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A SOFT EXOSKELETON FOR HAND FINGER REHABILITATION APPLICATION USING FULLY ELASTIC PNEUMATIC ACTUATORS

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ABSTRACT

In recent years, there has been a growing demand for wearable actuators, that can be worn on individual body parts. This demand is dynamically increasing due to the numerous potential applications such as rehabilitation and enhancing load-bearing capabilities. Exoskeletons are mechanical structures that supplement or facilitate human movements and increase the body parts natural capabilities. Despite their wide range of applications, rigid exoskeletons have several deficiencies that required further developments. Soft actuators have been developed to address these deficiencies, forming one of the main categories of easily wearable exoskeletons. The two categories - rigid and soft exoskeletons - complement each other in their structures during applications. Soft robotic elements enable precise and delicate movements while providing adequate flexibility during use and rigid units are responsible for the stable frame structure and fixation. Their combined use is applied for rehabilitation, occupational safety, and enhancing work performance purposes. The aim of this article is to physically realize a device that has a legitimate purpose in the field of human hand rehabilitation. The goal was to design, manufacture, and functionally test the elements of a device capable of assisting in the rehabilitation of fingers using completely flexible actuators.

Keywords: soft actuator, soft exoskeleton, soft robotics, flexible hand rehabilitation

1. INTRODUCTION

In recent decades, robots and their diverse applications have received increasing emphasis. Due to technological advancements, new opportunities have emerged that facilitate or complement human activities in various fields. The continually evolving concepts have also led to the usage of robots near humans and even in direct contact with human body parts [1][2]. The demand for wearable robots on specific body parts or even the entire body is dynamically growing, thanks to their numerous applications, such as rehabilitation and load-bearing enhancement. One category of exoskeletons, or artificial external frameworks, consists of rigid mechanical structures assembled from hard parts that, when attached to a body part, supplement or facilitate human movements and enhance their natural capabilities [3][4]. Despite the broad range of applications, exoskeletons exhibited several shortcomings that necessitated further development of human-robot interactions. The soft actuators [5][6] were developed to address these deficiencies and represent the other main category of exoskeletons. The structures of the two categories—rigid and soft robots—complement each other in various applications. Their combined use is primarily applied for medical purposes, particularly in rehabilitation.

Exoskeletons are widely utilized in a variety of distinct applications. This is due to their versatile design options and the adaptable drive systems that can be modified according to specific needs. There is a significant demand for reducing the load on the human body and for enabling full movement of individual body parts across different fields [7][8]. Their proliferation is further supported by the dynamically growing demand for such devices. In practice, rigid or soft robotic elements are often used independently, or in combination with each other as hybrid systems. The combined use of these technologies offers numerous possibilities, paving the way for new and more efficient applications.

Healthcare Applications: The primary designs of exoskeletons aim to facilitate medical and nursing tasks [9]. The initial developments assisted humans in lifting and transporting patients by supporting the heavy weight with the exoskeleton. This weight-lifting capability is a feature of external frameworks that is not only exploited in healthcare but also in other fields, as the human limit for lifting weight is quite restricted. Beyond healthcare workers, these devices can also be used by patients for rehabilitation purposes. Various diseases, their complications, and permanent damage can cause musculoskeletal issues that exoskeletons can help address. Examples include muscle atrophy, the risk of edema formation after surgery or trauma, and the loss of joint flexibility [10].

Military Applications: The first major wave of exoskeleton development occurred in the military sector. However, due to the more profitable applications in industry and healthcare, as well as many unfavourable characteristics, these developments were eventually deprioritized. Several nations have engaged and continue to engage in the development of military exoskeletons, with the United States and Japan leading the way [11]. In military use, the primary goals are twofold: first, to increase muscle strength, thereby transferring the burden of carrying heavy loads to the exoskeleton; second, as a consequence, to reduce fatigue and enhance endurance. This is crucial because basic equipment, weapons, and supplies already represent a significant weight,

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making their long-term transport a demanding task. Additionally, this is compounded by the need to carry other special, heavier combat equipment and weapons [12].

Industrial Applications: The use of exoskeletons in industrial sectors is perhaps the most profitable, leading to their increasing prevalence. Their characteristics create a chain of advantages that make them popular in factories, processing industries, construction sites, and other physical labor environments. Thanks to their operating principles, they combine human decision-making and intelligence with the strength, precision, and tirelessness of robots [13]. In factories, exoskeletons are employed on production lines to enhance safe working conditions. By bearing the weight of the parts to be assembled, exoskeletons alleviate the burden on workers, thereby reducing fatigue-related issues such as accident risk, overexertion, and decreased productivity. Additionally, the precision of robots significantly reduces the number of errors. The weight-lifting capabilities of exoskeletons are also utilized in warehouses for material handling tasks. By replacing forklifts and loading machines, exoskeletons offer a cheaper and more versatile solution while reducing hazards [14].

2. DESIG OF A FULLY FLEXIBLE ACTUATOR

2.1. Factors affecting operation and requirements for the actuator

The primary goal in designing the actuator is for the device to bend at the desired angle and exert force simultaneously. Several characteristics influence these parameters of the soft actuator, which must be considered during the design process. These characteristics include material quality, dimensions, and design shape. The design shape is determined when attaching to the finger, as it is both a requirement and expectation that the actuator moves in the same direction as the selected body part. The geometric design and dimensions are more flexible properties. Since there are infinite combinations of these, data based on recommendations and experiences from the literature was used to understand the correlations. These experiences relate to the number of chambers, their height, and wall thickness.

Based on this, it can be concluded that to achieve maximum bending:
- Increasing the number of chambers reduces the required pressure.
- Increasing the chamber height up to a certain limit reduces the required pressure and increases force exertion.
- The wall thickness of the chambers is directly proportional to the required pressure.

Material quality also significantly affects the actuator's response to input. However, due to the design and nonlinear behaviour of the actuators, modelling the behaviour of different materials is challenging. Literature has established general correlations related to material quality in addition to morphology [15][16]. For identical dimensions and morphology:
- Materials with high stretchability and low hardness require less pressure to deform than stiffer materials for the same amount of deformation.
- Stiffer materials can exert more force at the same pressure.

From the operation of a soft actuator, several expectations can be formulated that every soft robotic element must meet:
- Sufficient flexibility for repeated shape changes.
- Does not suffer permanent deformation during operation.
- Returns to its original shape in the resting state.
- Provides complete air sealing in the chamber array.
- Fits the desired host unit.
- Pneumatic tube can be securely fastened.
- Long service life.

Due to its operation and function, the soft actuator must meet numerous requirements without which it would not be suitable for this purpose. Given its function as a finger-mountable rehabilitation device, it must comply with several requirements to ensure accident prevention and safe use in the immediate vicinity of the human body. Requirements arising from finger attachment:
- Capable of movement corresponding to finger motion.
- Safe for use near humans.
- Possesses 3 degrees of freedom corresponding to the three finger joints.
- Length and width significantly no larger than appropriate finger dimensions.
- Height does not hinder further movement, maximum 25 mm.
- Bending angle of 270°, matching the curvature of fingers.
- Designed to be securely fastened to a host unit.
- Can change shape quickly under pressure.
- Capable of achieving desired bending angle and exerting force at low pressure ($P < 100$ kPa).

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2.2. Determination of geometrical design and dimension

The enclosure dimensions are narrowed down to within a few millimeters for both length and width. To determine these dimensions, a smaller female palm was used as a reference, which roughly corresponds to a size S or 7 glove. The sizes are chosen so that they can also fit slightly larger fingers and palm. It is crucial to precisely determine and maintain the width dimensions of the fingers, as otherwise they may collide and hinder each other's movement. Additionally, it is important that they can be securely fastened onto the fingers with the host unit. The host unit must accommodate all fingers without significantly exceeding the width of the palm, as this would make wearing uncomfortable and also restrict palm movement.

The length of the fingers allows for a slightly wider range within which the dimensions can vary. These soft robotic elements should not extend beyond the fingertip, as improper grasping might occur with the device rather than the intended finger. However, the device cannot be shorter than the fingers either, as it would fail to move the entire fingertip, thus not achieving the desired effect of full finger movement. The attachment of actuators can be achieved in multiple ways, allowing for more flexibility in adjusting the lengths. These devices are primarily anchored around the center of the palm, extending beyond just the length of the fingers. This accommodates the bending of actuators, capable of bending up to 270°. When anchored around the palm, the fingers can bend relative to the palm, not just relative to each other, during movement across the three finger joints.

Based on measurement data, the subject's dimensions are as follows:

- Longest finger length: 84 mm
- Shortest finger length: 62 mm
- Largest distance from palm center to fingertip: 52 mm
- Smallest distance from palm center to fingertip: 35 mm
- Total palm length: 82 mm

Required minimum length:

$$l_{min}=62\text{ mm}+35\text{ mm}=97\text{ mm} \tag{1}$$

Applying the minimum size for the longest finger:

$$l_{min}-84\text{ mm}=13\text{ mm} \tag{2}$$

This size can also be applied to the largest finger, as it is longer than the finger's length, leaving a 13 mm extension beyond the palm for anchoring. Based on measurements, the height of the fingers is 19 mm. Boundary value for height dimension:

$$h_{max} = 19\text{ mm} \cdot 1{,}2 = 22.8\text{ mm} \tag{3}$$

Since the height value is not strictly limited, rounding gives me a value of 23 mm. Compared to the accepted value in the literature: 23 mm < 25 mm. Therefore, it does not exceed the established literature value of 25 mm for height.

In summary, the enclosure dimensions of the chambers based on the sizes of the fingers and the palm are:

- Length dimension: 97-136 mm
- Width dimension: maximum 19 mm
- Height dimension: maximum 23 mm

For the specific chamber array design, studies and experimental results were relied [17]. These studies include previously mentioned correlations and practical experiences that can guide the design of an actuator that operates according to expectations. The parameters examined in the study that have the greatest impact on the bending angle include the thickness of the bottom layer, wall thickness, distance between chambers, and the cross-sectional shape of the chambers (Figure 1).

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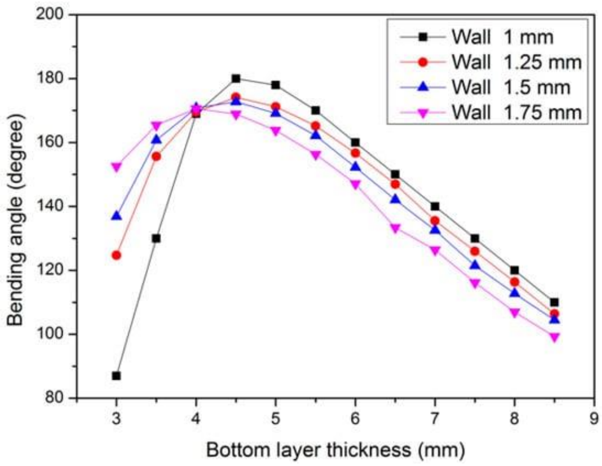

Figure 1: The effect of wall thickness and the thickness of the bottom layer on the bending angle [17]

Based on the diagram, it can be observed that a 1 mm wall thickness achieves the maximum bending angle, approximately with a bottom layer thickness of about 4.5 mm. Since this wall thickness is sufficient and also the most efficient, it was chosen for the actuator. The thickness of the bottom layer is set between 4.5-5 mm, which also depends significantly on precise casting, allowing for minimal variations. Next, it is deduced how much distance is needed between the chambers to expand adequately while reaching the walls of each other. The research examined distance values between 1 mm to 1.75 mm, as distances smaller than 1 mm cause the chambers to nearly touch in their resting position, while gaps of 2 mm or more minimize interaction, hindering bending.

It is evident that the gaps and bending angle are inversely proportional. Therefore, an intermediate value of 1.5 mm distance was chosen, which allows controlled bending yet is sufficient for operation. The 1 mm wall thickness pertains to the contact surfaces. Walls belonging to different sides of the chamber are of varying sizes to stretch better on the usable surface and side for us. The 1 mm wall thickness expands easily yet remains sufficiently robust and producible by casting. As there is no need for an increase in material thickness for the lateral and upper chamber walls, it was reduced. These walls were chosen to be 2 mm thick. Walls of 2 mm thickness stretch more slowly, so the deformation of chamber height and width is less measurable than with 1 mm thick walls, as will be the load on them.

Final step is determining the number of chambers, that is, how many of these chambers fit within the length range specified by the enclosure dimensions. When calculating the number of chambers, it is necessary to take into account the two end sections, so chambers cannot be used across the entire length, and also the thickened walls of the last two chambers. Since the actuator requires less pressure for operation, the greater the number of chambers, the maximum possible number of chambers is chosen. For this, the maximum allowable length value was used.

The number of chambers is denoted by:

$$l_{max} = n \cdot l_{chamber} + (n - 1) \cdot l_{gap} + 2 \cdot l_{last\ chamber} + 2 \cdot l_{closure} \quad (4)$$

Maximum 11.94 chambers can fit within this length, which means 11 complete chambers. The number of chambers is therefore n = 11.

The determined dimensions are as follows based on the chamber configuration:

- External height of the chamber: 16 mm
- External width of the chamber: 16 mm
- Length of the chamber: 8 mm
- Side wall thickness of the chamber: 2 mm
- Top wall thickness of the chamber: 2 mm
- Thickness of adjacent walls of the chamber in contact with each other: 1 mm
- Gap length between chambers: 1.5 mm

Accordingly, the enclosure dimensions of the actuator are:

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- Length: 129 mm
- Width: 18±1 mm, depending on casting
- Height: 20.5±0.5 mm, depending on casting

3. MATERIALS AND METHODS

3.1. Process of selecting flexible materials

Due to the non-linear response and unique design of the soft actuator, it is difficult to predict how the device will behave with different materials. To select the appropriate material, two materials were chosen with properties similar to those used in research [11]. It was found during testing that this material is suitable in terms of manufacturability and stretchability, but it is too soft with minimal inherent stiffness, and it undergoes significant deformation even under minimal load. The harder material they used is Elastosil M4601 silicone, which has a Shore A hardness of 28 and can stretch up to 700%. Based on experience, this hardness is suitable because the bending angle changes continuously with pressure variation, without reaching its maximum at low pressure values. During operation, the chambers stretch to the greatest extent, but they do not reach 300%.

A material with a similar hardness but lower elongation was chosen, which is Mold Max 30. According to tests, a material with higher hardness produces less deformation and bending for the same pressure variation compared to softer materials. This property is advantageous as it allows for more controlled actuator movement. A harder material with similar characteristics for casting was chosen, specifically the Shore A 40 hardness variation of Mold Max. The chosen materials were Mold Max 30, and Mold Max 40. The data corresponding to these materials for the listed criteria is contained in Table 1.

Table 1: Physical properties of selected materials

	Mold Max 30	Mold Max 40
Density [g/cm³]	1,18	1,14
Shore hardness	30 A	40 A
Tensile strength [kPa]	3978,27	3792,12
Elongation [%]	300	250
Mixture viscosity [Pa·s]	25	45
Shrinkage [mm/mm]	0,002	0,004
Pot life [s]	2700	2700
Operating temperature [K]	-220 – 477	-220 – 477

3.2. Production process of soft actuators

The soft actuator is produced by molding, for which the first step is creating the mold. Due to the hollow design of the actuator, this is challenging. Several casting methods can be applied for molding the chambers:

1. Casting the chamber array and the bottom of the actuator in two separate stages, followed by bonding them together with another layer of silicone after solidification. The advantage is precise and error-free formation of the chamber array, but the disadvantage is that joining the two parts may not always result in a perfect seal, potentially causing air leakage issues.

2. The chamber array can be made from a material that dissolves under heat or water exposure. In this case, casting is done in one step, and the formed chamber array is placed into liquid silicone. After solidification, the material of the chamber array is dissolved from the silicone rubber using heat or water, leaving the chambers empty. The advantage is no gaps or incorrect closures, but the disadvantage is that the material of the chamber array and the dissolution process must be perfect; otherwise, residual materials may remain in the chambers.

Among the casting options, the first method, the two-step casting, was chosen. This requires molds that allow separate casting of the bottom part and the chamber array. The chamber mold consists of two parts: one provides the internal cavity, and the other separates the chambers from each other. Autodesk Inventor software includes commands to create the inverse or negative of a selected object. This feature was used to design the molds, ensuring no dimensional errors or incorrect shaping starting from the

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original form. The molds were 3D printed because this technology is suitable for precise mold creation. PLA material was used for the molds, as it provides sufficient strength for mold suitability (Figure 2).

Figure 2: 3D printed molds of the soft actuator

4. RESULTS AND DISCUSSION

4.1. Measurement of bending angle

The primary goal of measuring bending is to understand the extent of deflection that the actuator can achieve under different levels of applied pressure. This is necessary because the actuator needs to produce similar bending results as the natural movement of a human finger. A human finger's three joints can flex approximately 90 degrees relative to each other, 270° when fully bent. This 270° is also a criterion for the device.

The orientation of the actuator affects its bending because, due to its flexibility, the device bends without support, influenced by gravity. Therefore, it's crucial to consider that the initial position influences the bending angle; the device bends differently when gravity assists the movement compared to when it works against it. Due to this influencing factor, the bending measurements in three positions were conducted for both devices.

In the first phase, the measurements of the actuators were conducted in a horizontal position, against gravity. During the measurement, the actuators were loaded with an initial value of 10 kPa, increasing the pressure by 5 kPa increments between each measurement. The device made of Mold Max 30 material reached the desired value at 45 kPa. In the case of the Mold Max 40 material, this was achieved at 55 kPa (Figure 3).

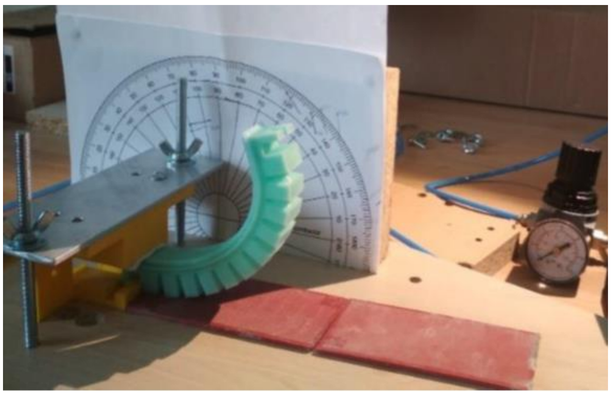

Figure 3: Measuring the bending angle against the gravity

As expected, the Shore 30 A hardness material is more flexible and requires less pressure for the same deflection. The devices can approach the maximum 270° deflection even in this position. Beyond the 90° mark, gravity assists the device and further bends the measured end (Figure 4).

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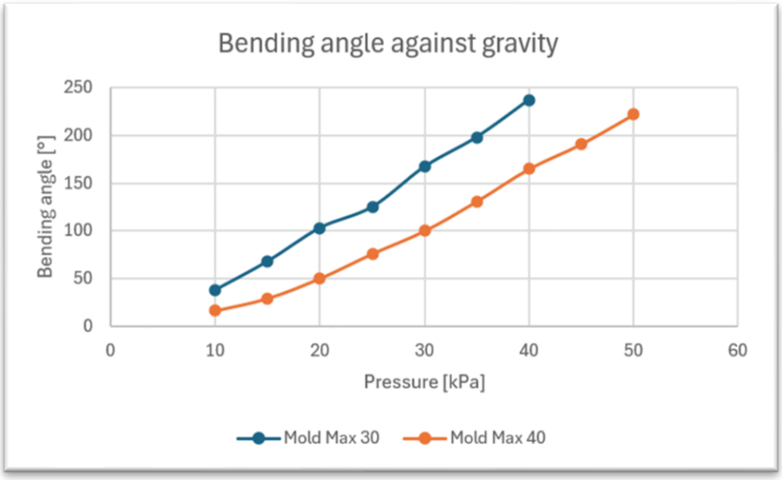

Figure 4: Bending angle measurements results against the gravity

In the second phase, the measurements of the actuators were conducted in a horizontal position, in the direction of gravity (Figure 5). In line with preliminary expectations and experiences, the 30 A hardness material also requires less pressure to achieve the same bending angle. In this position, the devices can also approach the maximum 270° deflection. Considering that the pressure values did not reach the permissible limit for either actuator, it is likely they would achieve the 270° deflection without obstruction.

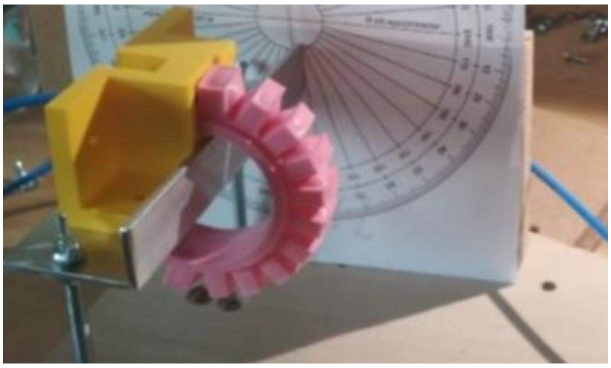

Figure 5: Measuring the bending angle in the direction of the gravity

It is observed that in the 0-90° bending angle range, gravity aids the deflection of the devices, resulting in significant bending even at low pressure. Beyond the 90° bending angle, the devices show progressively smaller deflections in response to the same pressure increase (Figure 6).

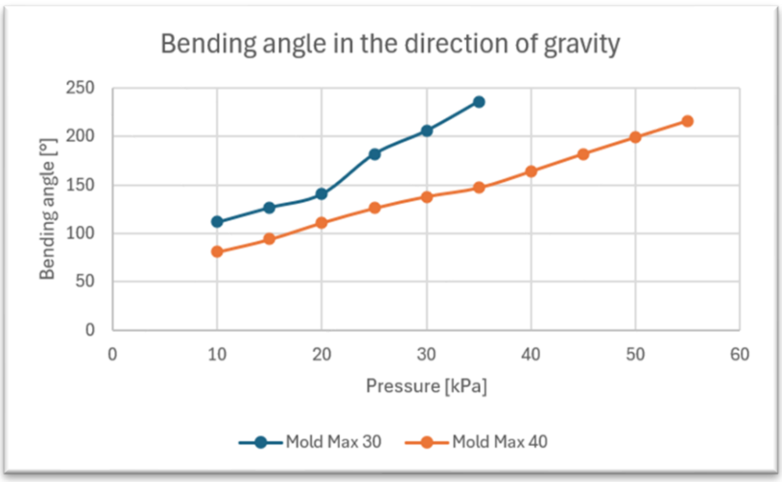

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Figure 6: Bending angle measurements results in the direction of the gravity

4.2. Measuring the exerted force

The significance of measuring the exerted force lies in determining whether the designed actuator can bend inert fingers and grasp objects. Establishing the necessary minimum force is challenging, as in cases of injured hands, the actuator functions merely as an assistive device, whereas in paralyzed hands, it must entirely move the fingers. These two applications require different levels of force. The force measurement was conducted using a load cell controlled by an Arduino Nano board. A 24-bit ADC converter based on the HX711, specifically designed for load cells, was used. The load cell can be calibrated in the Arduino IDE software environment, displaying the measured force in Newtons.

The force measurement was conducted at three different angles since the actuator's bending produces varying force values at different phases. The selected angles for measurement were 0°, 90°, and 180°. During the measurement, the actuators were initially loaded with a pressure of 10 kPa, with the pressure increasing by 5 kPa increments for each subsequent measurement. The force measurements continued up to the maximum allowable pressure for each material, which is 55 kPa for the Mold Max 30 and 80 kPa for the Mold Max 40. The material with 30A hardness exerts greater force at the same pressures compared to the 40A hardness material. As shown by the bending angle measurement (Figure 7), the 40A material exhibits less deflection, thereby exerting less force on the load cell. The 30A material achieves a force of 1 N at 50 kPa, whereas the 40A material reaches the same force at only 60 kPa.

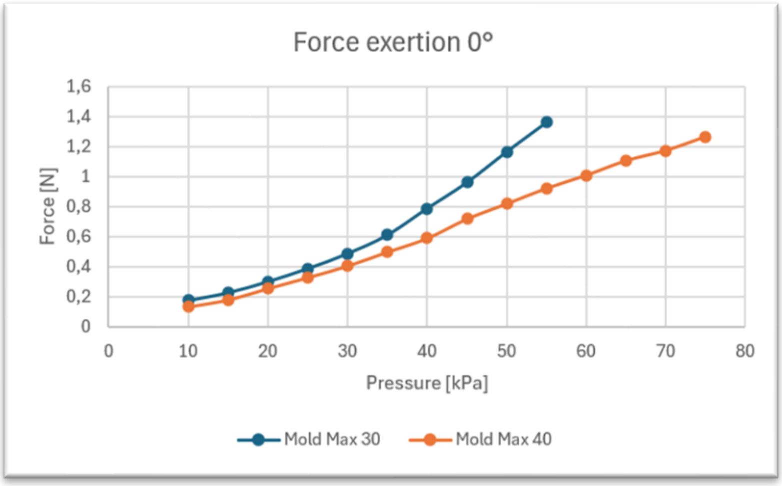

Figure 7: Force exertion at 0 degree starting angle

The measurement was also performed at a 90° deflection angle, as this is a common bending angle for finger rehabilitation. The material with 30A hardness exerts greater force at the same pressures compared to the 40A hardness material. The 40A material, based on the bending angle measurements, exhibits less deflection, thereby exerting less force on the load cell. In the bent state, the 30A material can only use the additional pressure to increase the force exerted. The material with 30 Shore A hardness is capable of exerting greater force at the same pressures compared to the 40 Shore A material (Figure 8). The reason for this is that the 40 Shore A material exhibits less deflection based on bending angle measurements, thus exerting less force on the force sensor cell. In contrast, the bent state of the 30 Shore A material device can redirect the additional pressure towards increasing force exertion.

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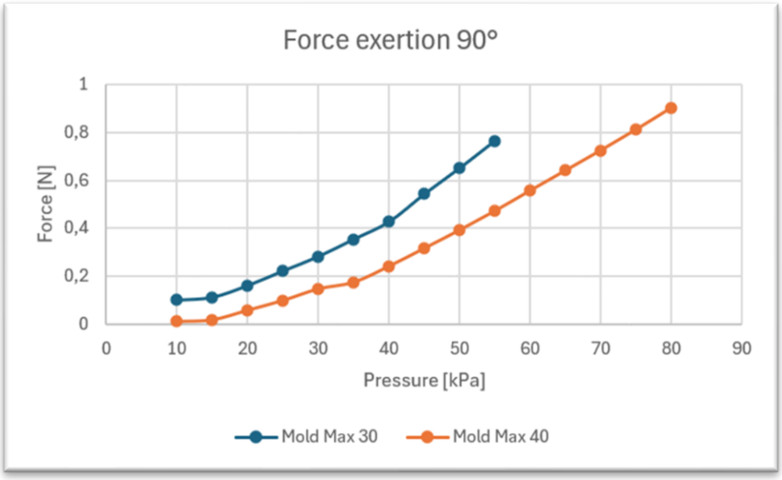

Figure 8: Force exertion at 90 degree starting angle

The last measurement was taken at a 180° angle bend, as movements resulting from finger flexion often reach this range, where the device must exert sufficient force to create a gripping force. During the measurement, the starting value was determined by the minimum pressure required, based on previously measured angular bends, to achieve a 180° bend against gravity. Before this value, the actuator does not engage with the cell, thus not exerting force on it. The starting value was 30 kPa for the 30 hardness, whereas for the 40 hardness, it was 45 kPa. During force measurements, the load was increased until reaching the maximum permissible pressure for each material: 55 kPa for the Mold Max 30 material and 80 kPa for the Mold Max 40 material. The increase in measured values is similar to that observed in the 90° force measurements (Figure 9). The material with 30 Shore A hardness is capable of exerting significantly greater force at the same pressures compared to the 40 Shore A material. The maximum force exerted is achieved by the actuator with 30 Shore A hardness.

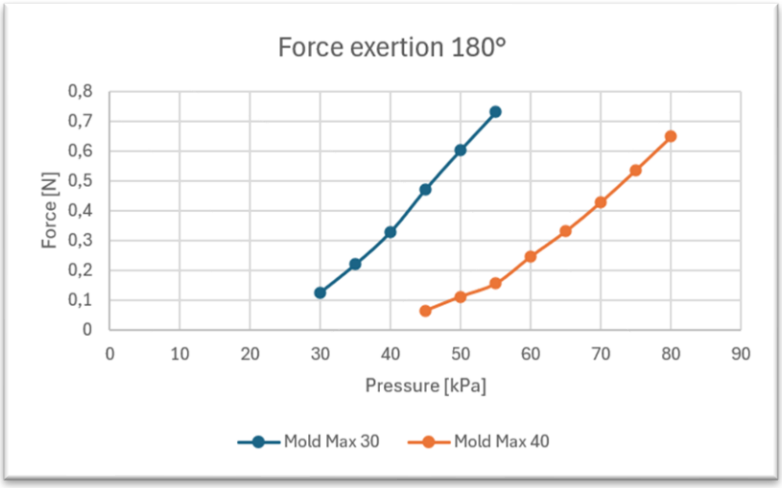

Figure 9: Force exertion at 180 degree starting angle

5. CONCLUSIONS AND PERSPECTIVES

Both Mold Max 30 and Mold Max 40 meet the basic requirements. From a manufacturing perspective, there is no significant difference between them; both are suitable for casting into such small gaps. The higher viscosity of the 40 Shore A hardness material makes it slightly more difficult to pour, but it does not pose a problem. Their properties are similar: lightweight, non-shrinking, sufficiently elastic yet with some rigidity. The measurement results show that both actuators can achieve the desired bend, with similar maximum force exerted. However, the 40 Shore A material is capable of maintaining similar force levels in more positions.

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The aim of the study was to design and implement an exoskeleton equipped with pneumatic soft actuators suitable for the rehabilitation movement of fingers when attached to the hand (Figure 10). Both the design and construction can be deemed successful as a functional device was completed. The compliance with the prescribed criteria is as follows:

- It is safe to use due to the chamber design preventing abnormal finger movements.
- It can be easily removed from the hand thanks to the Velcro fastenings.
- Wearing it minimally restricts natural hand movements while providing sufficient space.
- It is comfortable to wear with a weight of approximately 140 g
- It minimally adapts to the size of the palm due to the method of attachment.
- It is resistant within the temperature range of -20°C to 50°C.
- It is unaffected by humid environments.
- The actuator's material shows no permanent damage or deformation after multiple uses.
- It achieves the maximum desired bending at 0.6 bar pressure.
- It can achieve a bending angle of 270°.

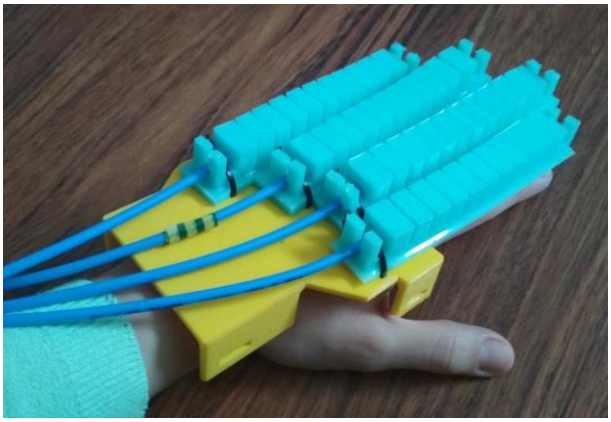

Figure 10: Fully assembled hand exoskeleton with entirely flexible soft actuators

The device meets the initial expectations and fulfills its function during operation. While the device adheres to dimensional limits, the experience of wearing it suggests that these dimensions are at their limits; specifically, the accommodating device could be of a smaller size.

This device offers numerous possibilities for further development. The mechanical design could be further refined to make the device smaller and more comfortable for long-term wear. Since the accommodating unit is made of rigid plastic through 3D printing, choosing a different material could be advantageous. An ideal material would be more flexible and better conforming to the shape of the hand, possibly even mimicking its contours, such as a reinforced textile. From perspectives of material and cost efficiency, designing a connection method that allows adjustable positions for finger attachment to the accommodating unit could be effective. This approach would eliminate the need for individual molds for each finger size, making a few general-sized devices sufficient. Longer fingers could be secured closer to them, while shorter ones could be fixed farther away. However, this must be within certain limits to avoid excessive bending of the palm.

Another crucial development opportunity lies in enabling controllable operation. Currently, the device requires manual operation, where the applied pressure is manually adjusted without any feedback on its position. For everyday use, it is essential for the device to operate autonomously. This requires sensors capable of detecting movement intentions, triggering the process accordingly. Such sensors typically detect muscle activity, like EMG sensors. Regulation would occur effectively with feedback during operation, such as force exertion or current bending angle and position, providing relevant feedback for adjustments.

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