Post-stroke Hand Rehabilitation Using a Wearable Robotic Glove

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Abstract The paper presents the research work done for development of a light-weight and low-cost robotic glove that post-stroke patients can use to recover hand functionality. The work focused on two directions for the robotic glove structure (exoskeleton and wearable soft robotic glove) and on two types of recuperative actions (tele-operation and program based actions). Given the performance tests ran for the robotic gloves, better results were shown with the wearable soft robotic glove that could also be combined with Functional Electrical Stimulation in order to improve the post-stroke hand rehabilitation.

Keywords Stroke · Robotic glove · Rehabilitation · Functional electrical stimulation

1 Introduction

Health is the most important issue for everybody. The cerebrovascular accident (or stroke) is the second leading cause of death. World Health Organization (WHO), as responsible for international health coordination, monitors and assesses health trends in order to plan and implement health policies. WHO has developed an international stroke surveillance system: the STEPwise approach to stroke surveillance (STEPS-stroke), described on its website (http://www.who.int/en).

A cerebrovascular accident (CVA) occurs when the blood supply to the brain is interrupted or reduced, which deprives the brain of oxygen and nutrients and can cause brain cells to die or death in case of a severe stroke.

Stroke patients often lose certain hand functions. It is difficult to open the affected hand to grasp due to increased resistance to passive finger extension and

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weakness in finger extensors [1]. Because of this impairment, post-stroke hand rehabilitation is essential for restoring independent behaviour.

The aim of our work was to design and develop an Intelligent Haptic Robot-Glove (IHRG) for post-stroke hand rehabilitation. Our work focused on developing a lightweight and low-cost robotic glove that patients can use to recover hand functionality.

The rehabilitation aims to help stroke patients to relearn the skills that were lost when they suffered the stroke. Any rehabilitation program means repetitive practice and begins in the hospital after the patient's overall condition has been stabilized (often within 24–48 h after the stroke) and could involve working with physiotherapist for months or years after the stroke.

Maciejasz, Eschweiler, Gerlach-Hahn, Jansen-Troy, and Leonhardt conducted a survey on robotic devices for upper limb rehabilitation, that includes a comprehensive, tabulated comparison of technical solutions implemented in various systems [2]. The control area of these systems is very large and complex and imposes a series of requirements regarding the size, the cosmetic appearance, robustness and embeddable control system.

A review of control strategies for robotic movement training after neurologic injury was presented by Marchal-Crespo and Reinkensmeyer [3]. The control must be simple with actuator able to exert high grasping forces [4]. A control strategy based on neural approach is presented by Rodriguez-Cheu and Casals [5]. A hybrid control technique is treated by Zhao et al. [6]. A digital controller that operates by means the EMG signal is analysed by Lucas et al. [7]. The feedback control by sensors is treated by Scherillo et al. [8], Birglen and Gosselin [9], Krut [10], Birglen and Gosselin [11], Xiujuan and Zhen [12]. A virtual reality system was developed in order to encourage repetitive task practice [13]. Luo et al. [14] developed a training environment that integrates augmented reality (AR) with assistive devices for post-stroke hand rehabilitation.

Matheson and Brooker [15] developed an exoskeleton to provide the actuation for flexion. Pneumatic muscle actuators were used to provide flexion force, and force sensors used to supply control inputs by the user. Hartopanu et al. [16] proposed a solution to combine a robotic glove with Functional Electrical Stimulation to be used as a tool in the rehabilitation process of patients who suffered a stroke.

Neurofeedback can improve rehabilitation when patients get immersive feedback that relates to the activities they imagine or perform. For example, if people imagine grasping an object with their affected hand, then an image of a grasping hand can help users visualize their activity. In the last years, a totally novel application for motor imagery (MI)—based Brain-Computer Interface (BCI) has gained attention by inducing neural plasticity and thus serve as an important tool to enhance motor rehabilitation for stroke patients [17]. Furthermore, immersive BCI stroke rehabilitation is an ongoing research effort in numerous American and European research projects (http://www.gtec.at/Research/Projects). The BCI system can also be connected to exoskeletons or rehabilitation devices.

2 Post-stroke Hand Rehabilitation Therapy

Because a part of the brain is damaged when a stroke occurs, the rehabilitation therapy will help the patient regain his/her lost hand functions in a non-damaged part of his/her brain. Functional Electrical Stimulation—FES could help the rehabilitation therapy through reducing spasticity and enhancing muscle control [18, 19].

Usually, post-stroke hand rehabilitation includes passive movements or exercises (movements done with the help of a physiotherapist) and more active exercises patients do with little or no assistance. Stroke rehabilitation can be exhausting and daunting.

Post-stroke rehabilitation has a lot of new approaches, that include new kinetic techniques, new electrical stimulation techniques, and in the last years, robotics methods.

The research team received from doctors a challenge to develop a robotic device to help the patients with stroke to recover the hand movement through an Intelligent Haptic Robot-Glove (IHRG).

The following set of guidelines were taken into account when designing and developing the robotic glove:

- natural/intuitive use and easy to wear.
- lightweight.
- not restricting the natural human kinematics or range motion.
- compliance and stability.
- sufficient adaptability to individual differences in patients' anthropometric dimensions (without mechanical regulation or tunings).
- reduced system costs.
- easy maintenance.
- high power-to-weight density and reduced energy consumption.

Given these requirements, our goal was to create a wearable robotic glove that assists the patient during hand movement.

Post-stroke hand rehabilitation is time dependent. Good results of post-stoke rehabilitation therapy could be obtained in the first 6 months after the stroke occured.

The muscle tonus is very weak in the first post-stroke stage. In time the muscle tonus increases, but not in a healthy way. It could be very spastic, which can affect the future movements. To avoid this outcome, in the first stage, if the muscle palsy lasts for too long time, it is indicated to apply electrical stimulation to the flexor muscles, to develop the spasticity in a gentle manner. During the second stage, when the spasticity is created, the electrical stimulation has to be applied to the extensor muscles of hand and fingers to maintain muscle balance.

Nowadays we have many types of electrical stimulation which include the square waveform signals or magnetic field, applied to extensor muscles. The signal parameters are modified in every stage and are determined by the spasticity.

At the beginning, electrical stimulation with the square waveform signals is applied in short pulses, which determinates an isotonic muscle contraction, followed by a double period of muscle relaxation. We can use this method for a few minutes, but no more than 10 min or we risk to develop muscle fatigue and improper hand movement.

Continuing the electrical stimulation technique, the square waveform signal could be applied in long pulses followed by double or triple periods of muscle relaxation. The time of this application is determinated by muscle fatigue and false movement. The session of electrical stimulation can be repeated twice a day, if the muscle fatigue has not appeared. This technique is recommended to be used for a long period such as weeks or months, until the patient develops correct active hand movement.

The patient must watch the movement and try to move the hand by him/her self while also imagining his/her hand movement (neurofeedback).

A new technique for post-stroke hand rehabilitation is the robotic approach, by using a robotic glove. In order to design and develop such a robotic glove we went through a series of research phases (survey, video motion analysis, virtual design, models design, mechanical design, actuation system design, control system design, implementation, testing, refirement).

3 Robotic Glove Design

A survey on the current state of research on the mechanisms and achievements that model or substitute the human hand was conducted. Thus we could identify two categories of systems that model or substitute the human hand:

- grasping anthropomorphic mechanical systems for prosthetics;
- grasping anthropomorphic mechanical systems for robots.

We decided to research on two directions for the robotic glove structure: exoskeleton and soft robotic glove. The soft robotic glove is a device that uses textiles to interface with the body in parallel with the muscles, using the bone structure, to support fingers' motion. We focused on designing a soft robotic glove that could use actuators and sensors that don't restrict hand movement.

Our research also addressed the study and design of an exoskeleton model for a robotic glove (as an assistance hand) and its associated actuation and control systems. This robotic glove must be attached to the human hand and allow the hand and fingers movements. Based on these requirements (the movement in different planes adapted to the patient's hand, the possibility to touch and grasp), specific biomechanical design of the components was done.

The robotic glove has to provide three features for grasping force:

1. The robotic glove should not disturb human finger movement.
2. The robotic glove has to allow a grasping force proportional to the human grasping force.
3. Robotic glove has to allow a variable compliance as the human finger so that the dexterity and stability of the grasping is preserved [20].

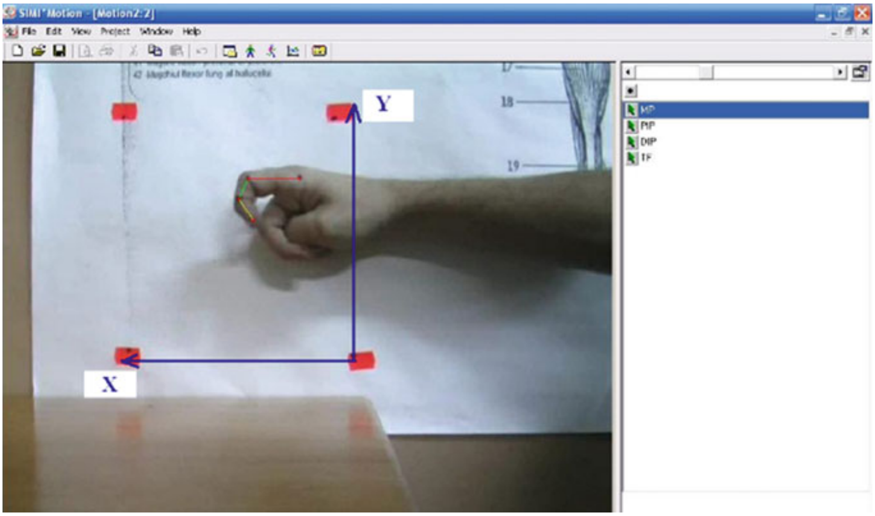

Fig. 1 Index finger motion analysis using SimiMotion software

Other research phase consisted of determining the variation laws of kinematic parameters of human hand movement based on studying its movement using a data acquisition system (video motion analysis) called SimiMotion (www.simi.com) (Fig. 1). In order to implement good movement for the robotic glove fingers, we analysed using image processing the motion of the human hand fingers and then we developed a tele-operated robotic hand accordingly (Fig. 2).

Based on the above analysis two types of robotic gloves were designed, developed and tested, including mechanical structures and actuation systems.

Fig. 2 Tele-operated robotic hand

4 Results

We focused on creating an assistive device (robotic glove) that provides post-stroke hand rehabilitation and showed that this system can substantially maintain normal biomechanics.

The robotic glove consists of three parts: mechanical exoskeleton or soft robotic glove, actuation system, and embedded control with minimum number of sensors.

To address the rehabilitation issues, we developed a lightweight exoskeleton that allows for basic motion using a natural sequence of muscle activation.

The exoskeleton system has a kinematic structure with five articulated fingers. Each finger is composed of three phalanges in order to have an anthropomorphic contact with the patient's hand. In order to get an effective rehabilitation effect, the mechanical structure must allow the finger to fulfill the same motions of a healthy finger.

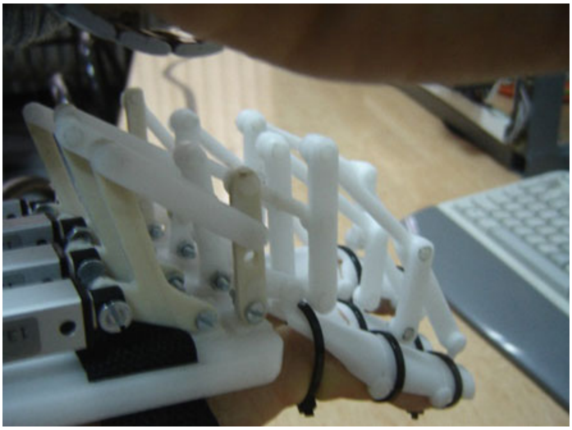

Fig. 3 Exoskeleton structure

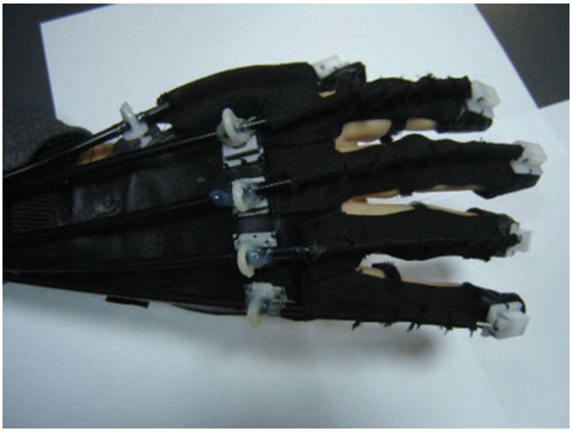

Fig. 4 Wearable soft robotic glove with Bowden tendons

Fig. 5 Wearable soft robotic glove with flexible tendons

We designed and tested different mechanical solutions, different motion transmission solutions and actuation systems (electric, pneumatic and SMA actuation systems).

Two structures were designed and developed:

- exoskeleton—the structure with phalanges (Fig. 3).
- soft robotic glove—the glove type structure (Figs. 4 and 5).

We designed, developed and tested two solutions in order to drive the movement from the actuation system to the robotic glove:

- through tendons (Bowden type (Fig. 4) or flexible tendons (Fig. 5) for the glove type structure).
- through bar mechanism for the structure with phalanges.

An embedded control system based on an Arduino Mega2560 board was developed and tested.

Two types of recuperative actions were implemented:

- tele-operation using a glove with flex sensors.
- program based actions; the doctor can choose a specific recuperative program or can create new ones.

Comparison of the actuation systems shows:

- Pneumatics (cylinders or muscles): difficult to control; voluminous; expensive.
- SMA: difficult to develop; small force; small stroke and complexity of position control.
- Electric actuators:
  - rotary actuators: problems to convert rotary movement in linear movement (need of additional elements).
  - linear actuators: easy to drive the linear movement; no difficult to control (Fig. 6).

Fig. 6 Wearable soft robotic gloves in action

Fig. 7 Robotic glove and FES. Tele-operation glove with flex sensors

Figure 7 presents a variant of the hybrid FES—flexible robotic glove system, which was tested in our laboratory. The tests were made on normal human subjects (members of the research team) who attempted to mimic the behavior of a post-stroke patient, described behavior by doctors and patients.

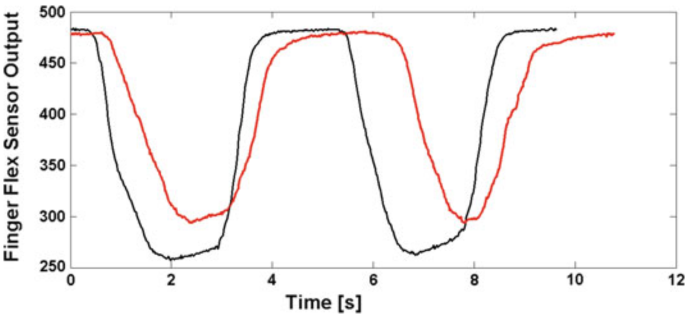

Fig. 8 Evolutions in time of the output of the index finger flex sensors

Figure 8 presents the evolutions in time of the output of the index finger flex sensors, one is on tele-operation glove (black line) and the other is mounted on the robotic glove worn by patient (red line). There is a small delay and the flexion of the robotic glove is smaller than of tele-operation glove.

5 Conclusions

The goal of our work was to create a robotic glove for patients as well as a tele-operation wearable glove integrated with flex sensors used to control the finger movements of the robotic glove.

Wearable soft robotic gloves seem to be the better solution for human hand rehabilitation as these gloves are lightweight, portable, and compliant wearable systems that can still be further refined.

The paper presents the hardware and software development that has been designed and implemented for the hand rehabilitation robotic glove. The practical tests showed the functionality and performances of the robotic gloves in common operating conditions.

The soft robotic gloves architectures will be more frequently used in assistive and rehabilitation robotics, due to their simplicity. Many development challenges and plenty of research remain to be done in actuator development, textile innovation, soft sensor development, human-machine interface (control), and biomechanics.

The architectures of the exoskeleton robotic glove require for the robotic glove and human joints to be accurately aligned, as misalignments would result in kinematic incompatibilities impeding the movement of the fingers or causing physical discomfort.

We consider this robotic glove not only shortens rehabilitation time post-stroke, but also brings a higher level of recovery than is achievable with the current physiotherapy methods.

The robotic glove is easy to use, and the setting time is short (less than 10 min), as doctors want. The next phase is clinical use followed by clinical research.

Our robotic glove can be combined with FES and neurofeedback to improve the rehabilitation, by making a better hand functionality recovery in a shorter time.

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