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Hand Exoskeleton—Development of Own Concept

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Featured Application: Potential applications of the work include research and implementation work on 3D-printed exoskeletons, especially for the upper limb.

Abstract: The article addresses the development of an innovative mechanical and information technology (IT) solution in the form of a three-dimensional (3D) printed hand exoskeleton, enabling the rehabilitation of people with special needs (with the participation of physiotherapists). The design challenges and their solutions are presented in the example of the own design of a prototype mechanical rehabilitation robot (a hand exoskeleton) to support the rehabilitation process of people with a lack of mobility in the hand area (both as a result of disease and injury). The aim of this paper is to develop the author's concept for a hand exoskeleton developed within an interdisciplinary team during the design work to date. The problem solved in the study was to develop a five-finger 3D-printed hand exoskeleton providing physiological ranges of movement and finger strength support at a level at least half that of healthy fingers, as well as taking it to the clinical trial phase. The novelty is not only an interdisciplinary approach but also focuses on developing not only prototypes but a solution ready for implementation in the market and clinical practice. The contribution includes the strong scientific and technical, social, and economic impact of the exoskeleton on the hand due to the fact that any deficit in hand function is strongly felt by the patient, and any effective way to improve it is expected in the market. The concept of the hand exoskeleton presented in the article combines a number of design and simulation approaches, experimentally verified mechanical solutions (a proposed artificial muscle, 3D printing techniques and materials, and possibly other types of effectors supported by sensors), and IT (new control algorithms), along with the verification of assumptions with a group of medical specialists, including in laboratory and clinical settings. The proposed specification of the hand exoskeleton offers personalised dimensions (adapted to the dimensions of the user's hand, as well as the type and level of hand function deficit), weight (approximately 100–150 g, depending on the dimensions), personalised actuators (described above), all degrees of freedom of the healthy hand (in the absence of defects), and the time to close and open the hand of approximately 3–5 s, depending on the level and degree of deficit.

Keywords: exoskeleton; 3D printing; computer-aided design; hand; biomechanics; rehabilitation

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1. Introduction

The high scientific, clinical, economic, and social importance of researching, designing, and manufacturing a human-personalised hand exoskeleton (i.e., an upper limb from the wrist to the fingertips of all five fingers) suitable for mass production and widespread use, preferably within the Industry 4.0 and eHealth paradigms, has challenged researchers, clinicians, and engineers for many years. The existing research gap is due in part to the complexity of the manipulative functions (basic grasping with one hand and both hands), ensuring their high precision and adequate quality of movement, including, in the case of the deficits of both hands and often with different aetiologies and symptoms, as well as technical problems related to the power of assistance, a large number of degrees of freedom, with a limited exoskeleton size and the need for near real-time control. The research in this area concerns both physiological movement (of the healthy hand) and hand(s) with deficits of various types and degrees. It is important to take into account the diversity of sources of the above-mentioned hand function deficits, from the motor (in the area of the musculoskeletal system) to the deficits in the area of the motor control system of neurological (strokes, traumatic brain injuries, etc.) or neurodegenerative (in the ageing process) origin, in the area of sensation and motor control and coordination. The large number of the aforementioned hand deficits in the populations of developed countries is due to the halting, but not reversal, of the epidemic of diseases of civilisation (cardiovascular diseases or strokes), which, along with traffic accidents, are the main causes of motor deficits, including in the area of the hand. In turn, a significant share of neurodegenerative deficits is due to the ageing of the populations of developed countries. These deficits result in reduced independence, including in activities of daily living requiring the use of one or both hands, such as washing, combing hair, dressing, preparing and eating meals, etc., but also in learning and working, including at the computer [1–4]. Supporting people with hand deficits with an appropriately designed exoskeleton can accelerate their recovery, reduce the need for support from medical professionals, provide remote therapy and care, and ultimately provide controlled independence.

The current rehabilitation model has been in development for about 110 years, and the neurological rehabilitation model is the work of the last 80 years. Research into their development, including improved efficacy in patients with hand deficits, is also accelerating due to technological advances in the areas of diagnosis, therapy, and care. The recent decades of advances in clinical practice in rehabilitation and physiotherapy have increasingly included technological innovations based on neurophysiological knowledge of normal biomechanics and motor control and pathological (disturbed) biomechanics and motor control. New areas of research have emerged: 3D-printed personalised prostheses and orthoses, rehabilitation robots, exoskeletons, brain–computer interfaces and neuroprosthetics, computational models (virtual patients and the digital twins of their systems and organs) in medicine [5–7], artificially intelligent systems to support diagnosticians and therapists, and predictive health statuses in preventive medicine, are resulting in the spread of personalised therapy and precision medicine [8–11] and increasing the effectiveness of preventive and therapeutic interventions. In addition, they are enabling the development and implementation of new therapeutic methodologies (robot-assisted therapy and virtual reality-based therapy) and technological synergies between existing solutions and novel approaches yet to be developed [12].

The problem to solve in our study was to develop a five-finger 3D-printed hand exoskeleton providing physiological ranges of movement and finger strength support at a level at least half that of healthy fingers, as well as to take it to the clinical trial phase.

The aim of this paper is to develop the author's concept for a hand exoskeleton developed within an interdisciplinary team during the design work to date.

2. State-of-the-Art in the Area of Hand Exoskeletons

A review of five leading bibliographic databases using specific keywords ("hand exoskeleton" + "medical application" and similar, and their combinations in English) yielded 111 publications published in the years 1997–2023, of which 68 (61.26%) appeared in the last 5 years and 97 (87.39%) in the last 10 years. Most of the results (56 publications, i.e., 50.45%) were publications on the use of a hand exoskeleton in a group of patients after a stroke. The review shows that the problem of constructing, testing, and using medical hand exoskeletons is a novel problem. In addition, it was observed that despite the efforts put forth (over 100 scientific papers), not one of the solutions studied so far has gone into mass production. Among the publications covered by the review, there is only one review paper and no meta-analyses, which would allow at least a partial reference to the current state of research.

The analysis of the publication showed that all the observed research in the field of five-finger exoskeletons of the hand (so-called all-grip) ended in the early stages of the prototype (technology readiness level [TRL] <7). It is worth determining in subsequent studies whether this resulted from difficulties in solving technological problems or rather the expected high barrier to entry into the market and unprofitability of implementation (e.g., due to the requirements of the Medical Device Regulation [MDR] and ISO 13485). Currently, in the medical technology market and in clinical practice, we have not seen a hand exoskeleton that would be ready for commercialisation and production, even as part of personalised mass production. This is currently possible within the paradigms of Industry 4.0 and eHealth, including the use of 3D printing [13–15]. It is believed that the current state of technology in the field of 3D printing, artificial intelligence, cloud computing, biosensors, telemedicine services, the Internet of Things (IoT), and over time extended to include virtual reality (VR), augmented reality (AR), affective computing (AC) and holography [14].

The hand exoskeleton is expected to improve the results of acute therapies (e.g., in the process of recovery) or long-term deficits of hand motor functions. In this area, the proposed hand exoskeletons are non-invasive human–machine interfaces adapted not only to specific user populations (people who have had strokes, traumatic brain injuries, amputations, or with congenital defects) but also solutions that are easy to personalise. Therapeutic use of the above group of solutions 24 h a day, 7 days a week, in the user's natural environment (at home, work, etc.) in place of the existing traditional therapeutic sessions and support of movement (as part of hospital or outpatient treatment) can improve not only learning movement and generating repetitions but can also accelerate the adaptation of the exoskeleton to the user thanks to artificial intelligence algorithms combined with faster electronic systems and sets of calibrated sensors. From a clinical point of view, this approach to the therapeutic exoskeleton of the hand is crucial for improving, restoring, or replacing lost hand function and enhancing or correcting physiological movement, as well as stimulating neuroplasticity through repetitive exercises [1–4].

2.1. Impact of Medical Hand Exoskeletons on Patient Recovery

Understanding how the medical hand exoskeleton, in the process of assisted therapy, affects the neurophysiology and biomechanics of human movement is a key contribution necessary to determining the clinical requirements of exoskeletons and the indications and contraindications for their use, assessing their usefulness in various clinical cases (including the kinds and degrees of deficits), and continuous improvement and modernisation. Unfortunately, in previous studies, assisted movements were characterised by a significant decrease in accuracy and fluency compared to free movements. In addition, they were accompanied by an average reduction of torque by up to 60% and a delayed onset of muscle fatigue reflected in a decrease in muscle effort by up to 65% [12]. A 50% reduction in muscle activity, a 61% reduction in the net metabolic rate, and a 99% reduction in fatigue were observed, even with relatively little support from the exoskeleton [16]. For the reasons mentioned above, the technical limitation of hand exoskeletons is the decrease in kinematic capacity [12]. On the other hand, hand exoskeletons allow the minimisation of fatigue, maintenance of the load, and reduction of the risk of injury. The use of an exoskeleton may reduce muscle fatigue and reduce the risk of joint degeneration and pain during exercise (lifting, holding, or carrying), both in healthy and ill people [16]. Therefore, with less effort and fatigue experienced by the patient, it is possible to achieve greater and faster improvement of hand function during the implementation of the rehabilitation programme compared to traditional methods. For the reasons mentioned above, robotic rehabilitation using the hand exoskeleton accelerates the rehabilitation process, shortens the recovery time, and reduces the need for constant supervision by a therapist [17]. Therefore, it is a benefit not only for the patient himself but also for the entire healthcare system, improving efficiency.

2.2. Specificity of Hand Exoskeletons Manufactured Using 3D Printing

Parametric modelling and the production approach [18,19] ensure that the dimensions and features of the hand exoskeleton are matched to the dimensions of a given hand, the type and degree of deficit, and the individual goals of the rehabilitation process. Real-time control combined with 3D printing technology translates into a better fit of the exoskeleton to the hand while providing a methodology for the universal use of an active exoskeleton to support hand movements [17]. Moreover, 3D printing provides cheaper and faster iterations for the development of exoskeleton prototypes of consistent quality. For the reasons mentioned above, more and more 3D-printed hand exoskeletons appear in the literature and support hand function or improve the effectiveness of the rehabilitation of people after a stroke or who are affected by other causes of hand motor deficits. They are limited by the earliness of the prototype and the small number of users tested (less than 10). In such a situation, the effectiveness of the hand exoskeleton may be jeopardised by a non-optimal combination of printing parameters and material properties or by the lack of refinement in the methodology of selecting the exoskeleton for the patient's needs and therapeutic goals. The 3D-printed soft exoskeleton of the hand HEXOES (hand exoskeleton with embedded synergies) has ensured maximum flexion angles in the metacarpophalangeal and proximal interphalangeal joints and the maximum angular velocity [20]. In a study by Dudley et al., a 3D-printed hand exoskeleton improved Fugl–Meyer and Box and Block tests, and increased electromyographic (EMG) activation of the extensor muscles was observed while wearing the exoskeleton. The 3D printing design uses new antibacterial polymers that can prevent skin infections during rehabilitation [21]. Yoo et al. designed a 3D-printed hand exoskeleton controlled by EMG signals to aid the gripping function in patients with cervical spinal cord injury (including quadriplegia). The subjects' hand function improved, as reflected in the Toronto Rehabilitation Institute Hand Function Test (TRI-HFT); the participants gained immediate functionality when eating after wearing the braces, and most participants were satisfied with the exoskeleton, indicating that it is intuitive and easy to use. No side effects of using the exoskeleton were observed [22]. The computational optimisation of the 3D printing process, as regards the characteristics and selection of the material in terms of the maximum tensile strength of the hand exoskeleton element, can be implemented based on the optimisation of the artificial neural network (ANN) supported by genetic algorithms (GAs) [23]. This can play a key role in personalising and enhancing the performance and safety of a medical device, such as the hand exoskeleton, and meeting the limitations of patient-specific solutions [23].In order to increase the effectiveness of the rehabilitation process, it is possible to combine the tactile stimulation of the fingertips with hand rehabilitation supported by an exoskeleton. An exercise with a glass handle (150 g, 300 g) showed a higher level of attention and involvement of users with additional tactile stimulation compared to the use of an exoskeleton alone, as well as with a greater weight of the glass [24]. The rehabilitative hand exoskeleton (HERO) combines 3D printing (including actuators) and textiles, as well as electroencephalographic (EEG) signal control, to recover finger extension and flexion movements. The torque of the DC motors has been converted into a linear force transmitted by the Bowden tendons for passive finger movement. With an exoskeleton weight of approx. 100 g, the participant was able to control the exoskeleton with a classification accuracy of 91.5% [25]. Hand exoskeletons support up to ten activities of daily living, with a significant reduction in muscle activity (i.e., by 12–32%) and without significant degradation of the functions of other healthy agonist muscles [26].

3. Own Hand Exoskeleton

In accordance with the above research directions, the Faculty of Computer Science, and the Faculty of Mechatronics of Kazimierz Wielki University in Bydgoszcz, together with EduRewolucje Ltd. from Bydgoszcz, are implementing a project called the "Development of a functional hand exoskeleton for active training and rehabilitation" as part of the nationwide "Things are for people" competition of the National Centre for Research and Development. The aforementioned project includes research and development work aimed at developing an innovative mechanical and IT technological solution in the form of a 3D-printed hand exoskeleton, enabling the rehabilitation of people with special needs (with the participation of physiotherapists). Work on the exoskeleton includes not only the design and manufacturing of its mechanical and IT parts but also clinical trials and resulting improvements to the exoskeleton and implementation. The prototypes of a mechanical rehabilitation robot (the hand exoskeleton) developed as part of the project will support the rehabilitation process of people with a lack of mobility in the hand area (both as a result of illness and injury). Dedicated software, developed as part of the project, will adjust the strength and type of movement of the exoskeleton of the hand to the type of deficit and the current needs and goals of the patient's rehabilitation programme and over time, his daily activities. In particular, we wanted to emphasise that our hand exoskeleton is five-fingered, which is not a rule. The novelty is not only an interdisciplinary approach but also focuses on developing not only prototypes but a solution ready for implementation in the market and clinical practice. The own contribution includes the strong scientific, technical, social, and economic impacts of the exoskeleton on the hand due to the fact that any deficit in hand function is strongly felt by the patient, and any effective way to improve it is expected in the market.

3.1. Design

According to the requirements, the hand exoskeleton that we designed should provide the ability to conduct rehabilitation and perform complex daily activities to people with motor deficits in the hand (from the wrist to the fingertips) of various aetiologies and limited exercise capacity in the recovery process. In terms of the control system, it should, by means of the sensors, capture and recognise in the controller the user's movement intention and support the movement thus recognised.

The entire internal and external geometry was developed based on computer models verified by 3D printing from a flexible material. The design solution is an evolutionary solution and is the result of work using the feedback technique used to improve the subsequent prototypes of the proposed solution. The presented solution is protected by the patent application P.442697: Artificial muscle of a rehabilitation glove [WIPO ST 10/C PL442697].

Our goal was to develop a type of artificial muscle that contains segments containing capacious pressure chambers while controlling the artificial muscle through the actuator of the muscle's cable.

Based on the physiological structure of the human hand, we proposed a hand exoskeleton of an adjustable size, driven by both pneumatic-like artificial muscles and tendons (in straightening and flexion movements) having all degrees of freedom, which ensured a high level of synergy with the human hand. A special feature of the hand exoskeleton is the artificial muscle of the rehabilitation glove produced by 3D printing, which features a uniform body design. The rehabilitation gloves here have a structure of separated artificial muscles attached to the fingers. They are made of flexible polymeric materials, which ensure a snug fit, keep the hand in place, gently stretch the phalanges, and prevent contractures. The proposed solution of the artificial muscle in the rehabilitation gloves has a monolithic structure, containing flexible segments whose form is changed using compressed air and a mechanical linkage. The use of two types of mechanical excitation (cable and pneumatic) enables better control of the movements of the monolithic body muscle. This allows for better possibilities as regards simulating rehabilitation procedures.

The artificial muscle of the rehabilitation glove supporting the work of the finger consists of a flexible body containing an opening for the connection of the pneumatic system and a transverse attachment to the glove cap of the wrists or to the ergonomic hand pad. The body is a monolithic element made with the 3D technique and has segments that contain pressure chambers inside them, connected at the base with an air duct and separated by a space in the upper parts. In the upper part of these segments, there is an opening for a cable, which is attached to the end segment of the artificial muscle and on the other side to the actuator. In the remaining openings of the upper segments, the cable moves freely. The air duct can optionally be separated by a longitudinal bar connected to the vertical walls of the segments. Preferably, the upper parts of the segments contain solid protrusions in which there is an opening. Teflon sleeves can be placed in the holes to facilitate the movement of the cable and protect the elastomeric segments against damage.

Figures 1 and 2 show the single element of the artificial muscle.

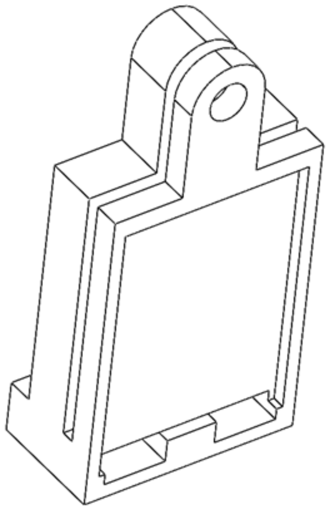


Figure 1. Part of the artificial muscle—external view.

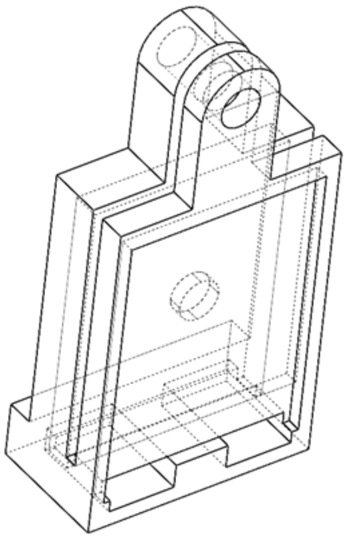


Figure 2. Part of the artificial muscle—internal view.

Figure 3 shows the final version of the artificial muscle.

The principle of operation of the above artificial muscle (the actuator) is illustrated in Figure 4. The bending force of an artificial muscle is caused by the interaction of the segments, which increase in size under pressure. The force between the two adjacent segments (F) is proportional to the product of the pressure (p) and the contact area (S).

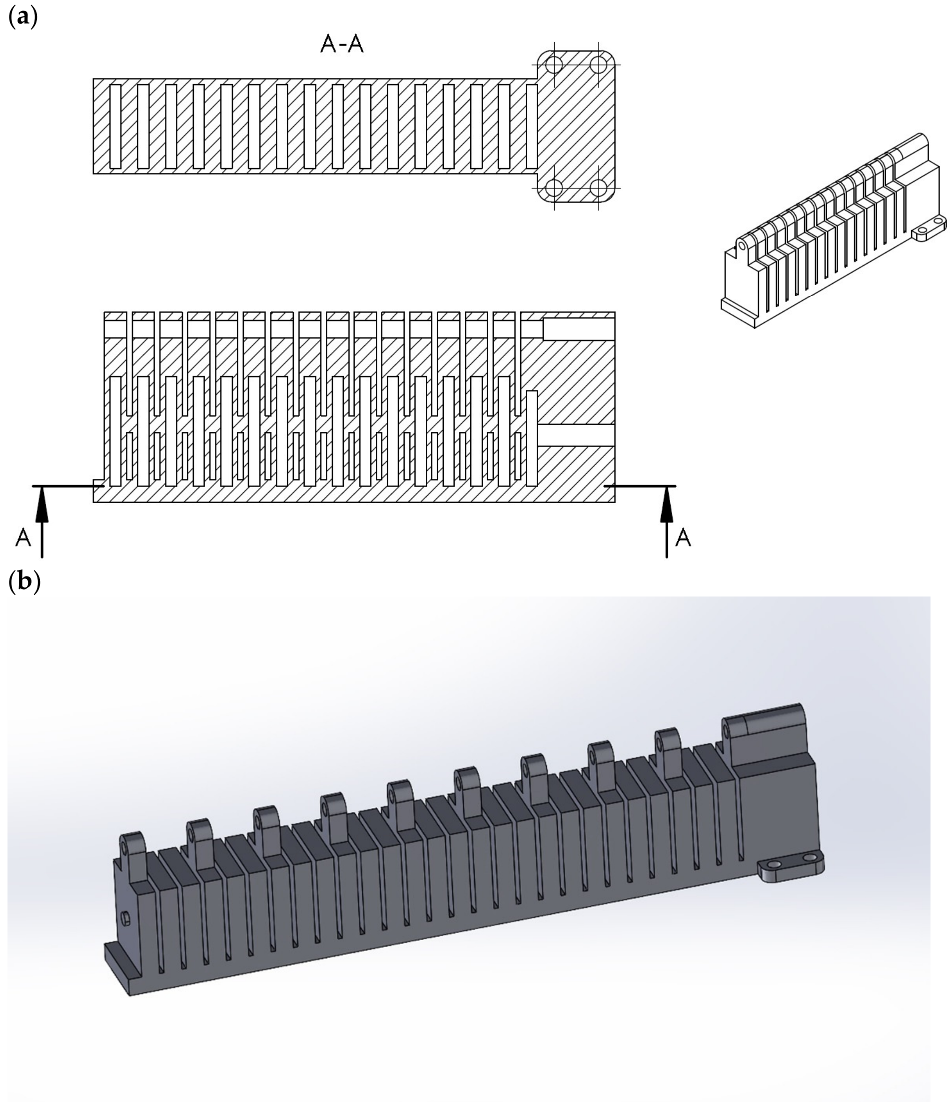


Figure 3. Final geometry of the artificial muscle: (**a**) a 2D perspective view of the muscle and (**b**) a 3D overview drawing, A—cross-section.

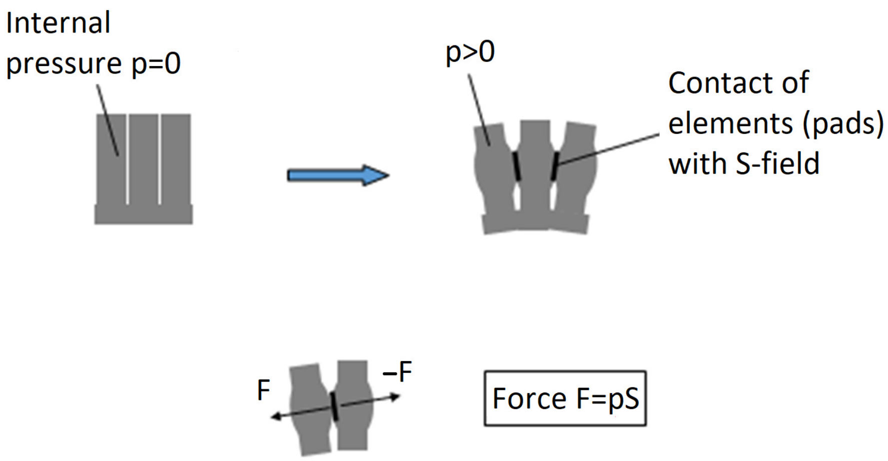


Figure 4. Illustration of the action of pressure in an artificial muscle.

Individual artificial muscles are assembled by rings on the fingers and through the transverse tabs to the cap of the wrist glove or to the ergonomic overlay on the palm. The increase in pressure in the pressure chambers occurs due to the opening of the conduit with compressed air dosed through the hole; in this situation, the muscle bends inwards. The proposed geometry of the muscle body (the initial flexion in the neutral position) improves the stable work along the finger in accordance with the degrees of freedom and eliminates the twisting and lateral bending of this muscle, which is crucial in proper rehabilitation (Figure 5).

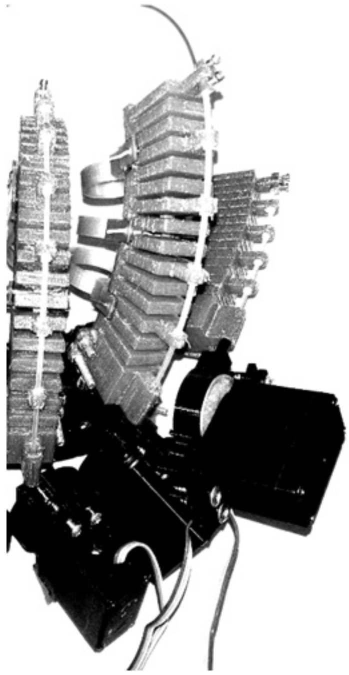


Figure 5. Parts of the exoskeleton.

Mechanical and electronic components (the sensors, control, and drive system) and software (for analysis and the control) can be adapted and manufactured in parallel due to different technologies and put together in the last phase of production.

3.2. Features

At least two modes of rehabilitation and support for the activities of daily living will be tested in the clinical trials: therapist-led and user-led. This is to develop an optimal fit to the specific individual needs of the user and to shorten the time of fitting and arming the exoskeleton for a new specific user.

The weight of the hand exoskeleton was minimised through the selection of structural and material properties, which reduces the burden on the users. The material selection and strength tests of the exoskeleton elements have been focused on ensuring the safety of the users and therapists. The entire muscle structure was made of thermoplastic elastomeric material in the form of a filament for the fused deposition modelling (FDM) printing with a hardness of 32 Shore. The artificial muscle allows the finger to be bent by more than 90 degrees and allows torsion plates to be attached to it, which are fixed at the base of the finger, enabling lateral movement of the finger (this has a positive effect on the rehabilitation process). The material is a biodegradable elastomer with a Shore D hardness of 32. It has a characteristic property: when it exceeds its elastic limit during stretching, it stops returning to its original shape but can stretch to 500% of its original dimension. Due to the elasticity of the BioFlex filament, it is recommended that it is used on machines with a direct filament feed over the head (the so-called Direct); we also used an indirect filament feed, the so-called Bowden.

Material used:

- Product type: BioFlex F3DFilament;
- Diameter: 1.75 mm (±0.03 mm);
- Net weight: 1 kg (±2%);
- Printing temperature: 200 °C to 225 °C;
- Nozzle type: steel, in sizes from 0.4 mm to 0.8 mm;
- Worktable: Glass/PC/COROPad;
- Table temperature: 60–80 °C;
- Closed chamber: no;
- Adhesive agent: StickIt;
- Retraction: no;
- Print cooling: maximum 80%.
- Example print parameters for Original Prusai3 MK3S+, 0.4 mm nozzle:
- Nozzle temperature: 230 °C;
- Table temperature: 50 °C;
- Retraction: 0.8 mm; 35 mm/s.;
- Print cooling: max. 50%.

To ensure the safety of the exoskeleton, bending, shear and torsion tests were performed on its components. It is important to note that not every component of the exoskeleton is subjected to the same loads and contact with the user's tissue; hence, ultimately, the strength and biocompatibility requirements of different components of the exoskeleton will vary. The exact values will be determined at the conclusion of the study, planned for September 2023.

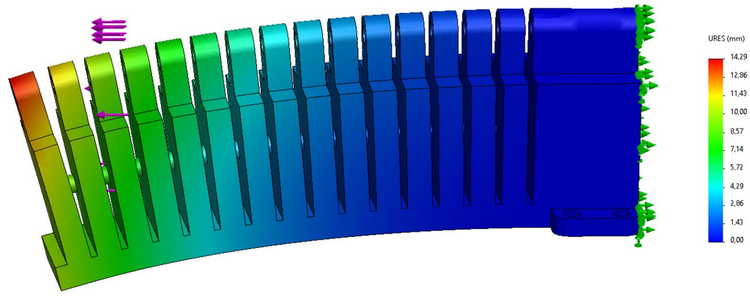
The specification of the hand exoskeleton is bound to take into account its dimensions (adapted to the dimensions of the user's hand, as well as the type and level of hand function deficit), weight (approximately 100–150 g depending on the dimensions), actuators (described above), all degrees of freedom of the healthy hand (in the absence of defects), the time to close and open the hand (approximately 3–5 s, depending on the level and degree of deficit), and energy output (yet to be tested).

Strength simulations were carried out to assess the stress and displacement range for a single component. The SolidWorks Simulation module was used for the tests. The tests were conducted for three load values: 100N, 200N, and 300N for the BioFlex F3DFilament material. Static analyses were performed to obtain a range of values for three parameters: the equivalent strain, total strain energy, and strain energy density. The correlations are shown below.

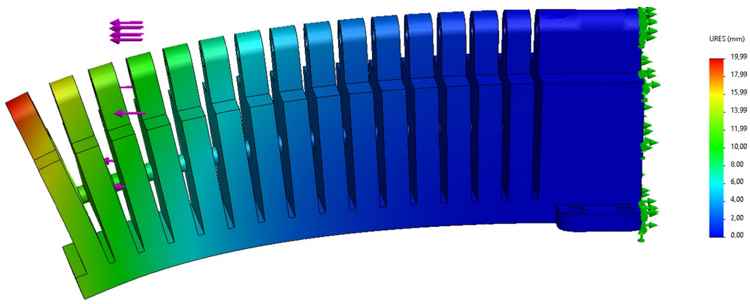
Equivalent strain (ESTRN) $ESTRN = 2\,[(\varepsilon 1 + \varepsilon 2)/3]^{(1/2)}$
where:
$\varepsilon 1 = 0.5\,[(EPSX - \varepsilon^*)^2 + (EPSY - \varepsilon^*)^2 + (EPSZ - \varepsilon^*)^2]$
$\varepsilon 2 = [(GMXY)^2 + (GMXZ)^2 + (GMYZ)^2]/4$
$\varepsilon^* = (EPSX + EPSY + EPSZ)/3$
Total Strain Energy = $\sum$ [(SX * EPSX + SY * EPSY + SZ * EPSZ + TXY * GMXY + TXZ * GMXZ + TYZ * GMYZ) * Vol(i) * W(i)/2] for I =1, N int
N int are the integration points (or Gaussian points),
W(i) is the weighted constant at the integration point, i,
and
(SX = X normal stress, SY = Y normal stress, SZ = Z normal stress, TXY = Shear in the Y direction on the YZ plane, TXZ = Shear in the Z direction on the YZ plane, and TYZ = Shear in the Z direction on the XZ plane);
Strain energy density = Total Strain Energy/Volume where Volume = $\sum$ [Vol(i) * W(i)], i = 1, N int.

Figure 6 presents the results of the strength simulations in terms of the deformations that resulted from the 100 N (a), 200 N (b), and 300 N (c) forces.

(**a**)



(**b**)



c)

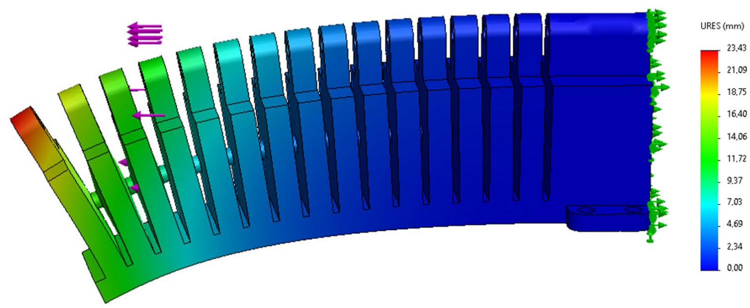


Figure 6. Results of simulation—strength tests. Range of deformation of the muscle body model under force: (**a**) 100 N, (**b**) 200 N, and (**c**) 300 N.

Figure 7 presents the results of the strength simulations in terms of the stresses that resulted from the 100 N (**a**), 200 N (**b**), and 300 N (**c**) forces.

Analyses of the range of deformation and stress values provided the basis for adopting the geometric and material parameters that meet the expectations of the project's authors.

(**a**)

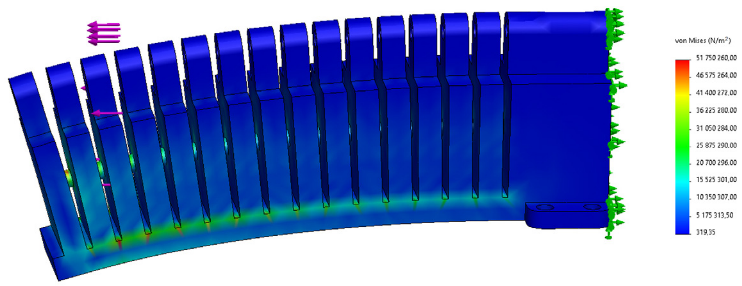
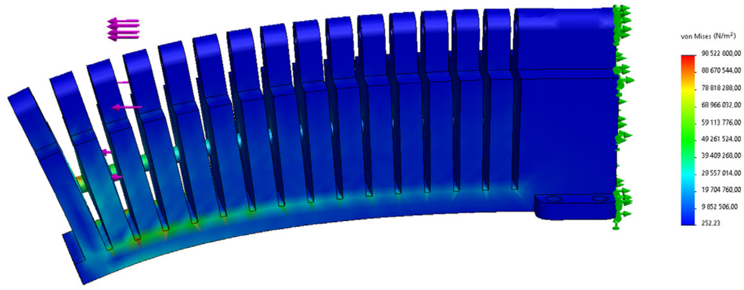


Figure 7. *Cont.*

(**b**)



(**c**)

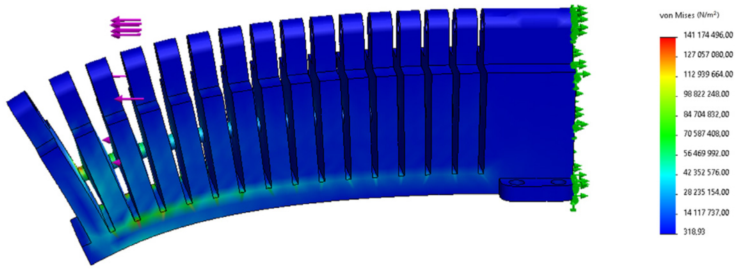


Figure 7. Results of simulation—strength tests. Distribution and stress range of the muscle body model under the following forces: (**a**) 100 N, (**b**) 200 N, and (**c**) 300 N.

3.3. Testing

Further tests were carried out as part of the tests close to the operational conditions in order to take into account the opinions of the end users, including the diagnosticians and therapists. The project will not only enable the development, testing, and implementation of an innovative rehabilitation device (the hand exoskeleton) but will also allow for the introduction of an innovative model of automated rehabilitation and even independent daily home rehabilitation for people with special needs in the field of hand therapy and monitoring of the long-term changes related to it (e.g., the maintenance of the functional effects of therapy). The development of our solution will contribute to increasing the availability of hand exoskeletons, optimising production and operating costs, introducing a quick way to adjust and modernise (e.g., as the user's health changes), enabling life-cycle analysis under the Industry 4.0 paradigm, and improving the accessibility and ease of everyday use and often burdensome rehabilitation (e.g., requiring commuting daily). In this way, the hand exoskeleton developed by us fills the existing research and clinical gap in the group of hand-worn robots, supporting diagnostics, therapy, and care. Its novelty also lies in the development of a series of detailed mechanical engineering and computer science technical solutions to create a functional hand exoskeleton.

4. Discussion

Previous research indicates that hand exoskeletons can help users with hand function deficits in therapy and care (including monitoring changes in health), supporting them in everyday activities and improving the efficiency of the rehabilitation process. Over the last 20 years, exoskeletons, especially those printed in 3D, have developed significantly as a group of products. This is due to their high adaptability (including in the process of therapy and home care), ease of control (including intuitive), low weight, safety, and ergonomics. However, the popularisation of 3D-printed hand exoskeletons still requires a lot of effort from all sides of the therapeutic process: families, their patients, and clinicians, but also the constructors and manufacturers of hand exoskeletons.

4.1. Limitations to the Development of Hand Exoskeletons

The observed technological limitations in the area of hand exoskeletons are partly the typical childhood problems of each piece of technology. It seems that these can be overcome with the development of mechanical engineering and computer science towards more specialised exoskeleton technologies. In addition, significant limitations in the development of arm exoskeletons still result from a low acceptance of this group of devices by patients, their families, and clinicians. This requires not only further raising social awareness in the field of medical robotics, but also promoting interdisciplinary cooperation in teams of scientists, engineers, and clinicians. There is also a not entirely justified perception of the high cost of this type of equipment; we are trying to change this by developing devices better suited to the markets of low-income countries without compromising product quality. It should also be noted that exoskeletons are considered to be high-tech, so it is difficult to expect a significant reduction in their price without their mass production [27].

4.2. Development Directions for Hand Exoskeletons

The directions of the development of hand exoskeletons run in several interdependent areas: scientific, clinical, social, and economic. The global challenge is not only the diseases of civilisation causing hand function deficits but also the increasing life expectancy, resulting in neurodegenerative changes and, consequently, another group of hand dysfunctions [28,29].

There is no doubt that both in developed and developing countries, physical activity decreases with age, which translates into a decrease in the ability to undertake everyday activities, which in turn results in the deterioration of physical and mental health, lower quality of life, and lack of independence. In this field, the potential of hand exoskeletons is very large: there are about one billion people over the age of 60 in the world. The shortage of doctors and caregivers makes the automation of monitoring, diagnosing, rehabilitating, and robotic care a necessity. For this purpose, artificial intelligence methods are increasingly used (mainly machine learning and deep learning for recognising, classifying, inferring, and predicting human activity). For this purpose, gyroscopic and accelerometer data collected from users 'smartphones are used. In a study by Hayat et al. [30], smartphones were used to monitor the activities of people with disabilities using artificial intelligence methods (e.g., the nearest neighbours, random forest, support vector machine, and short-term memory network). Long short-term memory (a recursive variant of artificial neural networks for the analysis of time sequences) achieved the best accuracy (above 95%), and the support vector machine gave a high accuracy of over 89% with a short calculation time (approx. 25 s) [31]. Training with the hand exoskeleton yields not only improved motor performance but also cortical excitability in post-stroke patients as a consequence of plastic reorganisation stimulated by the use of the upper limb [32–34]. The effectiveness of combining robotic therapy with analysis based on artificial intelligence has been confirmed in subsequent studies [35–38]. It should be noted that even in people with deficits in one hand (e.g., unilateral hemiparesis), the bilateral training of both hands is necessary to restore the hands to the cooperative functions needed for independent performance of the activities of daily living [39,40]. Further research directions set by global development trends are Industry 4.0 [41], eco-design and sustainable development [42], and associated material research [43]. The outstanding issues in the area today and the scope of the next key developments need to be further explored and discussed [29,44–46].

5. Conclusions

The concept of the hand exoskeleton presented in the article combines a number of design and simulation approaches, experimentally verified mechanical solutions (a proposed artificial muscle, 3D printing techniques and materials, and possibly other types of effectors supported by sensors), and IT (new control algorithms), along with the verification of assumptions with a group of medical specialists, including in laboratory and clinical settings. The proposed specification of the hand exoskeleton offers personalised dimensions (adapted to the dimensions of the user's hand, as well as the type and level of hand function deficit), weight (approximately 100–150 g, depending on dimensions), personalised actuators (described above), all degrees of freedom of the healthy hand (in the absence of defects), and the time to close and open the hand of approximately 3–5 s, depending on the level and degree of deficit. The above holistic approach allows for the identification and refinement of a single, state-of-the-art solution that best meets a range of technical and operational requirements, facilitating its future production and implementation in clinical practice. Here, 3D printing technologies allow not only improved personalisation of the final medical device but also the acceleration of the design and fitting processes and the provision of greater design freedom (including through CAD) not limited by traditional manufacturing methods.

6. Patents

Patent application P.442697: Artificial muscle of a rehabilitation glove [WIPO ST 10/C PL442697].

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