Novel approaches in hand rehabilitation

Grubišić, Ivan; Skala Kavanagh, Hana; Grazio, Simeon

PERIODICUM BIOLOGORUM
VOL. 117, No 1, 139–145, 2015

UDC 57:61
CODEN PDBIAD
ISSN 0031-5362

Novel approaches in hand rehabilitation

IVAN GRUBIŠIĆ[1]
HANA SKALA KAVANAGH[2]
SIMEON GRAZIO[2]

[1]Ruđer Bošković Institute/Centre for Informatics and Computing, Bijenička 54, HR-10000, Zagreb, Croatia

[2]"Sisters of Mercy" University Hospital Centre, University Department of Rheumatology, Physical and Rehabilitation Medicine, Referral Center for Spondyloarthropathies, Ministry of Health and Social Welfare Republic of Croatia, Vinogradska 29, 10000 Zagreb, Croatia

Correspondence:
Ivan Grubišić
Ruđer Bošković Institute/Centre for Informatics and Computing, Bijenička 54, HR-10000, Zagreb, Croatia
E-mail: ivan.grubisic@irb.hr

Received April 13, 2015.

Abstract

Hand rehabilitation is a constructive activity to gradually restore health and functionality of hand and fingers. Motion disabilities of hand and fingers are a common problem and can be a result of a wide variety of diseases and traumas. This problem is especially emphasized in the elderly population.

Common methods in hand rehabilitation include physical therapy that should be performed frequently. However, patients tend not to follow the program strictly and perform exercises the wrong way, making progress slower or even stagnant. With the development of novel contactless and non-invasive sensors for tracking hand and finger motion the hand rehabilitation can be further upgraded. In this paper we looked into existing hand rehabilitation systems and presented a concept of a novel system by empowering capabilities of new sensors with virtual reality (VR) environment. The existing hand rehabilitation exercises were analysed, adapted and verified in order to be implemented into the system.

INTRODUCTION

Hands and fingers play an important role in human life. With delicate motion control hands and fingers are involved in almost all human activities. Being one of the densest areas of nerve endings *(1),* fingers also represent the richest source of tactile feedback in the human body. The importance of hand and finger usage can be easily understood by exploring the human brain. One of the largest areas of the cerebral cortex is dedicated solely to controlling, receiving and processing sensations from hands and fingers *(2)*. The human hand consists of 27 bones *(3),* 27 joints, more than 120 ligaments, 34 muscles, 48 nerves and 30 arteries.

Because of the complexity of the musculoskeletal system and excessive usage during life, the human hand tends to be prone to injuries and diseases. Frequency of hand injuries is well depicted by a 2-year survey conducted in Denmark *(4)*. The survey showed that the rate of injury to the hand or wrist was 28.6% of all injuries, which was 3.7 per 100,000 inhabitants per year. 34% of the accidents were domestic, 35% were leisure accidents, 26% were occupational and 5% were traffic accidents. The most frequent causes for admission were fractures (42%), tendon lesions (29%) and wounds (12%).

Hand motion disabilities can also be a result of nerve compression syndromes, the most common being carpal tunnel syndrome. A wide variety of diseases leads to hand disability, where the most frequent one is osteoarthritis, while the most disabling one is rheumatoid arthritis. The problems of hand's functionality is especially present in the elderly population. In the age group 70-74 years more than 90% of women and little less than 80% percent of men have x-ray evidence of osteoarthritis in their hands. In the population group older than 80 years, percent rises to around 99% for women and over 95% for men *(5)*.

To increase the quality of life for the patients with hand motion disabilities adequate hand rehabilitation is needed. The rehabilitation commonly includes physical therapy, and if performed appropriately and frequently, it can help regaining partial or full functionality of hand/fingers.

There are three types of exercise used in rehabilitation for hand motion disabilities:

1. Range-of-motion exercises,
2. Strengthening exercises,
3. Aerobic or endurance exercises.

Range-of-motion exercises are performed without any weight in order to improve flexibility of joints and relieve stiffness from hand/fingers. Strengthening exercises usually include some sort of weight, such as therapy ball or strap, for gaining the muscle strength to support and protect joints. Aerobic or endurance exercises are also very important in rehabilitation, since a healthy cardiovascular system can reduce joints swelling in some cases.

Several virtual reality (VR) enhanced hand rehabilitation support systems have already been developed, and verified for effectiveness in various scientific researches *(6)*. Such systems usually empower hand/finger motion tracking device with an automatic motion assistant for independent rehabilitation therapies.

Lots of different sensory devices are used for hand/finger motion therapy, such as grip force measurement devices *(7)*, finger pinch force sensors *(8)*, VR gloves and exoskeleton systems *(9), (10), (11), (12)*. Currently, the most advanced device for hand/finger motion tracking is a hand exoskeleton system with functionalities in both directions, input and output. The device collects measurements of joint angles and forces as input to the system. On the other hand, the output is provided as physical force feedback from VR environment.

The importance of monitoring for the effectiveness of rehabilitation treatment is well recognized and represents the foundation of evidence-based health care *(13)*. However, currently used systems are not precise enough to detect and measure small differences that need to be monitored for adequate rehabilitation. In addition, most of the systems are inadequate for usage in severe cases of hand disabilities (such as last stages of rheumatoid arthritis and osteoarthritis).

For this purpose a novel hand/finger motion tracking instrument, the Leap Motion, can be used. It is simple, contactless, non-invasive and inexpensive sensor that has the ability to detect small changes in hand/finger positions with high precision and very fast acquisition rate. These characteristics make this device ideal for hand rehabilitation. In the following text a concept for the system will be presented and further discussed.

HAND AND FINGER MOTION TRACKING SENSOR

Leap Motion is an optical sensor specially designed for acquisition of 3D positions and orientations of hands and fingers. The main purpose of the sensor was to extend current input devices with 3D control for VR environments. The sensor was also found to be a good choice for a wide spectrum of other applications *(14, 15, 16)*.

The Leap Motion controller consists of three infrared light (IR) emitters and two IR cameras. The implementation of IR spectrum makes the projected rays invisible for the human eye, which makes the device comfortable for usage. The Leap Motion can be categorized into optical tracking systems based on stereo vision, since position data are calculated from stereo images. However, the system does not produce point cloud of the scene and the predefined detectable objects, just 3D positions and orientations of the hands and fingers. New release version 2.0 of the Leap Motion API enabled much better insight into hand metrics and positions. In this new version, a novel human hand modelling method was used, which improved the software's positions prediction of the fingers and hands not clearly visible by the cameras. With this improvement, the system is capable of acquiring data of all joints and bones for each finger, from wrist to fingertip.

Hand skeletal model introduced in Leap Motion SDK is shown on Figure 1. Finger type is defined as an integer, indicating the finger name: 0 = thumb; 1 = index finger; 2 = middle finger; 3 = ring finger; 4 = pinky finger. As depicted on Figure 1, for each finger the system gives an array of bones (metacarpal, proximal, intermediate, and distal) and 3D positions of five distinctive points:

1. carpPosition – base end of the metacarpal bone of the finger;
2. mcpPosition – metacarpophalangeal joint, or knuckle, of the finger;
3. pipPosition – proximal interphalangeal joint of the finger;
4. dipPosition – distal interphalangeal joint of the finger;
5. btipPosition – extreme end of the distal phalanx.

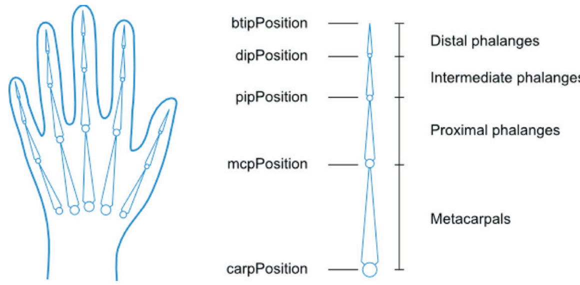


Figure 1. *Hand and finger skeletal model.*

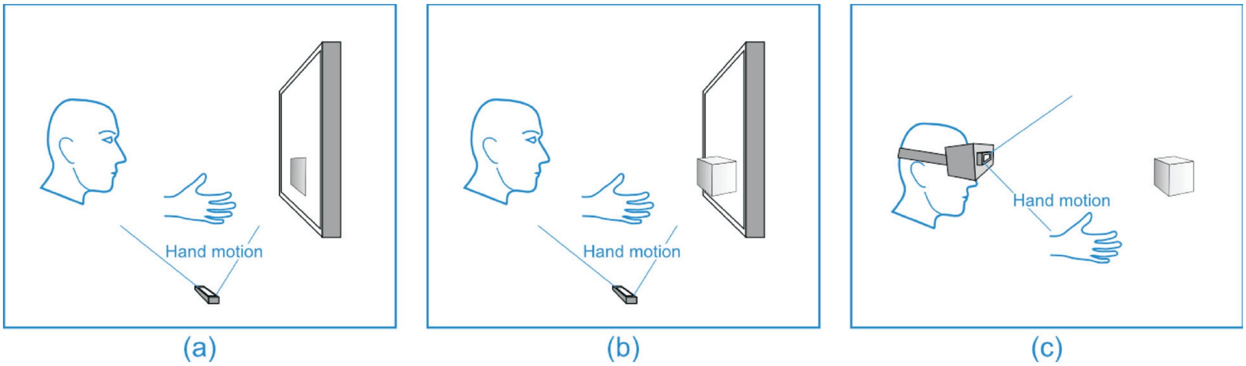


Figure 2. *System hardware setup: (a) Configuration with 2D display; (b) Configuration with 3D display; (c) Configuration with head mounted display.*

For each bone the system gives sizes, positions and orientations. In the skeletal model of the hand, the model for the thumb is an exception. The human thumb doesn't have four bones, like other fingers. The thumb misses the intermediate phalanx. However, the Leap Motion thumb model uses the same model as for the other fingers, but with zero-length metacarpal bone. With this approach the thumb has all of the bones at the same indexes as the other fingers, which is a much better solution for programming. As a result, the Leap Motion finger model for the thumb represents the real metacarpal bone as a proximal phalanx, and the real proximal phalanx as the intermediate phalanx. In addition to the finger skeletal information, the SDK gives also several hand properties, such as armWidth – the average width of the forearm; type – labels the hand as a left or a right hand; confidence – the measure showing how well the skeleton model and the observed data fit. Very important parameters, given by the SDK, are elbow and wrist positions, enabling the calculation of the forearm orientation.

According to the official announcement of the manufacturer, the Leap Motion controller should be able to acquire positions with sub-millimetre accuracy. Accuracy and robustness of the controller were further analysed and discussed *(17, 18)*. The analysis showed that accuracy of less than 2.5 mm could be obtained, with an average of 1.2 mm *(17)*. High robustness of the device was proven with a repeatability average of less than 0.17 mm. The measured standard deviation was below 0.7 mm per axis for movement to discrete positions on a path. By the conclusion of the analysis, the theoretical accuracy of 0.01 mm couldn't be achieved under real conditions. However, an overall average accuracy of 0.7 mm is significantly better than the accuracy of other controllers in the same price range.

HAND REHABILITATION SYSTEM

A. The System Hardware Setup

To conduct rehabilitation for hand/finger motion disabilities, an adequate hardware for VR environment needs to be set up. Here, we are presenting three possible solutions of hardware configurations:

1. Leap Motion + 2D display;
2. Leap Motion + 3D stereoscopic display;
3. Leap Motion + Head mounted display (HMD).

The first solution combines 2D display and Leap Motion as input device, as shown in Figure 2(a). This should be the most common solution, because a 2D display is a standard part of every computer, and any kind of 2D display can be empowered for this task. However, limitations are obvious, as the conversion of real 3D hand/finger motions to a 2D virtual world renders one dimension unavailable for preview. Losing this insight into the third (depth) dimension limits the set of applications.

The second solution upgrades the first solution with 3D sensation using a stereoscopic display, depicted in Figure 2 (b). Those displays are not as common as the ones used in the first solution, and have a distinctly grater purchase price. However, usage of this configuration enables a much wider set of applications and a more realistic virtual environment.

The last solution is the most advanced one, and it should enable a full 3D experience, shown in Figure 2(c). Because of a wearable head mounted display, the area in front of the user will be available for free hand movement. This setup makes real 3D space (motion of hands/fingers) and virtual 3D space (shown on display) basically identical.

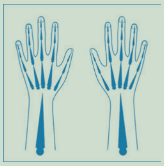
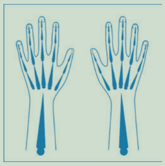
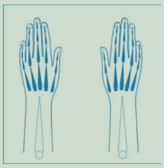
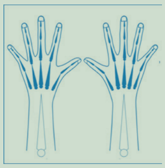
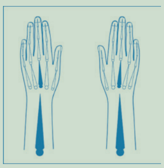
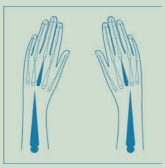
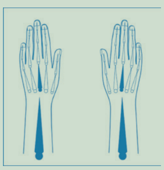
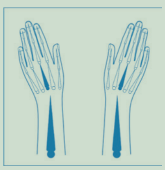
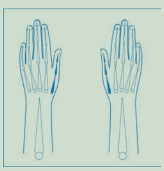
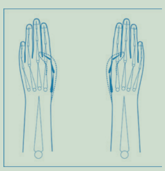
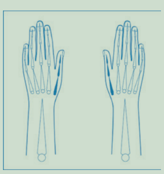
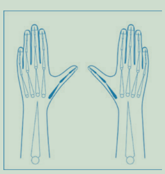
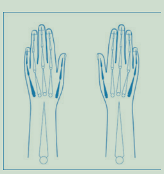
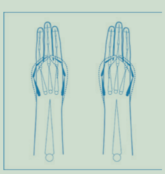
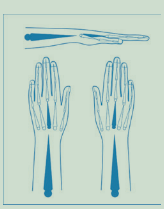
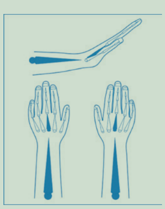
B. The System Software Design

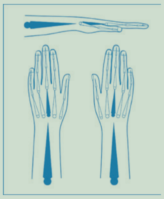
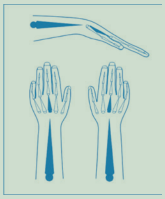
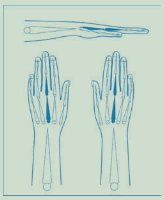
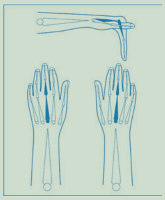
The present concept for the system software is designed by utilising three main components; a database, an intelligent assistant and a VR engine. The database is a well-defined collection of data specific for a user. There will be three main types of data stored in the database:

1. User's personal information,
2. Specialist medical reports and prescription data,
3. Rehabilitation progress data.

Personal information of the user should include sex, age, hereditary disease risk, and all other personal data

TABLE 1
Exercises.

No.	Start position	End position	Description	Adaptation	Measurement	Quality control
0.			Neutral position; Prior and posterior to each exercise;	All fingers straight and gently spread; Elevated fore-arm;	Position of each bone and joint;	Compare captured and default bones and joints positions;
1.			All fingers straight and close together; Maximally spread fingers;	Neutral position prior to the exercise; Elevated fore-arm;	Angles between bones in each finger (metacarpal, proximal, intermediate, and distal);	Straightness of hand (forearm and metacarpal of middle finger);
2.			Hand is straight; Maximal radial deviation;	Neutral position prior to the exercise; Elevated fore-arm;	Angles between forearm and hand (metacarpal of middle finger);	Straightness of fingers (metacarpal, proximal, intermediate, and distal);
3.			Hand is straight; Maximal ulnar deviation;	Neutral position prior to the exercise; Elevated fore-arm;	Angles between forearm and hand (metacarpal of middle finger);	Straightness of fingers (metacarpal, proximal, intermediate, and distal);
4.			Fingers are straight; Maximal flexion in metacarpal joint;	Neutral position; Elevated fore-arm; Rotated for 90°;	Angles between bones in thumb (metacarpal, proximal, intermediate, and distal);	Straightness of hand and fingers(forearm, metacarpal, proximal, intermediate, and distal);
5.			Hand is straight; Maximally spread thumb;	Neutral posi-tion prior the exercise; Elevated fore-arm; Rotated for 90°;	Angles between bones in thumb (metacarpal, proximal, intermediate, and distal);	Straightness of fingers (metacarpal, proximal, intermediate, and distal);
6.			Hand is straight; Thumb opposition with other fingers;	Neutral position prior to the exercise; Rotated for 180°;	Angles between bones in fingers (metacarpal, proximal, intermediate, and distal);	Straightness of fingers (metacarpal, proximal, intermediate, and distal);
7.			Hand is straight; Maximal dorsal flexion in the wrist;	Neutral position prior to the exercise;	Angles between forearm and hand (metacarpal of middle finger);	Straightness of fingers (metacarpal, proximal, intermediate, and distal);

8.			Hand is straight; Maximal palmar flexion in the wrist;	Neutral position prior to the exercise;	Angles between forearm and hand (metacarpal of middle finger);	Straightness of fingers (metacarpal, proximal, intermediate, and distal);
9.			Hand is straight; Maximal flexion in carpal joints for all fingers except thumb;	Neutral position prior the exercise;	Angles between metacarpal and proximal phalange of all fingers;	Straightness of fingers (proximal, intermediate, and distal); Straightness of hand (forearm and metacarpal of middle finger);

which could influence the rehabilitation progress. Specialist medical reports and prescription data are the most valuable data for creating future exercise plans and prognosis of expected results. Rehabilitation progress data should contain all important data collected during exercises performance sorted by date.

The intelligent assistant is the „brain" of the system. The main purpose of the assistant is to create daily exercise plans, and to guide the user during exercises. Daily exercise plans are created by analysing all of the information stored in the database. For example, the assistant can advise the user to repeat an exercise for a various number of times, or even to take a day off if it is the best choice according to data analysis. During training, the assistant should constantly analyse collected data in real time, and give the user advice and guidance for optimal performance of a given exercise.

The VR engine software part is responsible for all feedback from system to user, and should be implemented on the game engine software already supported by Leap Motion SDK, Unity 3D. The VR engine will be empowered by the intelligent assistant to show guidance and results on the chosen VR hardware configuration.

EXERCISES FOR HAND REHABILITATION SYSTEM

For the purpose of conducting hand rehabilitation with this system, we selected several common rehabilitation exercises. Being an optical sensor, Leap Motion can be used only on an empty hand. Because of these limitations, only range-of-motion exercises can be monitored. However, some of the exercises needed minor adaptation in order to be monitored by the system. Unlike the original versions, all of the exercises need to be performed with forearms placed on an elevated surface. This adaptation is done within exercises 1-5, depicted on Table 1. Also, all active parts of the hand have to be optically visible by the system. To satisfy this condition, some of the exercises were rotated for 90° or 180° around forearm vector, exercises 4-6.

The Leap Motion can produce errors if a closed hand is introduced to the system. However, this error can be significantly reduced if an opened hand is introduced to the system prior to closing. In order to ensure low error, we proposed a neutral position state, depicted on exercise 0 in Table 1. The neutral position is a characteristic state with all fingers straight and gently spread. This state should be performed prior each exercise with forearm placed on an elevated surface.

Each exercise has a specific role and involves characteristic bones of a hand and fingers. The measurement column, in Table 1, describes bones involved in each exercise, and emphasizes their important properties. The most frequently used property is the angle between the bones. The angle can be calculated from the bones vectors with formula:

$$\theta = \arccos\left(\frac{\vec{u}\cdot\vec{v}}{\|\vec{u}\|\cdot\|\vec{v}\|}\right) \tag{1}$$

Where $\vec{u}$ and $\vec{v}$ are 3D vectors of the bones, and θ is the angle between them.

Quality control column depicts elements and parameters of the hand skeletal model, and indicates how well the exercise is performed. The most frequent quality control is straightness of hand, and straightness of fingers. Straightness of hand is defined with the angle between forearm and hand (metacarpal of middle finger). Straightness of fingers is defined with angles between metacarpal, proximal, intermediate, and distal bones of each finger not activated by the exercise. Straightness factor is produced as a sum of all calculated angles and it is better if the value of the factor is lower.

Finally, total of nine exercises were proposed to be integrated as part of the rehabilitation system program. Ten other exercises were tested and rejected. These exercises could not be used because of two main reasons:

1. Performance involves tools (such as ball);
2. Performance could not be measured with any minor adaptation.

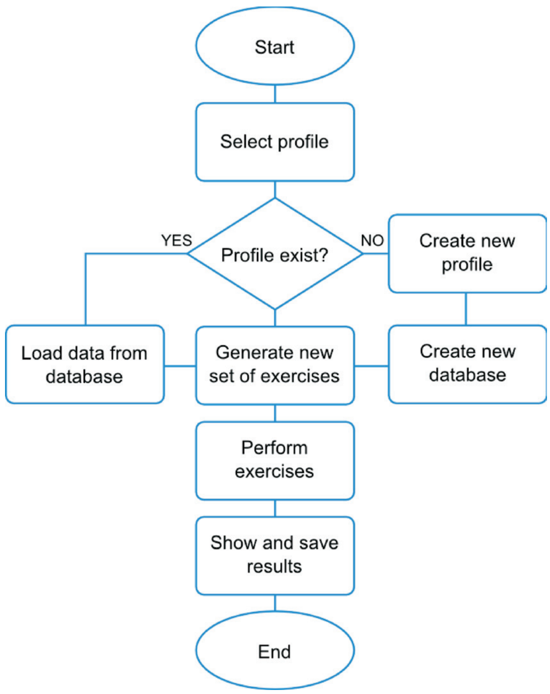


Figure 3. *System usage workflow.*

REHABILITATION PROCEDURE

Workflow of the system usage is depicted on the Figure 3. Prior to each usage, the user needs to log in to their pre-existing profile, or create a new one. The creation of a profile requires filling up the user's personal information, specialist medical reports and prescription data. Afterwards, the system creates a database for the profile. If the profile already exists, the system just loads data from the database. In the next step the system creates a new set of exercises, based on the data.

Commonly all exercises should be performed minimally four times, and a maximal latitude should be position where significant pain starts. However, the system should be able to analyse given information with data acquired during past sessions, and to choose accordingly the times of repetition and the maximal latitude.

Exercises are performed one after another, according to a previously generated plan. At the same time, the system gives the user advice and guidance for best performance of a given exercise. After training, the system shows and saves results. The user can also view old results and look into daily progress diagrams.

CONCLUSION

In this paper, an overview of existing hand rehabilitation systems was depicted. Furthermore, after showing known limitations of existing systems for this task, a concept for a novel system is presented. This system is based on the Leap Motion controller, which is an optical sensor based on stereo vision. The system incorporates the controller with advanced software, enabling rehabilitation progress monitoring and customization of the exercise program.

For rehabilitation purposes, nine common range-of-motion exercises were selected and adapted. In addition to the description and adaptation, we also suggested measurement and quality control properties for each exercise.

The concept of the system can also be extended with a reminder, and a remote monitoring component. The reminder will ensure regular training, while the monitoring component will enable specialists to remotely check the progress of the rehabilitation.

Acknowledgement: *The authors acknowledge the support of scientific research project „Methods of scientific visualization" (098-098 2562-2567), founded by the Ministry of Science, Education and Sports of the Republic of Croatia. The work was created on the basis of the Agreement on Cooperation in the Development of new Diagnostic and Therapeutic methods concluded between Ruđer Bošković Institute and „Sisters of Mercy" University Hospital Centre, University Department of Rheumatology, Physical and Rehabilitation Medicine, 2013.*

REFERENCES

1. WALLACE W A, COUPLAND R E 1975 „Variations in the nerves of the thumb and index finger". *J Bone Joint Surg Br 57-B (4):* 491-494
2. JOHNSON S H 1998 „Cerebral organization of motor imagery", Contralateral control of grip selection in mentally represented prehension. *Psychol Sci 9:* 219–222
3. NOELLE M AUSTIN 2005 „Chapter 9: The Wrist and Hand Complex". *In:* Levangie P K, Norkin C C *(eds)* Joint Structure and Function: A Comprehensive Analysis (4th ed.). F. A. Davis Company, Philadelphia. ISBN 0-8036-1191-9
4. ANGERMANN P, LOHMANN M 1993 „Injuries to the hand and wrist. A study of 50,272 injuries". *The Journal of Hand Surgery: British & European Volume 18 (5):* 642-644
5. HAUGEN I, ENGLUND M, ALIABADI P, NIU J, CLANCY M, KVIEN T K, FELSON D T 2011 „Prevalence, incidence and progression of hand osteoarthritis in the general population: the Framingham Osteoarthritis Study", Clinical and epidemiological research. *Ann Rheum Dis:* 1581-1586
6. KAWASAKI H, KIMURA H, ITO S, NISHIMOTO Y, HAYASHI H, SAKAEDA H 2006 „Hand Rehabilitation Support System Based on Self-Motion Control, with a Clinical Case Report", Automation Congress, WAC '06. World, p 1-6
7. SKALA KAVANAGH H, DUBRAVIĆ A, LIPIĆ T, SOVIĆ I, GRAZIO S 2011 „Computer supported thermography monitoring

of hand strength evaluation by electronic dynamometer in rheumatoid arthritis – a pilot study". *Period biol 113(4):* 433-437

8. OLANDERSSON S, LUNDQVIST H, BENGTSSON M 2005 „Finger-Force Measurement-Device for hand rehabilitation" in Rehabilitation Robotics Conf. ICORR, p 135-138
9. HARTOPANU S, SEREA F, POBORONIUC M, IRIMIA D, LIVINT G 2013 „Design of a Hybrid FES-Mechanical Intelligent Haptic Robotic Glove," in Proc. of the 17th International Conference on Systems Theory, Control and computing ICSTCC2013, Sinaia, Romania, 11-13 October, p 687-692
10. BROKAW E B, BLACK I, HOLLEY R, LUM P 2011 Hand Spring Operated Movement Enhancer (HandSome): A Portable Passive Hand Exoskeleton for Stroke Rehabilitation. *IEEE Trans on Neural Systems and Rehabilitation Eng 19(4):* 391-398
11. JITING L, SHUANG W, JU W, RUOYIN Z, YURU Z, ZHONGYUAN C 2011 Development of a Hand Exoskeleton System for Index Finger Rehabilitation. *Chinese Journal of Mechanical Engineering 24(5)*
12. WEGE A, HOMMEL G 2005 „Development and control of a hand exoskeleton for rehabilitation of hand injuries." IEEE/RSJ International Conference on Intelligent Robots and Systems, Edmonton, Canada.
13. GUMMESSON C, ATROSHI I, EKDAH C 2003 The disabilities of the arm, shoulder and hand (DASH) outcome questionnaire: longitudinal construct validity and measuring self-rated health change after surgery. BMC Musculoskeletal Disorders, p 4-11
14. BASSILY D, GEORGOULAS C, GUETTLER J, LINNER T, BOCK T 2014 „Intuitive and Adaptive Robotic Arm Manipulation using the Leap Motion Controller", ISR/Robotik, 41st International Symposium on Robotics, Proceedings of, p 1-7
15. ZUBRYCKI I, GRANOSIK G 2014 „Using Integrated Vision Systems: Three Gears and Leap Motion, to Control a 3-finger Dexterous Gripper", Recent Advances in Automation, Robotics and Measuring Techniques, Advances in Intelligent Systems and Computing Volume 267, p 553-564
16. KHADEMI M, HONDORI H M, MCKENZIE A, DODAKIAN L, VIDEIRA LOPES C, CRAMER S C 2014 „Free-hand interaction with leap motion controller for stroke rehabilitation". CHI '14 Extended Abstracts on Human Factors in Computing Systems, p 1663-1668
17. WEICHERT F, BACHMANN D, RUDAK B, FISSELER D 2013 „Analysis of the Accuracy and Robustness of the Leap Motion Controller". *Sensors 13:* 6380-6393
18. GUNA J, JAKUS G, POGAČNIK M, TOMAŽIČ S, SODNIK J 2014 „An Analysis of the Precision and Reliability of the Leap Motion Sensor and Its Suitability for Static and Dynamic Tracking". *Sensors 14(2):* 3702-3720