Journal of Polish CIMEEAC
Faculty of Ocean Engineering & Ship Technology
GDAŃSK UNIVERSITY OF TECHNOLOGY

STRUCTURAL SOLUTIONS TO BE USED IN EXOSKELETONS OF HAND FINGERS

Paweł Maćkowiak, Bogdan Ligaj

University of Science and Technology in Bydgoszcz
ul. Kaliskiego 7 bud. 2.3 p. 403 , 85-796 Bydgoszcz, Poland
tel. (52) 340-82-12
e-mail: pawel.mackowiak@utp.edu.pl

Abstract:

This study is a presentation of state of the art in the field exoskeletons of hand fingers. Exoskeletons of hand fingers have been characterized on the basis of an analysis of currently existing structural solutions. The goal of this research is to present a new concept of the device being a modification of Shield's exoskeleton. Despite a large demand for hand exoskeletons the currently available solutions often fail to meet requirements of doctors and patients. Due to many freedom degrees characteristic of a human hand a compromise is necessary between simplicity of the device and the possibility of performing basis grasps.

Słowa kluczowe: *exoskeleton, hand, fingers*

1. Introduction

A patient disability has a negative influence not only on the treatment costs but also on their psychological and physical condition, self-esteem and social relations. [6].

In the case of strokes the best results of recovery are obtained not later than in the first months of treatment. Treatment of movement disabilities involves gymnastics of extremities in order to reorganize the nervous system, that is, making active neurons take over the functions of damaged neurons. This requires assistance of a qualified therapist and a lot of time to be spent each day on exercising. Therefore a demand for robots and other technical devices to substitute therapists is continuously growing. One of such devices is an exoskeleton [6].

The range of movements and activities to be performed by an exoskeleton is not fully known yet as it should be biomechanically compatible with individual (natural) axes of joints, separately for each joint, and the rotation angular velocity in the joint should be, according to recommendations, 1000 °/s. It is natural velocity of a finger joint operation. Torque in particular joints is 4 Nm in the knuckle joint 1.5 Nm in the dip joint. The mass of exoskeleton and its dimensions should be minimized. The existing solutions do not provide sufficient range of movements, the movement speed and independence of movements in each of the joints of a hand [4].

The aerospace and weapon industries are getting more and more interested in the development of hand exoskeletons. Support for astronauts during their space missions through exoskeletons is caused by difficulties connected with the necessity of wearing sophisticated equipment.

It limits: the range of movement, power of hands, comfort, accuracy and increases exhaustion of an astronaut.

The aim of research in this area is development of a hand exoskeleton which could be connected with the astronaut glove and the rest of his/her suit. The hand should provide more power, dexterity and securely grasp [5].

An optimal solution would be separately controlled fingers but it is permitted to connect some fingers in order to decrease the mass and provide structural simplicity. These solutions should imitate physiological movements of a hand. Attempts to build hand exoskeletons are being undertaken with the use of materials that undergo deformation under the influence of heat or tension (artificial muscles) [5].

The aim of this study is to analyze the concepts of available solutions and construction of new exoskeletons. In this study the following devices have been analyzed: Shields, Wege, CAFE, RMII, Handexos, Li Jiting. The second research goal is to propose modification for Shield's exoskeleton.

2. Shield's Exoskeleton

The prototype constructed by Shields is a three finger structure. It provides independent movements for the index finger, middle finger and one movement for two connected fingers the ring and the small finger. Each finger of the exoskeleton reflects movements in the in the knuckle joint and proximal interphalangeal joints. These movements are coupled with each other. In order to reduce the number of necessary drives, the function of the device was limited only to active finger bending.

A single member of the device used to bend a joint is made up of a mechanism consisting of 4 levers. Each joint mechanism is designed in such a way that its rotation axis overlaps with the finger joint rotation axes on which it is to be worn. In connection with this, the length of beams and initial angles between them, must be separately matched to each finger. Dimensions of a hand are not the same for all the people which involves the necessity to produce each device individually[7].

The drive of the device consists of 3 motors placed on the forearm. Transmission onto the wrist goes through Cardan cylinders where a steel line, connected with one of the levers, is pulled by means of a screw mechanism. The torque providing a finger with the possibility to bend in the knuckle joint is 3,8 Nm. The total time of a hand opening and its complete closing is 2 seconds [7].

3. Wege device

Another solution is an exoskeleton of a finger constructed by Andreas Wege. The design provides separate movements in each finger joint including bending, straightening, abduction and adduction in the knuckle joint. Finger's ability to move is provided by levers connected with the hand by means of orthopedic appliances. At the end of each lever there are wheels with steel lines wrapped around them. The other end of each line is wrapped around a wheel placed on the geared motor cylinder [8].

The device has some disadvantages including too big height and too large size of the drive system.

4. Device of Rehabilitation Institute in Chicago

Another solution is a prototype of CAFE device developed by the Institute of Rehabilitation in Chicago. It is an exoskeleton of the index finger [4].

Torque applied to particular joints is equal to half of the mean value of naturally occurring torques in healthy patients. The range of movements in the successive joints is: -15-75º, 0-90 º, 0-90 º. A prototype is fixed on the radial side of the index finger. Slide wheels guide a drive line above the joints to the target points of the fastening [4].

By using replaceable connectors of particular parts of the exoskeleton it is possible to adjust it to a vast number of people. A part of the exoskeleton is made of aluminum and steel. The mass of the part which is engaged in direct movement of a finger has been reduced to 138 g. Width of the device along the finger is 8 mm [4].

Each joint has a separate drive in the form of a pair of dc servo motors. The motor is mounted on a plate situated on the forearm. The power is transmitted by means of lines. All the drive mechanism of one finger consists of 6 motors and six lines. Reduction gears are mounted directly above the joint [4].

5. RMII Glove

RMII glove is an exoskeleton which applies force to the end of the finger and uses a non-contact sensor for determination of the finger end position in relation to the hand. Movement is provided by light pneumatic servomotors attached to the end of: a thumb, an index finger, a middle and a ring finger. The force applied to each finger can be equal even to 16N for pressure 100 PSI (0,689 MPa) acting on pistons of the servomotors [2]. The exoskeleton is placed on the palm which makes the hand grip more difficult.

6. Handexos device

Handexos device consists of five independent modules corresponding to human fingers. Each module consists of three members, one for every finger bone. The members have a shell like structure which is adjusted to the dorsal part of the finger. The device is mounted to the hand by means of Velcro fabric, commonly called Velcro tape [1].

The structure of a drive provides a solution for active extension and passive bend of the finger module [1].

Energy is transmitted by means of steel lines placed in a covering. The set for the finger straightening consists of a single motor straightening all the joints.

The set bending a finger consists of three lines, one for each segment of a finger. Each line is wrapped around three bending wheels situated on the opposite side of a finger in relation to straightening wheels. Bending lines are connected with three compressed springs leading to a finger bending when an action unintended by the user takes place. Initial tension of the springs can be adjusted by means of three screws. [1].

7. Li Jiting device

Exoskeleton designed by Li Jiting is a device mounted on the dorsal side of the index finger. It consists of three modules enabling 4 movements. These movements are: bending, straightemning, abduction and adduction [3].

While designing the members the length of finger bones has to be taken into consideration as well as the necessity of leaving empty spaces to avoid collisions of particular modules.

Abduction and adduction in the knuckle joint is performed by a direct rotation of the abducting wheel, to which a bending module is attached. The exoskeleton is made mainly of aluminum with the use of rolling bearings. Mass of the whole is 160 grams and, according to authors, it is acceptable for a human hand [3].

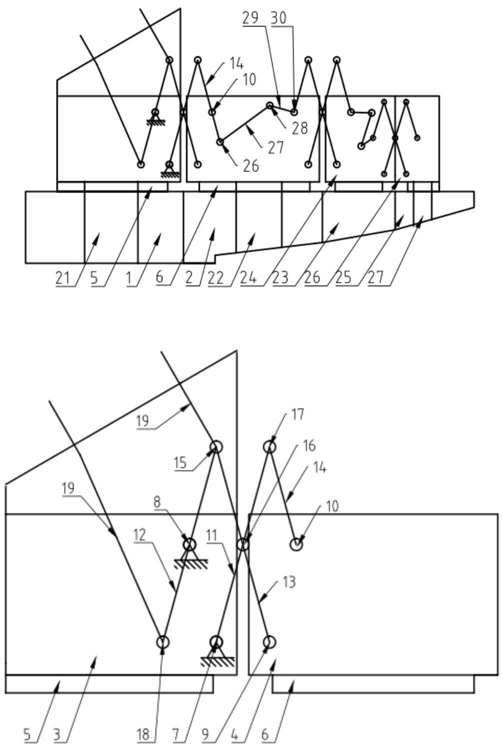
Adjustment of the exoskeleton to users with different lengths of finger bones is possible through shifting two screws between different seats [3].

The drive is transmitted by means of a band. The propelling system is situated far from the patient hand in order to reduce loading. It consists of 4 motoreducers mounted on a panel providing power for four connections [3].

8. New design solution

The proposed concept of a new solution is based on Shields's device, which was supplemented with an additional member enabling bending in the end joint of finger. Thus, the prototype device was provided with the possibility of active extension. The palm part of the finger was left uncovered thanks to which it is possible to use the sense of touch.

The device is fixed to the finger bones (element 1 and 2) by means of elements 3 and 4 put on a finger in the form of a channel bar (rys.1). Elements 3 and 4 are covered from the side of a finger with a layer of neoprene foam 6 and 5. In element 3 and 4 there occur ports for pins 7,8,9,10. Respectively, on each pin there is a beam, as shown in the scheme. On pin 7 there is beam 11, on 8 – 12, on 9 – 13, on 10 – 14. Beam 12 and 13 are connected rotationally by pin 15. The same connection is between 11 and 13, which are connected by pin 16, and 11 and 14 are connected by element 17.



Rys. 1. Structural scheme of the proposed solution

Respectively, on each pin there is a beam as in the scheme. On pin 7 there is beam 11, on 8 – 12, on 9 – 13, on 10 – 14. Beam 12 and 13 are connected rotationally by pin 15. The same connection occurs between beam 11 and 13, which connects pins 16 and 11 and 14 is connected by element 17. In beam 12 there is additional pin 18 to be connected with steel line19. Steel line 20 is attached to pin 15. When line 19 is pulled by the propelling system elements 4 are set into rotary motion in relations to element 3. The middle of this motion rotation falls on the axis of the bending finger joint. During pulling line 20 there occurs a rotary movement of elements 4 in relation to element 3 and in the opposite direction thus the joint becomes straightened.

Elements 3 and 4 are mounted on the fingers by means of belts 21 and 22. Elementa 24 is fixed on the middle phalanx 23, whereas on the distal phalanx 25 element 26 is mounted by means of belt 27 Movement of the described member is transferred onto the remaining ones by means of lever 28 which is connected by pin 29 with lever 14 rotating on pin 10. On the other side, lever 28 is connected with lever 31 by means of pin 30 rotating in relation to the axis of pin 32 . Lever 31 sets into motion element 24 by rotating, causing bending of the successive joint. The movement is also transmitted onto the connection of elements 23 and 25.

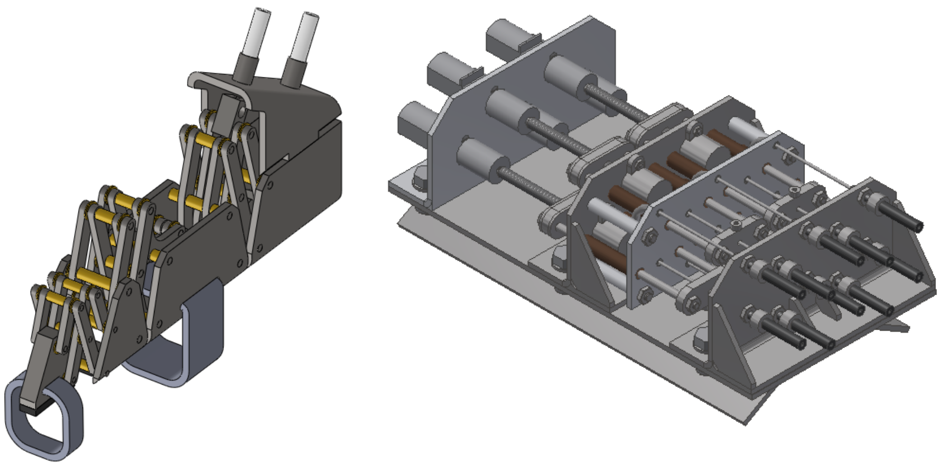


Fig. 2.Lump model of: a) finger exoskeleton b) propelling system

The device mass is limited to 180 g per one finger. In relation to the existing solutions it is a comparable value.

A method for matching the length of push rods and angles of the transmission mechanism levers between the device members has been developed. In the transmission drive mechanism there is a propelling lever l_1 and propelled lever l_2 between the device members (fig.3). The levers are connected with articulated joints 1 and 2 by a push rod. The levers rotate on pins in opposite directions . Lever l_1 on pivot I, lever l_2 on pin II. The goal of calculations is to find a dependence between α angle and lever l_1 and β angle and lever l_2, as well as to determine the dependence between a change in α angle and a subsequent change in β angle.

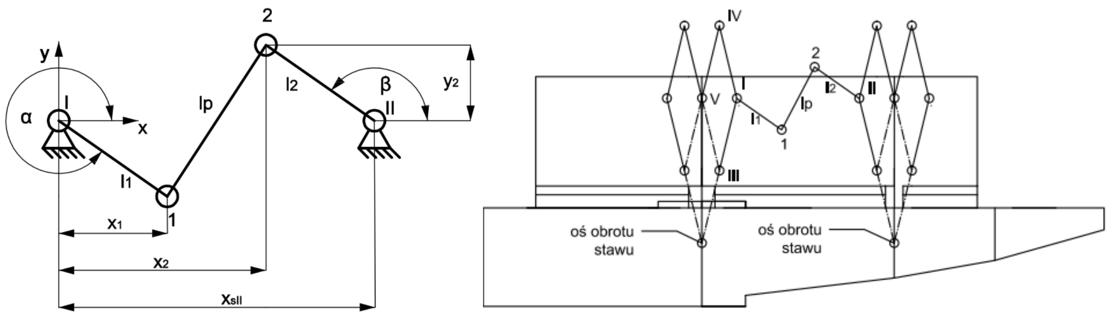


Fig. 3. Schemes of the mechanism operation mode.

Axis of pin I is accepted to be the beginning of the coordinate system. Coordinates of pin II axis are x_{sII} and y_{sII}. Determination of the location of pins was performed in a graphic form (fig. 3). In order to achieve overlap of the rotation axis of a finger joint with the device rotation axis it is necessary to act in accordance with the algorithm:

- determination of the joint rotation axis ,
- placement of pin III maximally close to the finger surface and the transverse plane crossing the joint,
- drawing a straight line crossing the rotation axis of a joint and point III,
- determination of pin I location through providing a length equal to the distance between the rotation axis and point III on the above straight line,
- pin I through providing a length equal to the distance between the rotation axis of a joint and point II, on the above straight line,
- the pin located in point V is at the height of point I, in a distance equal to the sector between point III and I,

- point IV is determined through parallel displacement of the sector between point III and V to point I,
- putting the remaining pins above a given joint is determined through mirror reflection in relations to the axis connecting a point of the joint revolution and point V,
- determination of location of pivots above the remaining joints is performed in an analogical way.

The length of the lever is supposed to be as large as possible though not colliding with any other elements of the device. Initial angles α and β are matched so as to reach the maximum value of torque. The propelled lever should be able to make a rotational movement in the range of 90 º. The propelled lever should be able to make a movement in the same range. The maximum torque for application of the same length of levers l_1 and l_2 is obtained in the moment when a push rod forms a rectangular angle both with lever l_1 and lever l_2. The optimal solution is to obtain such a situation in the middle of a full range, that is, for rotation of lever l_1 by angle 45 degrees.

The calculations accepted a Cartesian denotation of a point coordinates 1 (x_1, y_1) and 2 (x_2,y_2).

The following system of equations was created..

$$\begin{cases} (x_2 - x_1)^2 + (y_2 - y_1)^2 = l_p^2 \\ x_2 = x_{sII} + l_2 \cos\beta \\ y_2 = y_{sII} + l_2 \sin\beta \end{cases} , \tag{1}$$

X_2, y_2, β are the unknown in the equations . The below presented equations are a solution to the above system of equations. Values β_1 oraz β_2 are solutions to a square equation.

$$\beta_1 = \arcsin\frac{mn - \sqrt{n^2 - m^2 + 1}}{n^2 + 1} \pm 2k\pi , \tag{2}$$

$$\beta_2 = \arcsin\frac{mn + \sqrt{n^2 - m^2 + 1}}{n^2 + 1} \pm 2k\pi , \tag{3}$$

where:

$$m = \frac{l_p - (x_{sII} - l_1 \cos\alpha_n)^2 - s^2 - l_2^{\,2}}{2l_2 \cdot (x_{sII} - l_1 \cos\alpha_n)} , \tag{4}$$

$$n = \frac{y_{sII} - l_1 \sin\alpha_n}{x_{sII} - l_1 \cos\alpha_n} , \tag{5}$$

Coordinates of pin II x_{sII} and $y_{sII,}$ length l_1 and l_2, initial angles α_p and β_p were accepted as initial data for the purpose of solving the equations. Length of push rod l_p = 18,439 mm.

Table 1. A list of values of angles and initial coordinates of the lever ends accepted for calculations

Lever I		
x_{sI}=	0	mm
y_{sI}=	0	mm
l_1=	12	mm
α_p=	270	º

Lever II		
x_{sII}=	26	mm
y_{sII}=	0	mm
l_2=	12	mm
β_p=	180	º

Coordinates of points of the propelling and propelled levers were determined and a diagram was made (fig. 4) in order to illustrate the results. Distances between points of the lever ends should be located in equal distances from each other. If points on a circle drawn by the lever are distributed non uniformly it means that its speed is variable. Motion of the lever propeller with constant angular velocity will then result in the propelled lever variable angular velocity. The closer each other the points are the smaller the angular velocity of the lever is within the determined by them range. The further from each other they are the higher the angular velocity of the lever within the determined by them range. Through changing the initial values of α_p and β_p angles the motion range can be limited as well as speed control in the initial and final stages of the finger bending. This period has been divided into nine equal parts at the end of which the pin the propelling lever and the push rod were in the points denoted in the diagram (fig. 4).

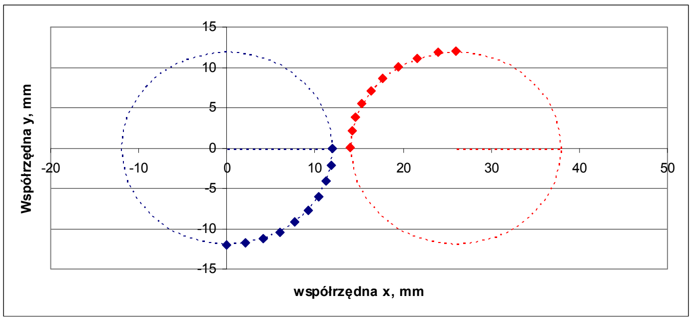
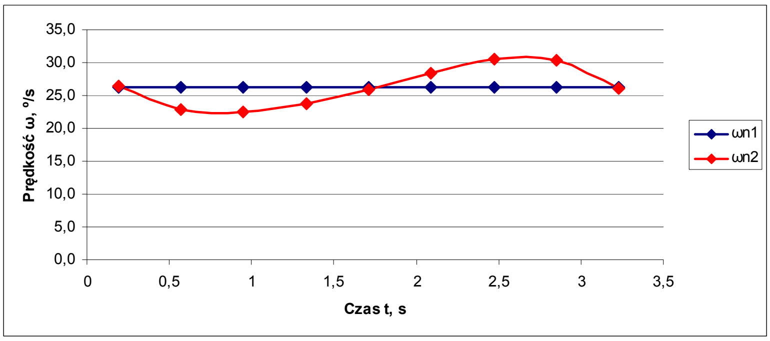


Fig. 4. Diagram of distribution of propelling and proppelled levers ends intime intervals approximately 0,38 s



Rys. 5. Diagram of speed of the propelling and propelled lever

The determined locations of the drive lever with resolution co 10 °, that is, distant in time by 0.38 s, determine the location of the drive lever. On this basis it is possible to determine the mean angular velocity which was reached by the lever in particular periods of time.

$$\varpi_{n2} = \frac{\beta_n - \beta_{n-1}}{\Delta t}, \qquad (6)$$

The results are presented in a diagram (fig. 5).

9. Conclusions

Having reviewed the literature on the subject of biomedical engineering and devices enabling rehabilitation and return to normal functioning of people with dysfunctions of hand grasp activities it can be said that there is a large demand for devices meeting needs of patients, doctors and therapists.

Analyzing the existing construction solutions which support grasp activities of a hand it can be concluded that they fail to meet the expected requirements. None of the devices is commonly manufactured or used by patients with dysfunctions of the upper limb. It results from the fact that the proposed solutions are characterized by a complicated structure, high production costs or are too large in terms of dimensions and mass, making it difficult to use them while moving.

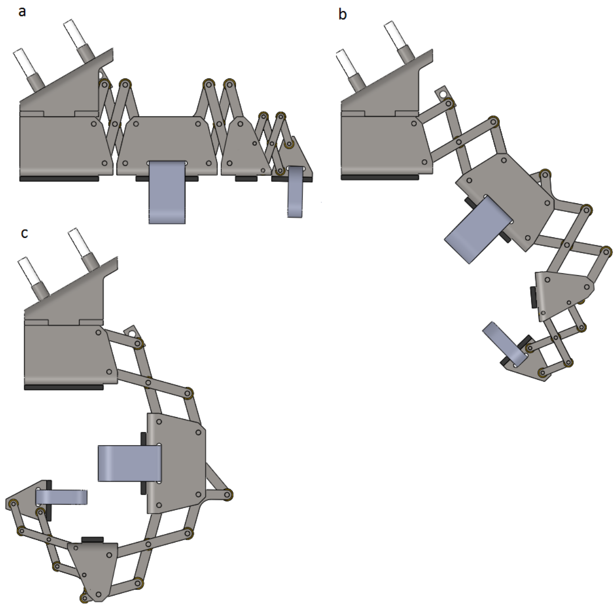


Fig. 6. Location of members of exoskeleton 006 during motion: a) straightened position – bending 0 º; b) bending 45 º; c) bending 90 º

The proposed structural solution and developed algorithm allows to adjust geometric dimensions of the device to the dimensions of a hand of a given person.

Location of the mechanism rotation axis beyond its geometry and using the dorsal part of hand for the whole device to be placed on does not limit the hand grasp possibilities. Thus the device enables full bending in all the joints by 90 º (fig. 6), which makes it stand out from many other structural solutions whose range, 60-90 º depending on the considered joint.

Thanks to coupling movements in a few joints and a closed band system, the number of motors and drive mechanisms necessary to perform movement. It limited mass of the drive part of the device 1kg, which is acceptable for a forearm to be placed on it. It was decided to use a screw gear in the drive whose efficiency is lower than 50 %. A disadvantage of this solution is higher consumption of energy during opening and closing the grasp on an item, whereas an advantage is a possibility of total disconnection of the feed from the system while holding an object or the hand immobility.

Most of the gripping activities involve keeping the finger members in a given position which supports economic effectiveness of this solution.

Connection of five exoskeletons of fingers will

Make a complete exoskeleton of a hand. Five separate screw gears are used for the drive. The index finger, middle finger and thumb will have a separate drive. This is a condition necessary to make most possible hand grasps.

The ring finger and the small finger can move in a coupled way. Therefore they can share one drive. The last screw gear is meant to support antithetical movement of the thumb.

This study can be used as a start to trigger further developments of structural solutions of exoskeletons of hand fingers and knowledge associated with them

References

[1] Chiri A., et al., *Mechatronic design and characterization of the index finger module of a hand exoskeleton for post stroke rehabilitation*, w: Mechatronics on Database Eng., vol.17, No.5, 2011, s.884-894.

[2] Jack D., et al., *Virtual reality-enhanced stroke rehabilitation*, w: Transactions on neural systems and rehabilitation engineering, IEEE Database Eng., vol.9, No.4, 2011, s.308-317.
[3] Jiting L., et al., *Development of a hand exoskeleton system for index finger rehabilitation*, w: Chinese journal of mechanical engineering, vol.24, No.5, 2011, s. 1-12.
[4] Jones C., et al., *Design and development of the cable actuated finger exoskeleton for hand rehabilitation following stroke*, w: Transactions on mechatronics, USA, 2012, s. 1-10.
[5] Paleari M., et al., Hexec: *A hand exoskeleton designed to be embedded in the astronaut's eva glove*, w: Center od Space Human Robotics, Italy, 2012.
[6] Sarakoglou I, et al., *Exoskeleton-based exercisers for the disabilities of the upper arm and hand*, w: Rehabilitation robotics, Austria, 2007, s. 499-522.
[7] Shields B, et al., *An anthropomorphic hand exoskeleton to prevent astronaut hand fatigue during extravehicular activities*, w: System and humans, USA, 1997, s. 668-673.
[8] Wege A., et al., *Mechanical design and Motion Control of a hand exoskeleton for rehabilitation*, w: Mechatronics and automation, Germany, 2005, s 155-159.