Research

Soft Hand Exoskeleton with Three-Dimensional Printed Soft Pneumatic Actuators

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Abstract:
The hand is an extremely complex organ, so restoring its function presents a challenge. There are various types of orthoses prescribed for impairments. Hand exoskeletons are intended to improve the function. They consist of a static base and dynamic components. The latter include actuators, most often rigid ones, such as electric motors. While the systems they employ are powerful and precise within a limited range of motion, they have numerous shortcomings, which can be circumvented by incorporating insights from soft robotics into orthosis design. Soft actuators can be manufactured, typically inspired by muscles. Their operation depends on supplied energy, design geometry, and material properties. Due to their characteristics, they are suitable for numerous applications across different fields, including orthotics and prosthetics. We developed a prototype orthosis consisting of a static base and a functional part, incorporating dynamic components. The static base was assembled from 3D-printed components. The functional part includes cable pulls, 3D-printed soft pneumatic actuators and a compressor. The most important dynamic components are the actuators. We printed various models and tested them. They achieve different maximum forces and contractions, with their operation influenced by several factors. The resulting hand exoskeleton has many characteristics of a good medical device; however, it has several, albeit solvable, shortcomings. Both the static base and the actuators need improvement, as the latter are not yet powerful enough for practical use, but adequately demonstrate the orthosis's operating principle.

Keywords: Orthotics; Hand exoskeleton; Soft robotics; Soft pneumatic actuators; 3D printing

1. Introduction

1.1. Anatomy and biomechanics of the hand

The human hand is an exceptionally complex organ with a wide range of functionalities. It serves as a tool for interaction with the environment, aimed not only at physical survival but also at social participation. Coordinated hand movements are essential for grasping and manipulating objects, which is fundamental for performing all daily activities (Bos et al., 2016; Hlebš, 2019). Impaired hand function can significantly reduce an individual's quality of life (Křižnar et al., 2019), which is why orthotists and prosthetists seek for possible solutions to restore it.

The hand is a very compact structure and biomechanically one of the most complex biological systems (Duncan et al., 2013; Du Plessis et al., 2021; Hlebš, 2019). It is the most movable segment of the upper limb. It has many degrees of freedom (DOF), 21 in total, allowing for many movements within a wide range of motion (ROM) (Du Plessis et al., 2021). The hand can be placed in various positions. Functional ones - grips - can be divided into two groups: working or firm and precise or fine (Hlebš, 2019). Movements are performed and coordinated by muscles that are functionally interconnected, so the position of the wrist affects the performance of finger muscles and thus hand function. A slight dorsal flexion of the wrist (20°-30°) prevents the finger flexors from acting on the wrist, thereby increasing and stabilizing grip strength (Coppard & Lohman, 2015; Hlebš, 2019).

1.2. Pathologies

The functions of the upper limb are much more complex than those of the lower limb, making it harder to fully restore them in case of various impairments (Du Plessis et al., 2021). Common causes of hand impairments include central nervous system disorders, peripheral nerve damage, congenital defects, arthritic changes, burns, tendon injuries, and other injuries such as sports injuries. An orthosis is usually needed to optimize function (Křižnar et al., 2019).

1.3. Hand orthoses

In Europe, hand orthoses are commonly classified by function into three groups: static, passive dynamic, and active dynamic. Static orthoses are prescribed for immobilization, maintaining position, and correcting deformities; passive dynamic orthoses prevent or reduce contractures and exercise muscles; active dynamic orthoses improve upper limb function—enabling grasp, release, performing specific tasks, or improving upper limb positioning in space (Ortar and Burgar, 2001).

The most used hand orthoses are static orthoses (Coppard & Lohman, 2015). They are composed solely of static elements (Ortar and Burgar, 2001). Dynamic orthoses consist of static elements with added dynamic elements, such as elastic bands or spring wires, assisting the patient by regulating the range of motion and the plane in which the movement is executed. These are called passive dynamic orthoses (Hsu et al., 2008; Pervez and Nagrare, 2022). When dynamic elements include actuators, these are active dynamic orthoses, also known as exoskeletons (Pervez and Nagrare, 2022). They can be defined as wearable robotic devices that help the user perform specific movements (Du Plessis et al., 2021).

1.4. Actuator

Robotic devices are programmable systems designed to perform various tasks. They must have the following subsystems: a drive unit, sensors, actuators, a body or mechanism for transmitting forces or torques, and a controller (Chen et al., 2017). An actuator is a device that can activate or drive a mechanism by drawing energy from a generator and supplying it to another device. The general principle of an actuator is the conversion of any type of energy into mechanical energy, resulting in movement. Examples of actuators include electric motors and pneumatic pistons (Chen et al., 2017; Whitesides, 2018).

Traditional robotic systems are made of rigid, mechanically inflexible materials and are driven by equally rigid electric actuators. They move at high speeds and consequently generate large forces. The downside is that such systems are often rigid in movement, heavy, and energy intensive. These characteristics make them potentially dangerous during human interaction. Additionally, achieving complex movements requires technologically advanced control systems. Based on their transportability, robotic systems can be either tethered or untethered (Whitesides, 2018). The former are more prevalent. They include non-portable drive units (Du Plessis et al., 2021). Systems using rigid actuators are powerful and usually precise but only within a limited range of motion. This makes them less effective in adapting to various environmental conditions and different users. The field of soft robotics is currently undergoing development to overcome these limitations (Pan et al., 2021).

1.5. Soft robotics

Soft robotics is a rapidly evolving field (Higueras-Ruiz et al., 2022; Whitesides, 2018; Xavier et al., 2022), still in its relatively early development stages (Whitesides, 2018). The inspiration for designing systems is drawn from nature, particularly biological models of various organisms like starfish, worms, snakes, fish, and human muscles (Whitesides, 2018; Xavier et al., 2022). Bio-inspired design is based on the realization that nature offers solutions to problems that existing engineering methods still find challenging. Soft robotics emulates nature by incorporating soft and elastic materials into systems (Majidi, 2018). These materials allow the creation of soft, highly deformable, and adaptable (compliant) components, including actuators (Pagoli et al., 2022). Hydrogels, electroactive polymers, and elastomers are used for their fabrication (Xavier et al., 2022). Often, silicones are utilized due to their favorable properties (Pagoli et al., 2022). The elastic modules of these materials are comparable to those of soft biological materials, including human tissues (Pan et al., 2021).
By leveraging the advantages of soft, adaptable materials, the need for complex actuation and control systems is avoided. The result is simpler task execution, lower production costs, and a more affordable final product. The material properties also lead to greater impact resistance, durability concerning the degree and number of deformations, and light weight of the actuators without sacrificing power. Most importantly, they enable safe interaction between humans and devices (Pan et al., 2021; Whitesides, 2018; Xavier et al., 2022).

1.6. Soft actuators

Soft actuators are types of actuators that are made from flexible or otherwise adaptable materials. Their operation is movement as a result of supplied energy, their physical shape, and the material from which they are made. They can move axially, radially, in a twisting motion, bending, or in various combinations of these movements (Higueras-Ruiz et al., 2022). Based on their mode of operation, several types exist, with soft pneumatic actuators being among the most commonly used. They can use either positive or negative pressure for operation. In recent years, there has been significant progress in this field (Pagoli et al., 2022). The production of more sophisticated soft actuators has been enabled primarily by advanced additive technologies, initially used for printing molds in which liquid elastomeric material was poured, hardened, and retained the shape of the mold. Nowadays, more direct printing of actuators is increasingly used. Common technologies include Fused Deposition Modelling (FDM), Direct Ink Writing (DIW), and Stereolithography (SLA) (Wallin et al., 2018).

1.7. Applications of soft pneumatic actuators

Soft pneumatic actuators are suitable for numerous applications in various fields due to their properties, including industrial and service robotics, rehabilitation and other biomedical sectors (Kalita et al., 2022). Their use is particularly beneficial in environments that are highly dynamic and sensitive to physical interaction (Xavier et al., 2022). Interest is also growing in developing wearable soft rehabilitation and supportive robotic devices, where soft actuators are being incorporated into orthotic designs (Cianchetti et al., 2018; Kaviri et al., 2023).

1.8. Hand exoskeletons

The term "exoskeleton" refers to the hard outer structure or shell of some animals that supports their body. Similarly, hand exoskeletons are designed to fit on the dorsal, lateral, or

(less often) palmar sides of the hand and fingers. In rehabilitation they are frequently used to restore motor functions in patients with hand impairments or to provide haptic feedback in virtual reality environments (Kaviri et al., 2023; Du Plessis et al., 2021).
Based on the rigidity of their components, exoskeletons can be divided into rigid, soft, and hybrid types, which are combinations of both (Du Plessis et al., 2021; Noronha & Accoto, 2021; Pérez Vidal et al., 2021). The mechanism of action for rigid exoskeletons involves transmitting forces or torques to the joints through rigid mechanical structures. There are various designs (Du Plessis et al., 2021). Most of rigid exoskeletons are bulky, massive, rigid in operation, and often tethered (Pervez & Nagrare, 2022). Additionally, their complex structure extends the donning time. Due to their rigid construction, they do not optimally conform to the shape of the hand, limiting the range of motion and potentially causing pressure-related injuries. Another major issue is the enormous cost of such systems (Gorgey, 2018). In contrast, soft hand exoskeletons are a promising trend in the field (Du Plessis et al., 2021).

1.9. Soft hand exoskeletons

Soft hand exoskeletons are generally designed like gloves with added flexible elements that transmit forces and torques to the finger joints. These elements can be various forms of pulling or pushing wires or cables (tendon-driven gloves) or continuous structures, such as soft pneumatic actuators (jointless structures). This allows for the creation of comfortable, compact, and lightweight exoskeletons. However, the main challenge is the electrical cables or air tubes that connect the exoskeleton to the drive unit, which is often not portable (Du Plessis et al., 2021). Recently, underactuated devices, which use fewer actuators to support multiple movements, have become prevalent. Typically, hand exoskeletons assist with finger flexion, but far fewer are designed primarily to support finger extension (Chen et al., 2021).
Most such devices are still in the research phase. Many are in early development stages, some are being tested on healthy individuals, a few are undergoing limited clinical trials, and very few are commercially available and used in clinical practice (Noronha & Accoto, 2021).

2. Material and Methods

2.1. Prototype development of a soft hand exoskeleton

We developed a prototype soft hand exoskeleton to assist with finger extension using 3D-printed soft pneumatic actuators. It consists of a static base and dynamic components, which make up the functional part of the orthosis. For the static base, we assembled an exoskeleton from 3D-printed components. The functional part of the orthosis includes cable pulls, 3D-printed soft pneumatic actuators and a compressor as an energy generator. The principle of operation is as follows: the compressor is activated, the pressure inside the actuator increases, the actuator contracts and pulls the cables, which extends the fingers. We tried to make the orthosis lightweight, comfortable, safe, easy to put on, use and maintain, untethered, relatively easy to make, accessible, adaptable in its function - in the sense that it is suitable for use with various pathologies and multiple patients and, if possible, adjustable in correction. The ultimate goal was a working orthosis with its practical use. Note: The term "exoskeleton" is used for "active dynamic orthosis", but sometimes it means "static base." The context clarifies the meaning.

2.2.1. Static base of the orthosis

In the computer-aided design (CAD) software program Autodesk Fusion 360 (2023) (Version 2.0.16490, Autodesk, Inc., San Francisco, California), we designed the components of the exoskeleton and printed them on a FDM 3D printer, the Creality CR-10 Smart Pro (Shenzhen Creality 3D Technology Co., Ltd., China). For the printing of softer parts of the static base, we used thermoplastic polyurethane (TPU), more specifically material varioShore TPU (colorFabb, Belfeld, Netherlands). This material has the advantageous property of foaming differently at various temperatures, allowing the printing of lightweight, soft, and comfortable components with minimal material usage. We adjusted the hardness of the components by changing the thickness or the number of layers during printing. We aimed to print components soft enough not to hinder the preserved movement of the hand, while still providing a sufficiently firm support for the dynamic components of the exoskeleton. We printed the guides with a harder material, TPU 95A (colorFabb, Belfeld, Netherlands). The printing process took about 22 hours (excluding modelling and drying). The assembly of the exoskeleton followed, where we glued and mechanically connected the parts.

The exoskeleton is mainly composed of 3D-printed components, with only a few additional essential parts, such as common Velcro straps for closing and attaching the orthosis to the hand (**Figure 1**). At the fingertips, we created distal attachments for the cables (or wires) by inserting regular rivets into the holes of the guides. These were also used to form attachment points for the cables (or wires) at the top of the actuator. We didn't use any specific materials, but commercially available straps, rivets, cotton cords and universal secondary glue (you can find them in every store), because they are sufficient to demonstrate the operating principle of the orthosis.

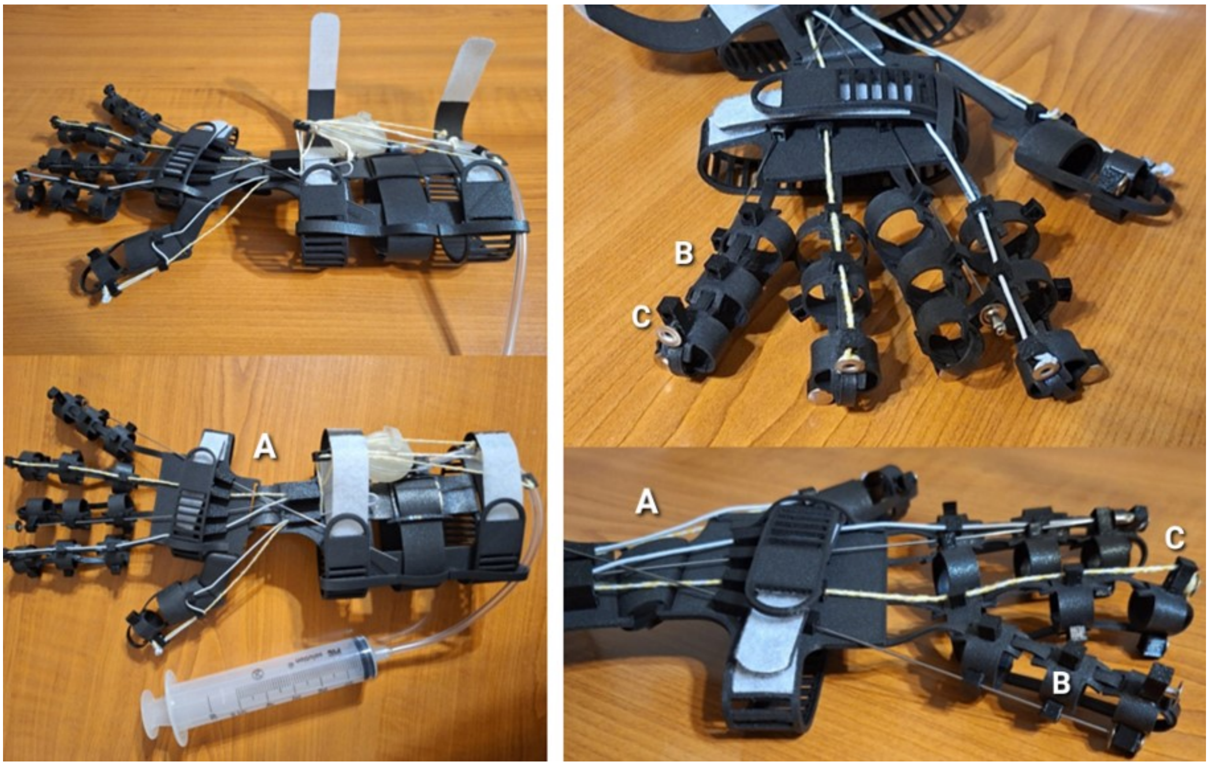

Figure 1. Final static base of the exoskeleton, with already added all tested options for dynamic components (left). The distal part of the orthosis is zoomed in to show the guides and cables (right). Letters indicate the following elements: **A**) the wrist joint, **B**) a guide and **C**) a distal cable attachment.

The static base consists of two main parts. More rigid components do not extend over the wrist joint and finger joints, being interrupted and connected by softer linking elements at these points. The first, proximal part covers the forearm area, including two fixation straps and a longitudinally adjustable strap for attaching the actuators. The second, distal part extends over the back of the hand, with four straps representing the connecting elements onto which the finger thimbles are placed. The strap passes through the thimbles on the dorsal side of the finger, bends distally across the middle of the finger pad, and runs along the palmar side of the finger to the most proximal thimble. This design allows for adjustability of the thimbles` positions, simply moving them up or down the connecting strap. Distally, at the fingertips, it forms a loop preventing longitudinal slipping of the thimbles under pulling force, while also facilitating easier removal of the exoskeleton after use. The finger pad is not compressed or completely covered, so sensory and proprioceptive feedback is not significantly reduced. Unlike the other fingers, the thumb is its own active subunit. We simplified the carpometacarpal (CMC) joint of the thumb, combining it with the metacarpophalangeal (MCP) joint and making it from a 1-millimeter strip in the shape of a trapezoid, trying to achieve an anatomically appropriate angle (with the second finger), without hindering movement, especially opposition. The two main parts of the orthosis are connected at the wrist joint, made from a 1-millimeter trapezoidal strip, glued into a cylindrical shape at the ends. The result is a joint considering minor anatomical ulnar deviation, not hindering wrist movement in abduction and adduction. It does not restrict dorsal flexion and only minimally restricts volar flexion (**Figure 1 - A**). The exoskeleton is designed to be compatible with other wrist orthoses.

2.2.2. Dynamic components of the orthosis – cables

On the completed softer static base, we attached stiffer guides (**Figure 1 - B**). These are small blocks with a hole in the middle, except for the distal cable attachments, which have an additional identical guide on top, providing some vertical force component to further prevent thimble slippage (**Figure 1 - C**). The basic force generated by the actuator is a pulling force, so we prefer the idea of the exoskeleton working in pulling, but we also tried and added guides for the potential use of pushing wires to extend the fingers. These were placed on the lateral side of the fingers, one on each thimble. They were attached lower than the joint pivots (**Figure 1**).

Cables run through the guides along the fingers, attached at both ends. One end is attached to the distal attachment on the dorsal side of the fingertips and the other to the actuator. We tested various options for the latter, as seen in **Figure 1**. The final attachment on the actuator is made from the same guide as those on the thimbles (**Figure 2**).

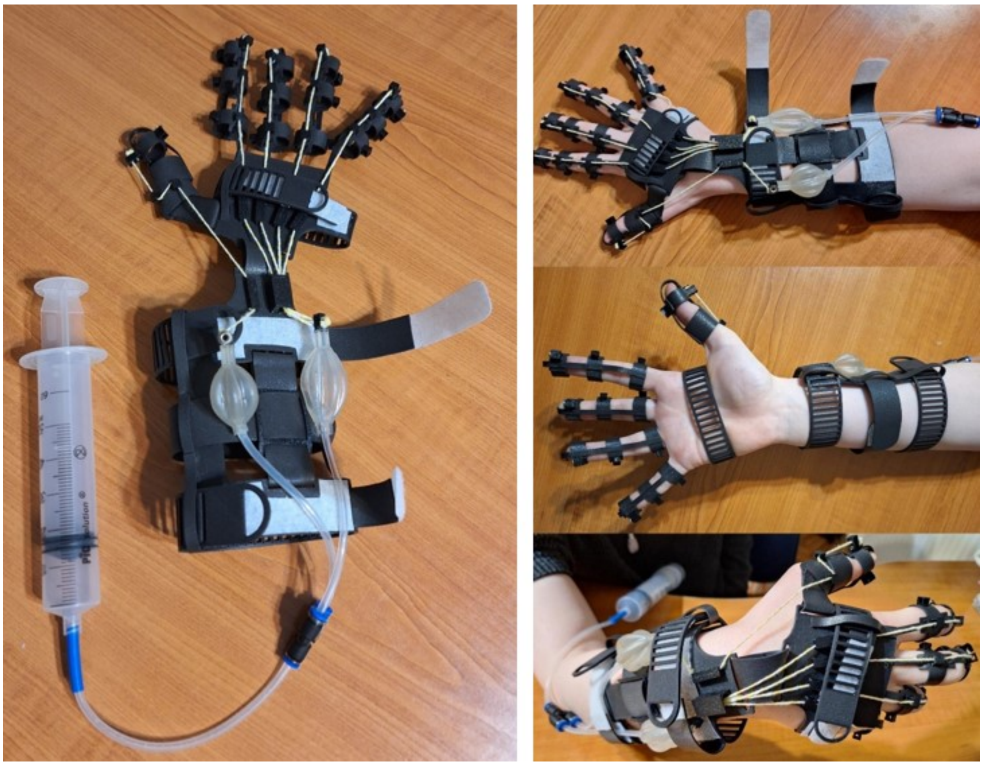

Figure 2. Final prototype of soft hand exoskeleton with 3D printed soft pneumatic actuators for assisting extension of all five fingers.

2.2.3. Dynamic components of the orthosis – actuators and energy generator

Actuators play a central role in the orthosis's function. Based on our practical needs and literature review, we decided to create soft pneumatic actuators that operate through linear motion. The pneumatic actuators were made by using 3D printing, inspired by designs from Sparrman et al. (2021) and De Pascali et al. (2022). The main difference in operation is that designs by Sparman et al. (2021) elongate with increased pressure, while designs by De Pascali et al. (2022) contract. Initially, we tried those by Sparman et al. (2021), but they were not effective, so we focused on those inspired by De Pascali et al. (2022). We designed various similar actuator models and printed test samples using VarioShore TPU (white actuators) (**Figure 3 - A**) and TPU A85 (black actuators) (**Figure 3 - B**). The larger ones (4 cm in height) performed slightly better (**Figure 3 - C**), but the smaller ones (2 cm and 3 cm) were more suitable for hand orthosis applications (**Figure 3 - D**). While the material softness affected performance, the relationship was not proportional to filament hardness – there was no noticeable difference between softer and harder actuators (not shown).

We then printed the actuators by a SLA printer (Elegoo Mars 3) using flexible resin with Shore hardness A43 - Liqcreate Elastomer – X (Liqcreate, Utrecht, Netherlands) (**Figure 3**). After printing they were cleaned in isopropanol and UV cured at 60°C for 30 minutes. The printed models tended to tear along the layers at higher pressures, especially larger ones and those with thinner walls. Despite post-processing, they felt slightly sticky. Based on those facts, quality concerns are rising. The actuator operates by inflating (increasing in diameter) and contracting (linear movement) under air pressure, creating a pulling force that pulls the cables and extends the fingers. For pressure generation, we initially used a 50-ml syringe, later switching to a small electric compressor. All types of models are shown in **Figure 3**.

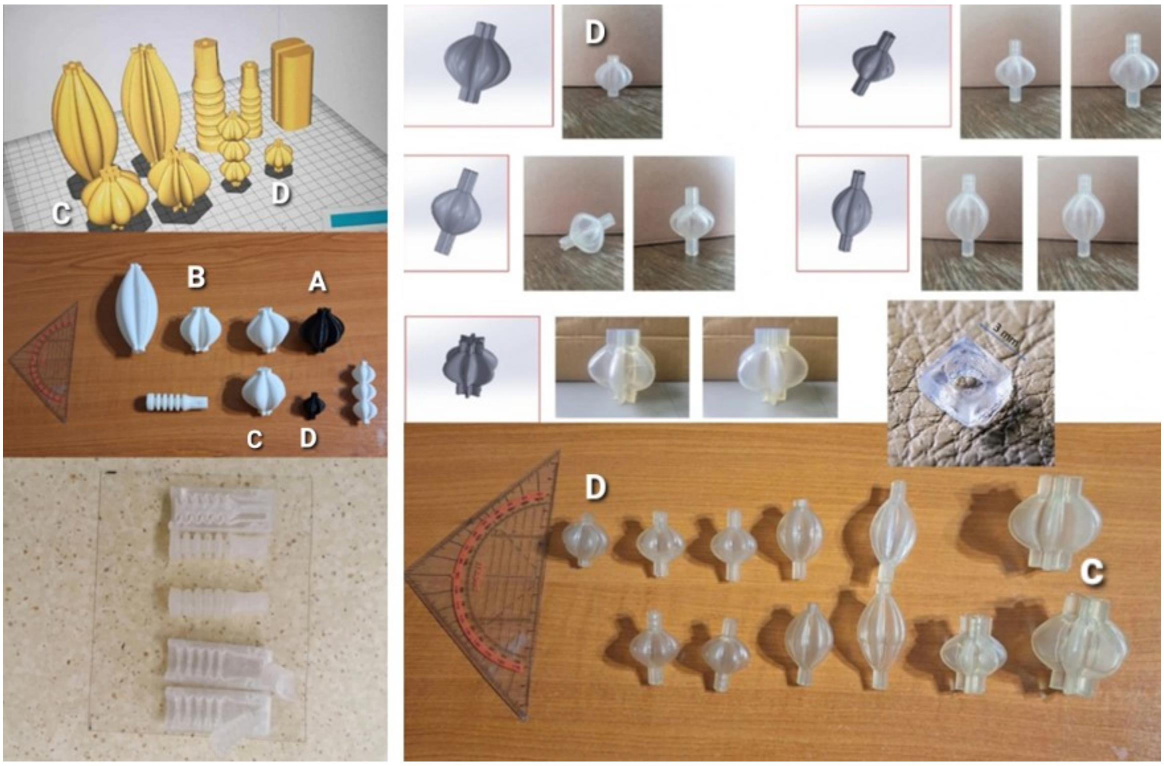

Figure 3. Different actuator models printed on FDM (left) and SLA (right) printer. **A**) an actuator printed with TPU A85, **B**) an actuator printed with TPU VarioShore, **C**) a large actuator and **D)** a small actuator.

We used two such actuators for the orthosis's operation: one for thumb extension and one for the other fingers extension. Although the goal was to achieve separate triggering and thus independent thumb extension from the other fingers, for demonstration purposes, both actuators were connected to the compressor to work synchronously. The compressor activates simply by pressing a switch, which suffices for demonstrating the operation.

3. Results

Most of the information on the exoskeleton’s structure and its components is already presented in the *Material and Methods*, as this article is primarily about the manufacturing process.

The actuators were tested before use to observe their response to increasing pressure. The tested actuators varied in rib (pleats) count, rib depth, length, wall thickness, and UV exposure time during printing, resulting in different maximum forces at various pressures and contraction sizes (**Table 1**).

Table 1. Test results of the top six printed actuators.

Sample	Number of ribs	Depth of the ribs [mm]	Thickness of the wall [mm]	Length of AFP [mm]	Total length [mm]	Exposure time [s]	Pressure [mbar]	Max force [N]	Contraction [mm]
T_2_2	8	5	0.8	30	50	48	320	4	3.7
T_4_1	8	4	0.8	40	60	64	120	3.5	7.3
T_3_3	8	5	1	40	60	64	110	3.1	7.6
T_2_1	6	6	0.8	40	60	64	388	2.2	7.1
T_6_1	6	4	0.8	30	50	48	150	2.1	3.4
T_2_3	6	6	0.8	40	60	64	388	2	5

Sample means tested actuator. Ribs are longitudinal pleats. AFP means actuator`s functional part and it is the part that changes its shape under the pressure. Total length incorporates the length of its neck. Length is also referred to as height in the text above. Exposure time means time of UV- exposure within the process of printing. Pressure means the pressure required for actuator to achieve its maximal force. Max force is the maximum pulling force produced by the actuator when the pressure is increased and contraction is the amplitude or linear displacement by which the actuator contracts when the pressure is increased.

We noted two common behaviours: a slight delay in activation with increasing pressure and a transition from contraction to expansion beyond a certain pressure, causing movement in the opposite direction (**Figure 4**).

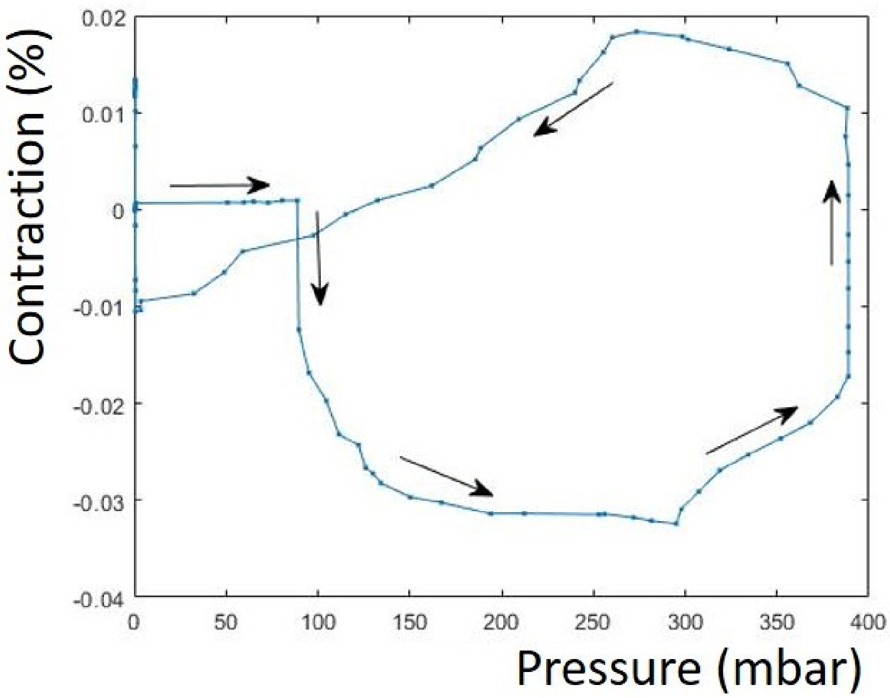

Figure 4. Relative actuator contraction on the ordinate axis in dependence on pressure (mbar) (on the abscissa axis).

The printed actuators do not yet generate sufficient force for practical use (maximum 4 N). Similarly, their contraction (linear movement) is generally insufficient (maximum 7.6 mm). The contraction size depends not only on force but also on the actuator's design, particularly its size, suggesting further research into the optimal design for greater movement. The pressure at which actuators achieve maximum force also depends on design, their geometrical structure, specifically rib depth. We confirmed that actuators` performance is not solely affected by material softness, which they are made of. They are functional within a pressure range of approximately 100 to 300 mbar. Below 100 mbar, there is no movement; within this range, actuators contract, but near 300 mbar, they begin to inflate, causing reverse movement. The graph above shows testing of a 2-cm actuator, which contracts by 0.032 or 3.2%, equivalent to approximately 6 mm (**Figure 3**).

A good ratio between actuator mass and generated force was achieved. Several good models generating forces from 2 to 4 N and weighing less than 1 g to a maximum of 3 g, were obtained, favoring force over weight. We also aimed to keep the actuators as small as possible, as size is a crucial factor in this sort of application.

The presented preliminary results demonstrate the actuators' and orthosis's operating mechanism. Actuator testing and optimization remain an active research area at the Faculty of Mechanical Engineering, University of Ljubljana.

The overall result of our work can be seen in **Figure 4.**

4. Discussion

The hand is a very complex structure, making its functional restoration challenging. Simple hand orthoses and also more complex ones made of rigid materials often do not meet functional needs. We recognize the potential advantages of incorporating soft components into the design of medical devices. Thus, we attempted to create an active dynamic hand orthosis from soft materials, which uses soft actuators to operate.

We present a prototype soft hand exoskeleton with 3D-printed soft pneumatic actuators (**Figure 2**). Also the static base components were 3D printed. The exoskeleton is suitable for use in various pathologies, somewhat size-adjustable, and correctively adaptable, being compatible with other wrist orthoses. It is soft, lightweight, comfortable, and breathable, minimally hindering sensory and proprioceptive feedback and preserving hand movement. It does not generate excessive forces or cause sudden movements and harmful torques on finger joints, making it safe. However, the device is still in the early research phase. It is a prototype with several shortcomings and conposed of improvised materials. The design is not optimal, with fitting still largely influenced by accurate dimension measurements. Precise measurements of the thimble circumferences, length and width of the surface on the dorsal side of the hand and the length of the connecting finger straps are required for perfect fitting of the device. The exoskeleton itself does not perform direct correction, meaning that additional orthosis is needed for the purpose of correcting position of the wrist or any other joint, required for example with spastic patients. The principle of “pulling” cables could be replaced by “pushing”, but a more compact static base would be required. As better explained: with a pulley, the force produced by the actuator (and its contraction) could be reversed and thus finger extension achieved, not by pulling, but by pushing the cables. Pneumatics is not an optimal energy source, the exoskeleton also does not yet include a sensible control mode. The quality of the actuators is questionable. They are not yet powerful enough, generating too little force and too little movement, respectively contraction. However, useful conclusions about what affects their performance have been achieved. Actuators could also be replaced by pneumatic bending actuators, or by actuators of a completely different type. The device does not meet mandatory standards, we have not tested its applicability and it is therefore not yet suitable for clinical use.

We have demonstrated the potential use of additive technologies for the manufacture of medical devices and presented an example of the implementation of soft robotics solutions in the field of orthotics and prosthetics.

5. Conclusions

Creativity and inovative ideas are the driving force behind development, which is essential if we want to achieve ever better solutions for patients that will improve their quality of life. This was the main reason we attempted to develop a new type of active dynamic hand orthosis. The resulting hand exoskeleton is suitable for use in various pathologies, adjustable to some extent in size and adaptable in correction. It is soft, lightweight, comfortable, and breathable. It does not overly impede sensory perception and proprioception, nor does it restrict retained hand movement. It does not generate excessive forces or abrupt movements, nor does it cause harmful torques on finger joints, making it safe for use. Nevertheless, it is only a prototype and thus has several, albeit solvable, shortcomings. We believe indiviidual components hold promise, so additional research must be invested to arrive to in-practice-usable hand exoskeleton.

Conflicts of Interest: The authors declare no conflict of interest.

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