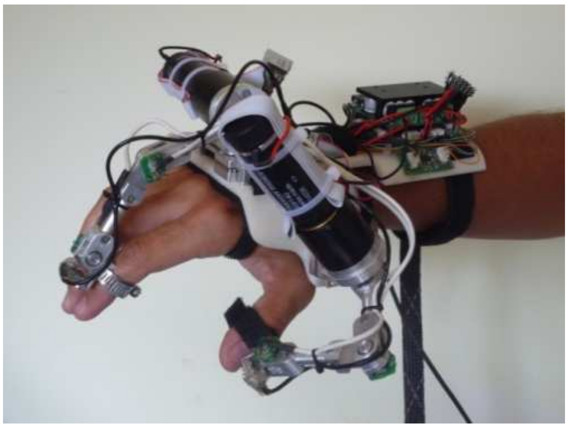

Figure 1. *HEXOSYS-I prototype*

HEXOSYS-II [14], on the other hand, is a four-fingered rehabilitation device developed with a focus on realizing a lightweight device. Results of experiments to measure average force levels exerted by a human hand are mapped on actuator selection while optimization procedure to select link lengths of the device attempts to match exoskeleton and finger workspaces [15]. The developed prototype of HEXOSYS-II is shown in Figure 2.

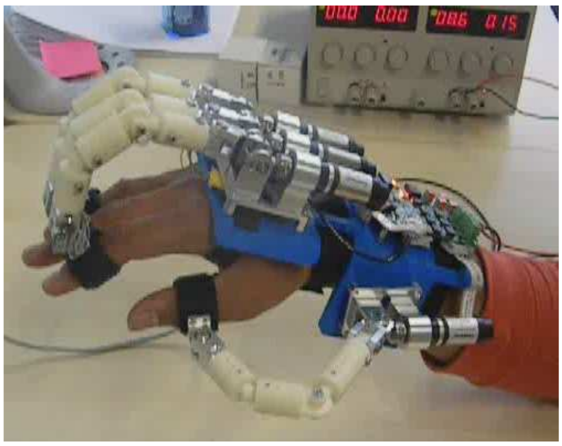

Figure 2. *Hexosys-II prototype*

State-of-the-art

In the last two decades, researchers have pursued several hand exoskeleton rehabilitation devices. They can be broadly categorized into (i) continuous passive machines (CPM) (ii) active exoskeletons.

CPM

These exoskeletons incorporate passive force feedback in the control loop by applying forces to the wearer based on scheme of energy removal from the human-machine interface. Notable examples include WaveFlex CPM and HIT CPM. The former is a commercial anatomic rehabilitation exoskeleton that offers the stroke patients to have a complete composite fist [16]. For each finger phalanx, a sophisticated attachment permits the finger to follow a natural trajectory. The light mass, balanced and portable design allows continuous use of the device for longer period of time while easiness in removal and donning is ensured by use of the finger attachment clip. HIT CPM, proposed by Fu *et al.* [17] is a tendon driven mechanism for rehabilitation of hand injuries. The main goal of this research was to realize a palm-free design having capability to exert forces in both directions while flexing and extending.

Active exoskeletons

Active exoskeletons function by application of forces through energy addition into the human-machine interface. The primary benefit of the control based on active components is construction of any force sensation since such a control is inherently general. Prominent examples of active exoskeletons are developed by researchers at Dartmouth Medical Centre USA, Politecnico di Milano Italy, Sabanci University Turkey, HongKong Polytechnic University and KAIST Korea.

Dartmouth exoskeleton [18] is one of the earliest rehabilitation glove conceived in early 1990s. The main objective was to realise a system based on human hand anatomy that can produce pseudo-natural movements. Finger extension has been achieved using springs to attain the default position of the hand as fully extended. Finger and thumb flexion has been accomplished through five cables connected to motors in a way so as to imitate the tendons natural placement. Potentiometers have been used as sensory elements.

Milano exoskeleton system [19] is a 2 DOF hand rehabilitation device that is composed of a glove and a plastic supporting structure that reduces loading on the fingertips and guides the patient fingers. The system has been designed to be adaptable and is actuated by two servomotors mounted on forearm at palmar side. Two wires used to transmit the maximum force are joined to the fingertips at one end and rolled up to the pulleys of the servos to the other end. One wire is used to flex the thumb while the other flexes the four fingers at the same time. The sensory system consists of two potentiometers mounted on the pulleys of the servos for position recording. The system has been reported as cumbersome in donning and removal.

Unlike the above two exoskeleton systems, Sabanci exoskeleton [20] is based on rigid link mechanism. The main objective was to realise a system for assistance of finger motion throughout its natural ROM in a coordinated fashion while limiting the tension in tendons within acceptable range. This has been achieved using four bar linkage mechanism with actuation in direct-driven mode and transmission using capstan. The coordinated movement of finger phalanxes has been ensured with compliant springs. The sensory system consists of an optical encode located with the motor, potentiometers positioned at joints coinciding proximal interphalangeal (PIP) and distal interphalangeal (DIP) and force sensing resistors (FSR) mounted on each exoskeleton segment. The system can measure finger movement, interaction forces and muscle activities simultaneously.

Hong Kong exoskeleton [21] is a rehabilitation device having complete five fingers offering 2 DOF motion in each finger. The main objectives were to realise lightweight, portable and an intention driven hand exoskeleton. The first two objectives have been tried to achieve by mechanical design of the system while to achieve the last objective, the exoskeleton is equipped with electromyography (EMG) sensors to detect the patient’s intention to open or close the hand. The hand takes 4 seconds to go from complete extension to complete flexion. The system offers flexibility in terms of accommodation of different hand sizes. The system is not backdrivable and it takes around 5 minutes to put on the device after the knuckle lengths for the particular user have been adjusted.

KAIST exoskeleton [22] is a 1 DOF rehabilitation device for stroke patients training to perform activities of daily living (ADL). The primary aim was to develop a system that can realise various grasp types including lateral, cylindrical and pinch grasps. This has been attained by using a novel mechanical design that can move four fingers and the thumb simultaneously in full ROM during grasping. A designed four bar linkage structure has imitated the path of fingertip movement while grasping. A cable mechanism is responsible for driving the thumb movement. The direction of thumb movement can be changed freely based on the shape of objects under grasp by adding a passive revolute joint at carpometacarpal (CMC) joint of a thumb. The exoskeleton assists patients to grasp objects using the impedance control scheme.

Other examples of exoskeleton-based rehabilitation devices include hand-wrist assisting robotic device (HWARD) [23], hand mentor pro [24], hand exokeleton (HANDEXOS) [25], hand exoskeleton rehabilitation robot (HEXORR) [26] and handspring operated movement enhancer (HandSOME) [27].

Discussion and conclusion

Robot-assisted therapies offer benefits in terms of accuracy, precision and repeatability. These therapies, exploiting the integration of virtual reality (VR) and robotics/haptics, can transform monotonous rehabilitation exercises into engaging and appealing tasks e.g. a game. Visual cues can also characterize a patient's performance during exercises by addressing psychosomatic variables. Because of these potential benefits, robot-assisted therapies are gradually replacing manual therapies.

While there are still several complex challenges related with robot-aided prosthetics that needs to be addressed, technological advancement in this domain has been undoubtedly impressive. Clinical results obtained from stroke patients give very encouraging hope for the future. Exoskeletons-based rehabilitation devices face challenges in several domains like actuators and sensors, neurophysiology, hand biomechanics, ergonomics and human robot interaction (HRI). The constrains on power/ratio of actuators available in the market and strength of materials impose a great challenge on having an ergonomic device with light mass/inertia and less volume still providing a reasonable force levels. The volumetric and bulky structure or complicated mechanism can in the worst case even harm the tissues of wearer's hand. Also, the social acceptance of such rehabilitation devices is a function of their physical dimensions. Primarily due to these mechatronics limitations, most of the existing designs have been associated to very restricted and limiting specifications.

It is anticipated that in future, novel rehabilitation strategies including patient assessment and therapy schemes will be discovered. The new approaches may be outcome of more deep studies of neuromuscular system. The rehabilitation devices of next generation will not be limited to clinics and hospitals. Future devices will also beneficiate patients as home-based modules tailored to their specific exercise strategy. Recent advances in areas like tele-rehabilitation robotics, bio-robotics and nano-robotics, focusing neural interfaces, intelligent implants and online adaptation are expected to shape the future of rehabilitation.

Going beyond helping physiotherapists, the exoskeleton-based devices can serve purpose of motion assistance to disable persons in order to help them in performing ADL thus making their social life pleasant and less cumbersome. These devices can also facilitate physiologists in understanding working of the human body.

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