6th International Conference
ðComputational Mechanics and Virtual Engineering ð
COMEC 2015
15-16 October 2015, Braşov, Romania

MECHANICAL AND ACTUATION SOLUTIONS FOR A ROBOTIC GLOVE

Dorin Popescu, Sorin Manoiu-Olaru, Livia-Carmen Popescu, Cosmin Berceanu, Anca Petrisor
University of Craiova, Craiova, ROMANIA, dorinp@robotics.ucv.ro

Abstract: *This paper presents the research activities and results for robotic glove development with application in post-stroke rehabilitation. In order to implement a good movement of robotic glove fingers a human hand motion was analysed by image processing, a tele-operated robotic hand and some robotic gloves were developed. The mechanical structures and actuation systems were tested and compared.*
Keywords: *robotic glove, mechanical structure, actuation system, rehabilitation*

1. INTRODUCTION

According to the data from the European Union, cardiovascular disease (CVD) remains the leading cause of death in Europe (more than 40% of men and 50% of women). In Romania, according to Romanian Society of Cardiology and the statistics provided by the Ministry of Health for 2011, CVD is responsible for 62% of deaths, ranking the third in the world. The first place is coronary heart disease, followed by cerebrovascular accident (stroke).
A cerebrovascular accident (CVA) represents the loss of brain function due to disturbance in the blood supply to the brain. In case of a disturbance for more than a few seconds, brain can neither receive blood nor oxygen causing permanent damages.
Available hand rehabilitation devices vary greatly in structure and mechanical properties but all have the general purpose of assisting with finger extension. The majority of devices currently on the market are active systems powered by electric or pneumatic motors. A survey on rehabilitation exoskeleton hands and on robotic devices for upper limb rehabilitation, including hand rehabilitation is achieved by Maciejasz et. al. [1]. That paper brings together some theoretical and practical points of view on the implementation and control of such a system while highlighting the growing need.
In the last decade, numerous concepts and techniques to enable assessment of physiological properties of the hand, its structure, especially the anatomy and functional features were presented. Some researches [2, 3] allowed the development of kinematic structures to replicate as much as the kinematics of the human hand as possible. These configurations have approached both empirical simulation methods and techniques enabling sophisticated, more accurate, more precise animation of the basic functions.
A study on the state of research on the mechanisms and developments that models or substitutes the human hand was done. Thus we could identify two categories of systems that models or substitutes the human hand:
- gripping anthropomorphic mechanical systems for prosthetics (prosthesis: i-Limb, Luke, DECHEV, RTR II) [4, 5, 6];
- gripping anthropomorphic mechanical systems for robots (robotic hand: HRP-P, UTAH-MIT, SHADOW, DLR II, UBH III, NASA-DARPA) [7, 8, 9, 10, 11].
Stroke rehabilitation for hands includes passive movements or exercises that are movements done with the help of a therapist and more active exercises you do with little to no assistance. We received a challenge from the doctors to develop a device for helping the patients with CVA to recover their hand movement. The goal of our work was the design and develop an Intelligent Haptic Robot-Glove (IHRG) for the patients' rehabilitation, that have had a cerebrovascular accident. In order to implement good movement for the robotic glove fingers, a human hand motion was analysed by image processing, a tele-operated robotic hand and some structures of robotic glove were developed. The video-based motion capture and motion analysis are used in areas like sport [12], medicine, biomechanics [13], but may find application in any field treating motility, movement.

2. JOINTS AND FINGERS BIOMECHANICS ANALYSIS

Design of the IHRG consists of three parts: mechanical exoskeleton, actuation with motors, and local control using minimum number of sensors and observers. The human hand rehabilitation function can be counted as one of the most difficult systems to emulate with a mechatronic device. This difficulty is mainly due to two reasons. On one hand is the unavailability of large space for components placement while on the other hand is the high number of DOF. These requirements can be summarized as: low mass/inertia, unconstrained range of motion, minimum complexity, comfort, compliance.

The first phase of research was dedicated to the study and design of the exoskeleton model for an assistance hand (a robotic glove) and associated actuation system. This system must be attached to the human hand and allow the hand and fingers to move. Based on these requirements (the movement in different planes adapted to the patient's hand, the possibility to touch and grasp, the opening / closing of the hand) specific biomechanical design of the components was achieved, taking into account the new criteria and requirements:

a) a mechatronics approach is necessary, the mechanical structure cannot be designed independently of the sensory system, the actuation or control system;

b) mechanical compliance should be introduced to increase dexterity of the movement, manipulation of objects.

The proposed system has to provide three features for grasping force:

1) The system has to allow a grasping force proportional to the human grasping force;

2) The system shall not disturb human finger movement;

3) Robotic glove has to allow a variable compliance as the human finger so that the dexterity and stability of the grasping is preserved.

In the context of developing an exoskeleton structure to assist the development of techniques for the rehabilitation of the main functions of the hand, in the context of different patients with various problems of malfunction, the developed architecture should cover the diversity of issues and anatomical structures. An example of this variety is shown in Figure 1 (left side) in which two different hands can be analyzed from the point of view of dimensionality of the phalanges and also anatomically.

Figure 1: Hand configuration (left side). Hand in a grasping operation (right side) [2]

Therefore, developing an exoskeleton that wishes to achieve desired rehabilitation operations will require completion of several milestones:

• a clear understanding of the basic functions of the hand and the implementation of these functions with a corresponding kinematic structure;

• accurate simulation of the proposed prototype and the analysis of the kinematics obtained by sets of appropriate tests;

• adaptive verification of the performance and adjustment of model parameters.

For a fair assessment of hand functions, we need to analyze in detail the three main components: the palm, the fingers (four) and the thumb [14]. The first component (palm) plays a minor role in functional rehabilitation operations. It serves only as a support structure enabling actuation of the fingers.

The fingers (four) perform, in principle, the function of the grasp, obtained by flexion of the phalanges of each finger (Figure 1, right side). The fingers consist of three phalanges, each phalanx is separated from the other through interphalangeal joints; MP (metacarpal joint), PIP (Proximal interphalangeal joint), DIP (Distal interphalangeal joint). The thumb has a complex function, achieving, in addition to the operation of flexion, and the operation of nearness by the hand axis.

An exoskeleton structure covering the functions required for the rehabilitation operations is shown in Figure 2. The proposed solution asks to develop a mechanical architecture consisting of a cascade of jointed elements whose design has to cover as much as possible the fingers while ensuring the support of the actuation system used.

The elements of joint and fingers biomechanics were studied and it was analysed:

• main anatomical joints of the upper limb.

• main human hand movements.

• axis of rotation of the joints and range of movement.

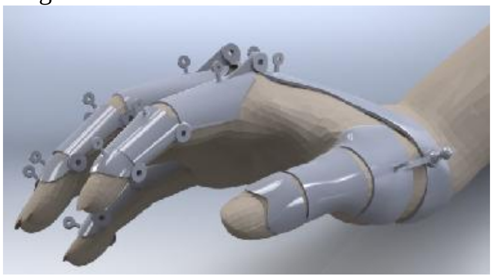

Figure 2: A virtual exoskeleton structure

The conclusions of this analysis will ground the system specifications for the human hand's rehabilitation.
After studying the anatomical model of the human upper limb and hand we can infer the following conclusions and findings:
- the anatomical model of the human hand includes at the level of phalanges 19 independent degrees of freedom;
- each finger of the human hand has a structure with four degrees of freedom, except the thumb of which structure is characterized by three degrees of freedom;
- actuation is done individually for each phalanx (anatomic joint) through tendons located both on the dorsal and palmar face of the hand;
- main actuators (muscles) of fingers are in the forearm;
- radio-carpal joint (wrist) has two degrees of freedom and allows extension-flexion and abduction-adduction of the hand relative to the forearm;
- human hand and upper limb have a huge number of sensors (tactile, temperature, vibration, etc.).

3. STUDY AND DESIGN OF THE EXOSKELETON FOR A ROBOTIC GLOVE

Some research steps have to be followed in order to design a robotic glove for post-stroke hand rehabilitation. These mean studies, analysis, interpretation, design, development, testing, and improvement. A study on the state of research on the mechanisms and achievements that models or substitutes the human hand was done.

3.1. Video-based motion capture and motion analysis

Next research step, after previous study, has implied the determining of the laws of variation of kinematic parameters of human hand fingers movement. The study and analysis of fingers movement used a video acquisition system based on hardware and software processing (SimiMotion - video motion analysis).
The data acquisition and image processing system consists of a fast video camera and a computer. The analysis procedure is based on attaching a series of markers on the hand to be analyzed. Positioning these markers represents identification points for SimiMotion software (Figure 3, right side). By attaching markers, the software automatically generates the equivalent model of the studied system and follows their movement during system operation on each frame captured by the camera, recording and analyzing the positions of markers simultaneously, which serve to obtain laws of motion.
In this paper the human index movement kinematics during flexion and extension was analyzed. A video recording was made about 5 seconds. It was analyzed (Figure 3, left side):
• metacarpal joint, denoted by MP;
• proximal interphalangeal joint (joint formed by the medial and proximal phalanx), denoted by IIP;
• distal interphalangeal joint (joint formed by the medial and distal phalanx), denoted by DIP;
• fingertip index, denoted by TF.

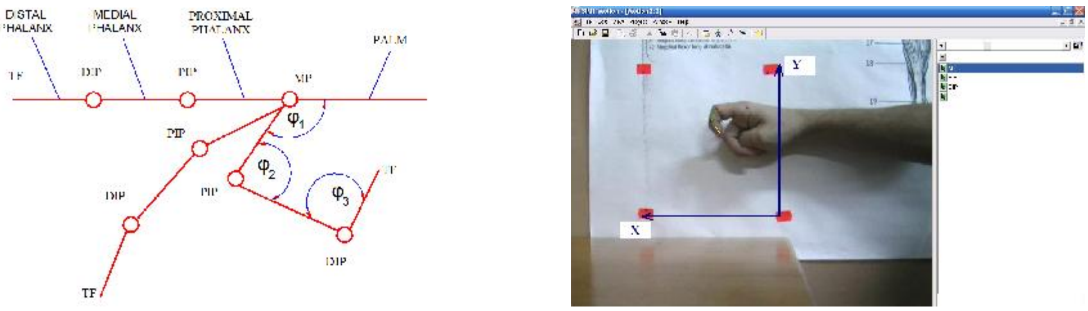

Figure 3: Index finger joints. SimiMotion software

3.2. Exoskeleton structure

To address the rehabilitation issues, we intended to construct a low-profile and lightweight exoskeleton that allows a basic motion using a natural sequence of muscle activation. First we developed virtual exoskeleton systems on the base of four-bar linkage mechanism (Figure 4). The system architecture is achieved by a cascade connection of a four-bar linkage mechanism, each mechanism associated to a joint of the finger (Figure 4). [15] Virtual model construction was performed using SolidWorks software that allows real-time simulation of the model, and then optimizing it by modifying the shape and dimensional parameters of each component separately.

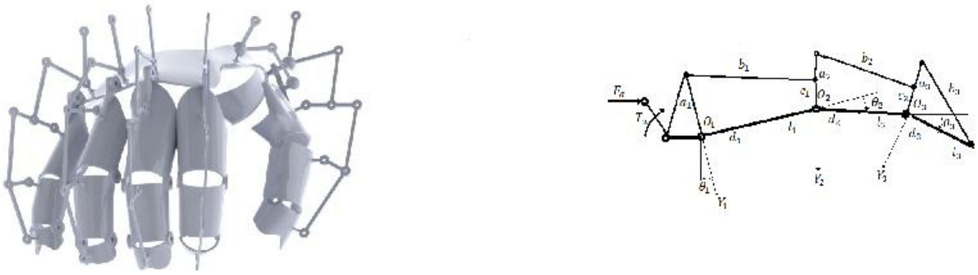

Figure 4: Virtual exoskeleton and four-bar linkage mechanism

The IHRG system has a kinematic structure similar to the natural hand with five articulated fingers. Each finger is composed of three phalanges in order to have an anthropomorphic contact with patient's hand. We tested different mechanical solutions, different motion transmission solutions and actuation systems (electrical, pneumatic and shape memory alloy). We tested two exoskeleton systems with two types of electric (rotary or linear) actuators. Since underactuated fingers have many degrees of freedom and fewer actuators, a glove will be used to constrain the finger and ensure the shape-adaptation of the finger.

In order to get an effective rehabilitation effect, the mechanical structure must allow the finger to reach the positions of a healthy finger.

Three structures were designed and developed (two as exoskeleton structure – with robotic fingers or phalanges):

- the structure with robotic fingers
- the structure with phalanges
- the glove type structure (soft robotic glove)

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

- through tendons (for the structure with robotic fingers and for the glove type structure);
- through four-bar linkage mechanism for the structure with phalanges.

First, some virtual exoskeleton structures were designed (Figure 5) with different actuation systems (linear or rotary electric servomotors). Then these virtual solutions were implemented practically (Figure 6, left side; Figure 7).

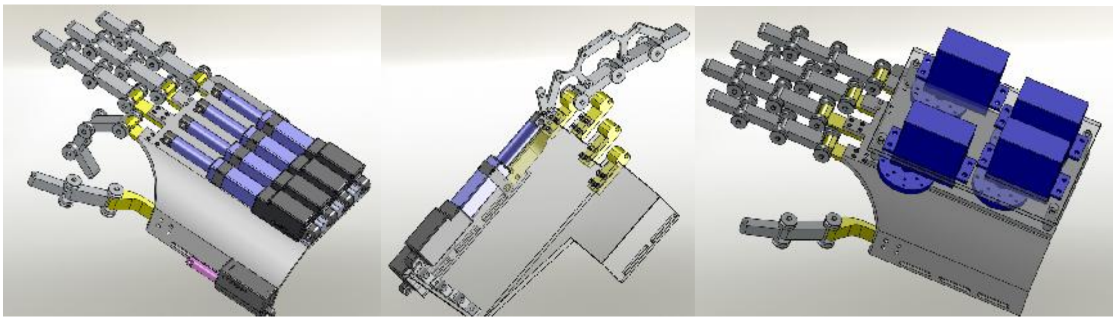

Figure 5: Virtual exoskeleton structures with different actuation systems

Most of the structural components of one of the first robotic glove have been made of hard polyacetal.
We developed a robotic hand (Figure 6, right side) for some teleoperation tests. We tried to develop a non-expansive robotic hand that follows the basic required characteristics. The basic components of our robotic hand are the silicone hand, the 5 actuators, the Arduino UNO R3 control board, the glove and the 5 bend/flex sensors. The operation of the fingers is similar to the human hand, respectively with tendons, each finger having its own tendon, namely a plastic string found in a plastic tube in order to increase the movement. At the other end, the tendon is actuated by using an actuator (servomotor). Tele-operation of the robotic hand is facilitated through the glove with bend/flex sensors.

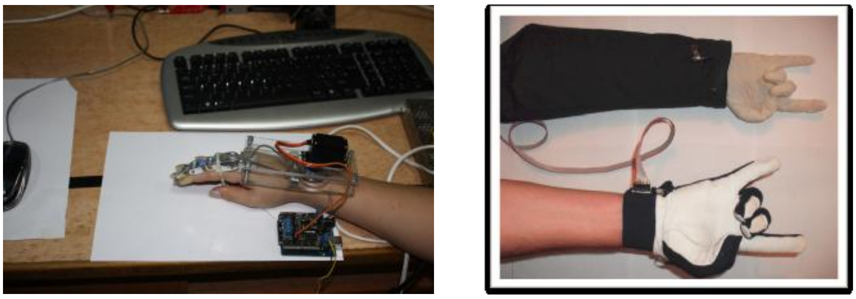

Figure 6: An exoskeleton structure. Tele-operated robotic hand

3.3. Actuation systems

Some different actuation systems (pneumatic cylinders, pneumatic muscles, shape memory alloy, electric actuators) were tested and compared. Considering the difficulties to achieve the exoskeleton with robotic fingers and to use it for a patient with CVA, after the tests with one robotic finger we decide to renounce to implementation of this solution for all five fingers.

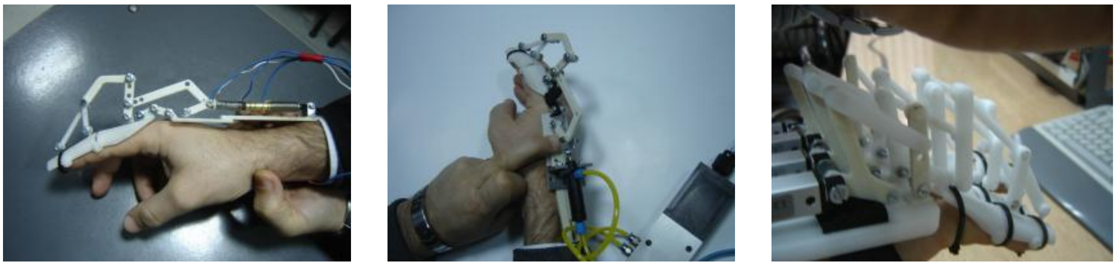

Figure 7: Exoskeleton structures and soft robotic glove

Beginning with two different types of shape memory alloy (SMA) elements we designed and developed a SMA actuator that it was tested with exoskeleton with phalanges (Figure 7, left side). Disadvantages of this type of actuation were small stroke and the complexity of the position control. Also, for exoskeleton type glove we implemented and tested two types of actuation systems: with pneumatic actuators (Figure 7, middle side) and with linear electric actuators. Glove type structure with linear electrical actuators and tendons drive was the easiest to develop and control although there are some difficulties to develop it. The exoskeleton with robotic fingers has some difficulties to develop and to use it for a patient with CVA. The structure with phalanges

showed some difficulties in design and developing and it has a reduced movement of the finger. 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:
A) rotary actuators: problems to convert rotary movement in linear movement (need of additional elements).
B) linear actuators: easy to drive the linear movement; no difficult to control.

4. STUDY AND DESIGN OF THE SOFT ROBOTIC GLOVE

Our goal is to create a portable wearable robot that assist the patient during movement. We proposed a device that uses textiles to interface with the hand in parallel with the muscles, using the bone structure, to support fingers' motion (Figure 8).

Figure 8: Soft robotic glove

The development of the robotic glove has been conducted considering the following set of guidelines: reduced weight; easy wearability; compliance; stability; high power-to-weight density and reduced energy consumptio; an embedded controller with easy programmability; reduced system costs; do not restrict the natural human kinematics or range motion; sufficient adaptability to individual differences in patients' anthropometric dimensions (without mechanical regulation or tunings); natural/intuitive use; simplified maintenance.
In comparison with rigid exoskeleton, soft robotic glove has a number of advantages: can be very light; has extremely low inertias, which reduces the metabolic cost of wearing them; it intrinsically transmits moments through the biological joints; since it are composed of textiles, it is easy to put on and take off; it can adapt easily to anatomical variations.

5. CONCLUSION

This paper presents the hardware and software developments that have been achieved and implemented for the robotic glove for hand rehabilitation. The practical results are shown that prove the functionalities of the robotic gloves in common operating conditions.
Wearable soft robotic gloves show to be a better solution for human hand's rehabilitation as lightweight, portable, and compliant wearable systems. We envision that such systems can be further refined.
Our IHRG is a lightweight, wearable device, a system to support a rehabilitation training of hand. It is a portable device that can be worn as a glove.

ACKNOWLEDGMENT

This work is supported by PNCDI-II-PCCA 150/2012 grant of the Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI).

REFERENCES

[1] Maciejasz P., Eschweiler J., Gerlach-Hahn K., Jansen-Tro A., Leonhardt S., A survey on robotic devices for upper limb rehabilitation, Journal of NeuroEngineering and Rehabilitation, 11:3, 2014.
[2] Grebenstein M., A Method for Hand Kinematic Designers, ICABB, Venice, Italy, 2010.

[3] Carrozza M. C., Vecchi F., Sebastiani F., Cappiello G., Roccella S., Zecca M., Lazzarini R., Dario P., Experimental Analysis of an Innovative Prosthetic Hand with Proprioceptive Sensors, Proc. IEEE Int. Conf. on Robotics and Automation, Taipei, Taiwan, pp. 2230-2235, 2003.
[4] Schectman L., Artificial Robotic Hand, US Patent no. 5080682, Jan. 14, 1992.
[5] Dechev N., Cleghorn W.L., Thumb Design of an Experimental Prosthetic Hand, Proceedings of the 2nd Intern. Symposium on Robotics and Automation, ISRA'2000 Monterrey, N.L. Mexico, November 2000.
[6] Massa B., Roccella S., Carrozza M. C., Dario P., Design and Development of an Underactuated Prosthetic Hand, Proc. of the 2002 IEEE Intern. Conference on Robotics and Automation, Washington, May 2002.
[7] Kaneko K., Harada K., Kanehiro F., Development of Multi-fingered Hand for Life-size Humanoid Robots, Proc. of the IEEE International Conference on Robotics and Automation, Roma, Italy, 10-14 April 2007.
[8] Jacobsen S. C., Iversen E. K., Knutti D.F., Johnson R.T., Biggers K.B., Design of the Utah-MIT Dexterous Hand, Proc. IEEE International Conference on Robotics and Automation, April 7-10, 1986.
[9] Shadow Robot Company, Design of a dexterous hand for advanced CLAWAR applications, 2003.
[10] Butterfass J., Fischer M., Grebenstein M., Haidacher S., Hirzinger G., Design and Experiences with DLR Hand II, World Automation Congress, Tenth Intern. Symposium on Robotics with Applications, Seville, 2004.
[11] Biagiotti L., Lotti F., Melchiorri C., Palli G., Tiezzi P., Vassura G., Development of UB Hand 3: early results, Proc. IEEE Int. Conf. on Robotics and Automation, pp. 4488–4493, Barcelona, 2005.
[12] Ciacci S., Merni F., Franceschetti F., Penitente G., Di Michele R., 3D Analysis with Simi Motion During a 110m Hurdles Race, 12th Annual Congress of the ECSS, Jyväskylä, Finland, .
[13] Copiluşi C., Dumitru N., Ciocan P., Motion laws determination, on experimental way, of joints from the human lower limb structure for certain activities imposed to the locomotor apparatus, Annals of the Oradea University. Fascicle of Management and Technological Engineering, Volume VII (XVII), 2008.
[14] Birglen L., Gosselin C., Kinetostatic Analysis of Underactuated Fingers, IEEE Trans. on Robotics and Automation, 20(2), pp. 211-221, 2004.
[15] Biagiotti L., Melchiorri C., Vassura G., Control of a Robotic Gripper for Grasping Objects inNo-Gravity Conditions, Proc. IEEE Intern. Conf. on Robotics and Automation, Seoul, Korea, pp. 1427-1432, 2001.