How to cite this article:

Authors: Jakub Kopowski, Dariusz Mikołajewski, Marek Macko, Izabela Rojek

Title of article: „Hand exoskeleton from Bydgoszcz – mechanical issues”

Mechanik, No. 4 (2019)

DOI: <https://doi.org/10.17814/mechanik.2019.4.35>

Hand exoskeleton from Bydgoszcz – mechanical issues

JAKUB KOPOWSKI
DARIUSZ MIKOŁAJEWSKI
MAREK MACKO
IZABELA ROJEK*

* Mgr inż. Jakub Kopowski (kopowski@ukw.edu.pl) – Wydział Psychologii, Uniwersytet Kazimierza Wielkiego, Bydgoszcz, Polska
Dr inż. Dariusz Mikołajewski (dmikolaj@ukw.edu.pl), <https://orcid.org/0000-0003-4157-2796> – Instytut Mechaniki i Informatyki Stosowanej, Uniwersytet Kazimierza Wielkiego, Bydgoszcz, Polska
Dr hab. inż. Marek Macko prof. nadzw. (mackomar@ukw.edu.pl), <https://orcid.org/0000-0002-8743-6602> – Instytut Mechaniki i Informatyki Stosowanej, Uniwersytet Kazimierza Wielkiego, Bydgoszcz, Polska
Dr hab. inż. Izabela Rojek prof. nadzw. (izarojek@ukw.edu.pl), <https://orcid.org/0000-0002-9958-6579> – Instytut Mechaniki i Informatyki Stosowanej, Uniwersytet Kazimierza Wielkiego, Bydgoszcz, Polska

The own study on hand exoskeleton is presented. It is described from mechanical point of view: starting from constraints caused by healthy human biomechanics, through possible functional deficits and their compensation by exoskeleton's biomechanics, up to material and technological limitations. There is described an application of the reverse engineering aiming at personalization of the mechanical features taking into consideration huge individualization of the hand mechanics, including pathological changes.

KEYWORDS: *assistive technology, exoskeleton, mechanics of movement, material features, hand-device cooperation, motor functions*

Introduction

Mechanical exoskeleton (outer skeleton) is a device placed on the body or part of the body, supporting the user's movement in a passive way (by partially relieving and supporting the movement with the help of rubbers, springs) or in an active way (using servomechanisms, hydraulic or pneumatic cylinders, etc.).

Attempts to construct the exoskeleton have been made for a long time - the solutions of Nikolai Yagna from the late nineteenth century are known, or the Hardiman industrial exoskeleton developed at General Electric in the 1960s (brought to the state of the prototype of the upper limb element). Dynamic development of this concept began at the turn of the 20th and 21st centuries along with projects financed by the US Defense Advanced Research Projects Agency (DARPA), aimed at developing an exoskeleton for the needs of national security and defense, and the development of medical exoskeletons [1-4].

One of the biggest challenges is to develop a functional hand-held exoskeleton - one of the most precise and versatile tools available to man - supporting primarily fingers and their manipulation capabilities. Deficits in this area reduce the quality of life related to health and are the subject of research in the fields of rehabilitation and physiotherapy as well as biomechanics [4-6]. Key requirements include:

- support for all grips: hook, cylindrical, pliers, three-point, double-sided and two-handed [3, 8],
- maintaining a four-point grip consisting in embracing the object with three fingers with simultaneous support on the inner surface of the hand [9],
- maintaining normal reflexes.
- From a mechanical point of view, the proposed solution must:
- take into account natural human motility, including dimensions of individual moving elements, angles, 18 degrees of freedom (DOF) for a five-fingered hand, including 3-4 degrees of freedom for each finger,

- provide finger speeds up to 0.2 m/s and acceleration up to 2 m/s² [10],
- ensure adequate mobility of the thumb, separate from the mobility of the other fingers,
- take into account the assumption of using experiments with a description of the kinematic chain of a hand, assuming that the individual elements of this chain are rigid and non-deformable,
- provide trajectories of motion consistent with the trajectories of real objects,
- enable control of individual fingers and their spatial-temporal cooperation,
- have as few controlled drives as possible [9, 10].

In the area of upper limb prostheses for children older than 3 years with the wrist and/or elbow preserved, the social e-NABLE movement is active. It is a group of volunteers, who design and manufacture prostheses (not medical devices) using 3D printing [11].

Own solution

During development of the exoskeleton on hand, own experience from work on the passive exoskeleton for children with weakness in the area of the upper limbs, printed with 3D technique, and over the element supporting the functioning of the elbow, was used [11]. In addition, modern technologies were used to optimize and personalize the structure of the exoskeleton: a station for analyzing the human motion system, 3D scanning, numerical analysis and 3D printing. This contributed to shortening the time of capturing the characteristic features of the upper limb and translating them into the language of mechanics, and then implementing them in the characteristics of a personalized exoskeleton without the use of physical castings or forms, and only using digital models.

Fig. 1. Stop-motion analysis of hand position

During designing, the following were supported:

- ProEngineer system to design the mechanical part,
- the ADAMS program for initial assessment by computer simulation methods to assess the correctness of assumptions and basic characteristics and optimize them in accordance with the assumed criteria, including solving the simple/inverse task of kinematics/dynamics crucial for the proper functioning of the exoskeleton at various types and levels of user deficits.

For the analysis of hand movement, a stand was developed not only for 3D scanning, but also for taking the time-lapse photos needed to calculate the mutual position and speed of individual hand elements (fig. 1). The analysis used proprietary software.

In order to reduce weight of the solution, the integration of mechanical and electronic components (drive, transmission systems, sensors, etc.) was assumed in the design. Work on the mechanical component included:

- estimation of loads: mass of manipulated objects up to 500 g, largest dimension of these objects: up to 100 mm,
- selection of mechanism type and structure,
- selection of geometrical parameters (fig. 2).

Fig. 2. Phalanx motion analysis (example)

For each phalanx, an element was developed to support its movement and interact with elements on other phalanges of the same finger in a way that ensures physiological, individual for each patient, bending angles and implementation of the entire finger bending sequence (including as part of the complex movement of all fingers): gradually from the tip of the finger to the phalanx nearest to the wrist. Design of the finger parts allows the distance between the fingers to be manipulated independently. This also contributes to a favorable reduction in the number of drives.

Two technologies of plastic printing were used to manufacture the mentioned elements: fused material deposition (FDM) and high accuracy stereolithography (SLA). The prototype used ready-made metal elements (mainly connecting elements). Ultimately, they will be printed from reactive metals (aluminum, titanium) in the technology of laser sintering of metallic powders (DMLS) to reduce the weight of the exoskeleton, while maintaining strength parameters (fig. 3). Combining these technologies was necessary, because various elements of the exoskeleton were to meet specific requirements (regarding: accuracy of execution, perfect fit to the shape of the upper limb, strength of elements, minimum weight, etc.).

Fig. 3. Printed element on the index finger

The inner part of the hand remained exposed, as it houses the main sensory centers enabling the use of preserved receptors on the basis of a two-point discrimination test carried out during the qualification for the exoskeleton. For this reason, it was possible to dispense with the installation of additional touch sensors and pressure measurement.

Servo mechanisms with the required momentum were chosen as the support sources, while the elements transferring this momentum to the phalanges are independent, unstretched lines in the closed loop, ensuring the sequential movement of all phalanges in the right order - their shortening causes the fingers to bend at the right angle. The return movement of fingers is carried out due to the interaction of these elements with elastic elements. The described drive is an alternative to the drive transmission by pushers or rods with additional flexible coupling systems increasing the degree of anthropomorphism.

Due to the current requirements of servos (up to 1 A of continuous current and 2 A of instantaneous current in total) and the need to protect the control system (in the prototype version based on the Arduino platform), when testing the prototype, one must use a laboratory power supply with a power resistor connected low resistance (as a shunt) to measure the voltage drop on it, on this basis calculating the current and disconnecting the servos at the control level if the current exceeds the set value. Tests with a battery of similar current capacity are also planned.

Adjusting procedure

The procedure for adjusting the exoskeleton for the hand includes:

- physical examination along with determining the degree of deficit, anatomical defects, functional deficiencies, method and scope of support,
- 3D scanning (Artec LEO and Artec EVA hand scanners) of healthy hand and the patient's hand during daily activities,
- scan analysis determining specific construction points of the hand exoskeleton,
- adaptation of the exoskeleton template to the functional needs of a particular user,
- 3D printing (Gaja 3D Multitool printer),
- tryouts, adjusting and exoskeleton tuning,
- training of the user and his family,
- trial operation,
- daily use of hand-held exoskeleton with the help of a user support system.

Acquiring proficiency by the user requires going through the functional training procedure combined with tuning the exoskeleton mechanism. Providing an exoskeleton may involve one hand or both, but their functional deficits and level of support do not have to be the same. Functional fitness of the hand changes during self-healing and recovery stimulated by rehabilitation.

Two cases:

- temporary use of the exoskeleton for the hand in debilitated patients,
- the use of exoskeleton by children acquiring only functional skills, in a way that does not collide with the child's natural motility, with the support of graphomotor and social functions - they require a separate approach, including due to the need for more frequent functional evaluation, replacement of elements, and in some cases - also higher failure rates.

Discussion

As part of research to date, many prototypes have been made using 3D printing technology, with limited functional properties, which have not undergone the full manufacturing procedure: from functional testing of the patient to use by the patient in real conditions. Burns et al. [4] developed the HEXOES exoskeleton providing the required maximum bending angles and angular velocities, respectively:

- for the metacarpal joint (MCP): 53.7 ± 16.9 degrees/s and 94.5 ± 41.9 degrees/s,
- for the interphalangeal joint (PIP): 39.9 ± 13.4 degrees/s and 74.6 ± 67.3 degrees/s [4].

Fig. 4. Selection of parameters for the exoskeleton on the hand and effects of rehabilitation [own study]

Fig. 5. Interoperability of ready-made exoskeleton elements supporting finger movement

The exoskeleton on the hand examined by Kim et al. [5] allowed for functional support of finger bending, including independently, and synergy of finger movements in the implementation of grips with joint support in healthy persons. A similar solution was presented by Zhang et al. [6].

Quasi-objective (i.e. using the FMA clinimetric scale) assessment of the effects of using the hand exoskeleton in the rehabilitation of patients with deficit in the area of upper limb function was presented by Wang et al. [13]. The study of Triolo et al. showed the effectiveness of support by the hand exoskeleton of the grip function, but not the function of manipulating the fingers of the upper limb alone [8].

The study of Heo and Kim [14] showed that support of the grip function by means of an exoskeleton on the hand is not always sufficient. The very construction of the exoskeleton does not mean an increase in functional possibilities or effectiveness of rehabilitation. Key stages include:

- functional capabilities assessment (what the user actually does),
- identification and analysis of functional needs (what the patient could do and what support from the exoskeleton on the hand is required for this,
- implementation of these findings in the exoskeleton template,
- tests and corrections,
- transfer of exploitation of the exoskeleton from the controlled to the natural environment (fig. 4).

The target effect is support for rehabilitation and independent functioning of the patient in normal home conditions. It is not always possible to achieve full efficiency. Some support may need to be modified as the functional state of the patient changes.

Fig. 5 shows the interaction of exoskeleton elements supporting the movement of fingers.

There were observed some limitations of own research in the scope of:

- fitting procedures: indications and contraindications, including those defined on the basis of physical examination, checked on a large group of patients,
- execution procedures: quasi-industrial technology for scanning, modifying and printing based on prefabricated templates,
- support: support for finger movements for the needs of everyday activities (maintaining independence); the need to refine precise movements, e.g. typing on a computer keyboard,
- performance: as part of randomized clinical trials.

Directions for further research include increasing the degree of implementation readiness (TRL). In the context of the development of much broader international research, completely new solutions can be developed as part of research on the use of exoskeletons in a state of weightlessness [15].

Conclusions

Designing the mechanical structure of the exoskeleton on a hand using 3D scanning and 3D printing allows for better adaptation of ready solution to the patient's needs under the so-called personalized therapy and allows to carry out work on the development of the project in a fully digital version (as part of the software for computational design support). The construction process is effective and can be a template for further solutions in exoskeleton technology.

REFERENCES

- [1] Mikołajewska E., Mikołajewski D. "Exoskeletons in neurological diseases – current and potential future applications". *Advances in Clinical and Experimental Medicine*. 20, 2 (2011): 227–233.
- [2] Mikołajewska E., Mikołajewski D. „Zastosowania automatyki i robotyki w wózkach dla niepełnosprawnych i egzoszkieletach medycznych”. *Pomiary Automatyka Robotyka*. 5 (2011): 58–64.
- [3] Mikołajewska E. „Egzoszkielety”. W: Przeździecki B., Woźniowski M., Gieremek K., Janicki S. (red.). *Wyroby medyczne. Zaopatrzenie indywidualne*. Warszawa: PZWL, 2016.
- [4] Burns M.K., Van Orden K., Patel V., Vinjamuri R. „Towards a wearable hand exoskeleton with embedded synergies”. *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society 2017*. (2017): 213–216.
- [5] Kim S., Lee J., Park W., Bae J. “Quantitative evaluation of hand functions using a wearable hand exoskeleton system”. *Proceedings of the IEEE International Conference on Rehabilitation Robotics (ICORR) 2017*. (2017): 1488–1493.
- [6] Zhang F., Fu Y., Zhang Q. “Experiments and kinematics analysis of a hand rehabilitation exoskeleton with circuitous joints”. *Bio-Medical Materials and Engineering*. Supplement 1 (2015): S665–S672.
- [7] Mikołajewska E. „Terapia ręki. Diagnostyka i terapia”. Warszawa: Soyer, 2016.
- [8] Triolo E.R., Stella M.H., BuSha B.F. “A force augmenting exoskeleton for the human hand designed for pinching and grasping”. *Proceedings of the Annual International Conference of the IEEE Engineering, Medicine and Biology Society 2018*. (2018): 1875–1878.
- [9] Mianowski K. „Nowe rozwiązanie chwytaka wielopalcowego z podatnością do obsługi specjalnych procesów manipulacji”. *Pomiary Automatyka Robotyka*. 2 (2010): 519–526.
- [10] John A., Musiolik A. „Analiza kinematyczna palców ręki”. *Modelowanie Inżynierskie*. 40 (2010): 111–116.
- [11] <http://e-nable.pl> (access: 22.03.2019 r.).
- [12] Mikołajczyk T., Kłodowski A., Mikołajewska E., Walkowiak P., Berjano P., Villafane J.H., Aggogeri F., Borboni A., Fausti D., Petrogalli G. “Design and control of system for elbow rehabilitation: preliminary findings”. *Advances in Clinical and Experimental Medicine*. 27, 12 (2018): 1661–1669.
- [13] Wang D., Meng Q., Meng Q., Li X., Yu H. “Design and development of a portable exoskeleton for hand rehabilitation”. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 26, 12 (2018): 2376–2386.
- [14] Heo P., Kim J. „Power-assistive finger exoskeleton with a palmar opening at the fingerpad”. *IEEE Transactions on Biomedical Engineering*. 61, 11 (2014): 2688–2697.
- [15] Villoslada Á., Rivera C., Escudero N., Martín F., Blanco D., Moreno L. “Hand exo-muscular system for assisting astronauts during extravehicular activities”. *Soft Robotics*. (2018): DOI: 10.1089/soro.2018.0020.