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Novel Deployment Possibilities of Pneumatic Muscles in Rehabilitation and Gripping

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Abstract
One of the most attractive aspects of pneumatic actuation is the light weight of the utilized components causing favourable response to commands. This positive response also known as compliance is due to air compressibility and can be adjusted via the control pressure. Compliance is an essential feature in the man-machine relationship as well as in high-precision operations like the handling of fragile objects or automated assembling. This feature ensures delicate contact and the safety of the human operator. The pneumatic muscle is an actuator with inherently compliant behaviour, rendering it adequate for equipment that requires a response of this type. The paper presents technical solutions developed by the authors involving the utilization of pneumatic muscles in medical rehabilitation equipment and soft gripper systems.

Keywords
pneumatic muscles, medical rehabilitation equipment, soft gripper systems

1. Introduction

Pneumatic or pressurized artificial muscles (PAM) are contractile actuators that function by means of fluids in liquid or gas form. Their role is to enable controlled linear or angular movements of amplitudes depending on the pressure of the utilized fluid. The linear or angular deformation of pressurized artificial muscles can be controlled by an optimized geometry and the selection of adequate materials. By implementing specific types of synthetic fibre reinforced elastomers pressurized artificial muscles can be obtained the performance of which exceeds that of pneumatic cylinders.

This paper focuses on linear pneumatic muscles whose functioning is based on the deformation of an elastic membrane under the action of compressed air. The functional principle of this muscle mimics that of biological muscles, generating displacement by changing their geometrical form when subject to pressure. Actuators of this type offer a number of benefits like the capacity of absorbing shocks and shoch-resistance, a favourable power-to-volume ratio: 1.1 W/cm^3 [1], a high power-to-mass ratio (500 W/kg – 2 kW/kg) [2], elasticity, compliance, easy connectivity, and safe operation.

The most recent generations of pressurized artificial muscles consist of an elastomer tube reinforced with synthetic fibres. The utilized elastomers include natural rubber, silicon rubber, as well as other types of synthetic rubbers, while the fibre can be made from metal, nylon, carbon fibre, glass fibre and other high-strength synthetic materials [3].

Over the years an increasing number of manufacturers became interested in developing linear pneumatic muscles. Bridgestone of Japan commercialized this idea already in the 1980s under the name Rubbertuators. The Shadow Robot Company introduced the Shadow Air Muscle (SAM) capable of contraction by up to 37% of its initial length [4]. The most important European industrial manufacturer of pressurized artificial muscles is Festo AG. & Co of Germany. Their pneumatic muscles consist of a flexible tube made from a composite rubber reinforced with aramid fibre. The utilized elastomer is chloroprene that forms a matrix including a 3D mesh of inelastic aramid fibres arranged by a diamond pattern (Figure 1). The reinforcement of the flexible tube by a 3D mesh of synthetic fibres was aimed at improving certain behavioural characteristics, like reducing radial and promoting axial deformation, while increasing flexibility and durability of the entire system.

This concept was inspired by the design of motor vehicle tyres. In the case of pneumatic muscles, however, the focus is on the careful placement of each aramid fibre, so that despite the large number of fibres these are not in touch one with another.

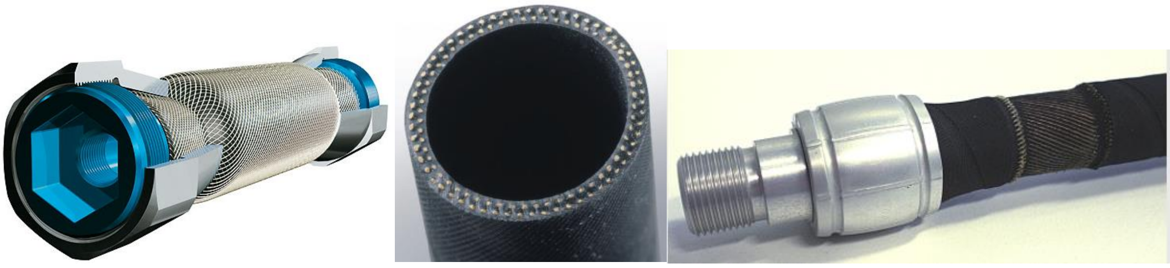


Fig. 1. Construction and structure of a Festo pneumatic muscle

The interior diameters of the elastic tubes used in pneumatic muscles manufactured by Festo are of 10, 20 or 40 mm, respectively, and the thickness of the chloroprene wall varies between 1 and 2 mm. In small diameter muscles the number of fibres is 60 arranged in two layers, while in large diameter muscles fibre number can reach 240. Each fibre hast a diameter of 0.1 to 0.3 mm [5, 6].

The Festo pneumatic muscle contracts rapidly and generates a traction force that is colinear with the muscle axis. This force reaches its maximum immediately at the beginning of the contraction, and decreases to zero by the end of the stroke. The muscle shortens proportionally with the internal pressure, its maximum contraction being 20% of its initial length.

Based on the known characteristics, advantages and disadvantages of Festo pneumatic muscles, this paper further presents a number of concepts developed by the authors at the Department of Industrial Engineering and Management at Transilvania University of Brasov, Romania.

2. Applications of Pneumatic Muscles

The research conducted by the authors was aimed at two types of applications. The first category envisages concepts of medical rehabilitation equipment for the various joints of the human body. The second category concerns the development of soft robotic gripper systems used in automated assembling operations.

2.1. Rehabilitation equipment of the lower limb bearing joints

Rehabilitation equipment are medical systems that facilitate the exercising of muscles at constant or variable speed, following the indication of specialists. Numerous studies have proved that the use of such equipment significantly reduces recovery time, and thus patients need a smaller quantity of pain medication. Consequently, the total costs associated with the recovery process are considerably reduced.

An innovative constructive solution was developed for rehabilitation equipment targeting lower limb joints (hip, knee, ankle), featuring a pneumatic muscle-based actuation system. Studies conducted on such recovery systems available on the marketplace have defined the motion angles to be achieved by the joints of the equipment matching the movements of a healthy human leg. These angles have the following values:

- for the hip joint: $\Delta\varphi_1 \approx 30°$;
- for the knee joint: $\Delta\varphi_2 \approx 60°$;
- for the ankle: $\Delta\varphi_3 \approx 60°$

Starting from the authors' invention patent [7] a device for rehabilitation by continuous passive motion was conceived. Its principle and prototype are presented in Figure 2. Rehabilitation exercising is achieved with the help of a pneumatic muscle that actuates a slide (D) with a maximum stroke of 300 mm. The equipment utilizes a pneumatic muscles of 20 mm interior diameter and 750 mm initial length. Taking into consideration that the axial deformation of the muscle is of about 150 mm, a two-pulley mechanism was inserted between the muscle and the slide. One of the pulleys is mobile in order to amplify the slide's displacement to the required value (300 mm).

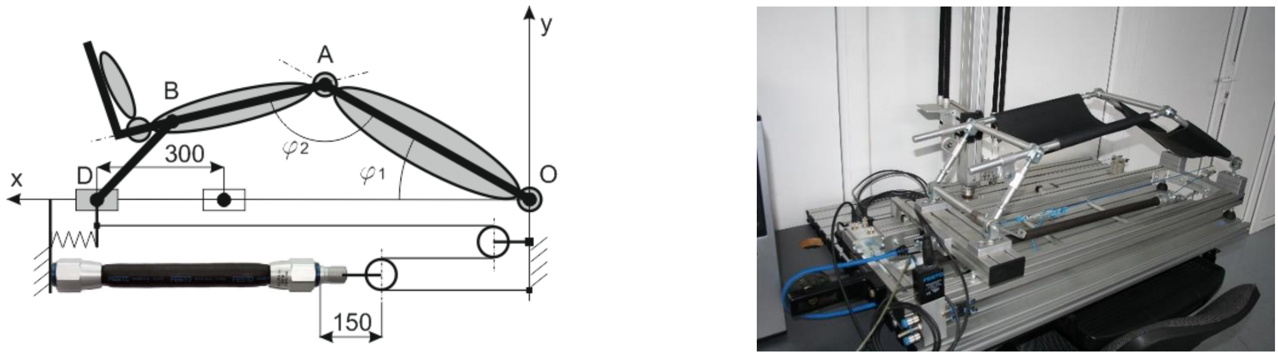
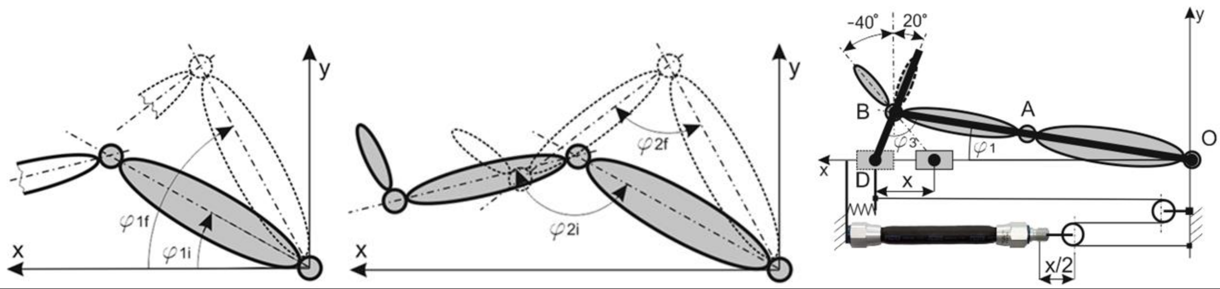


Fig. 2. Construction of the leg joints rehabilitation equipment

The amplitudes of the movements carried out with the help of this equipment are shown in Figure 3.



Hip	Knee	Ankle
$\Delta\varphi_1 \approx 32°$	$\Delta\varphi_2 \approx 55°$	$\Delta\varphi_3 \approx 58°$

Fig. 3. Angular amplitudes of the joint movements

Figure 4 presents the structure of the positioning system. It consists of: a pneumatic muscle controlled by an MPYE proportional directional control valve (Festo); a resistive position transducer mounted on the slide: an SPC 200 controller for the programming and saving of working positions, types of movements and their sequence (controller programming, operation and diagnosis are achieved by means of WinPISA software); the electronic elements for the transmission of information from the transducer to the controller, as well as of the commands issued by the controller to the proportional valve are included in the SPC-AIF interface [8].

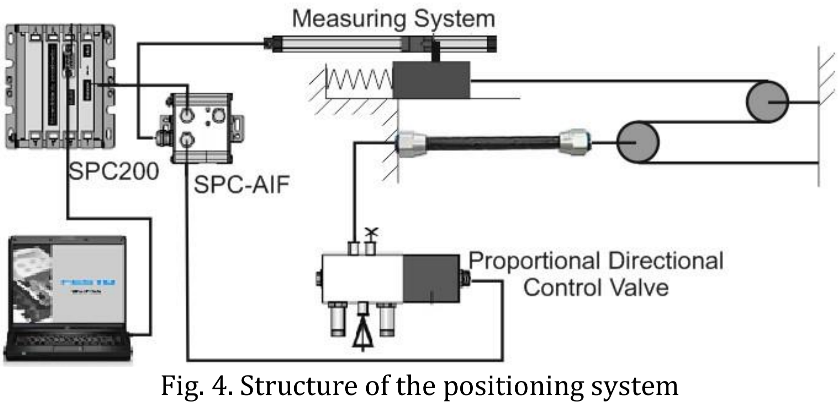


Fig. 4. Structure of the positioning system

The entire positioning assembly allows the programming of one or more rehabilitation exercise cycles, depending on the degree of mobility of each patient.

In addition to the functional features presented above, of importance is also the economic aspect associated with such rehabilitation equipment. The cost of the described constructive solution is estimated at 60-70% of the price of equipment available on the marketplace at present, that are actuated by electric motors.

2.2. Rehabilitation equipment of the hand joints

The simultaneous rehabilitation of the hands and the fingers has been made possible by an innovative piece of equipment actuated by a pneumatic muscle manufactured by Festo. The idea underlying this novel equipment is bio-inspired from the Fin-Ray effect caused by fish fins (Figure 5) [9]. The Fin-Ray effect was described by Leif Kniese in 1999 [10] based on the movements of the manta-ray fins. The fin skeleton of these fish consists of two bones displayed in a V-shape with connective tissue between. Traction on one side of the V causes the deformation of the fin [11].

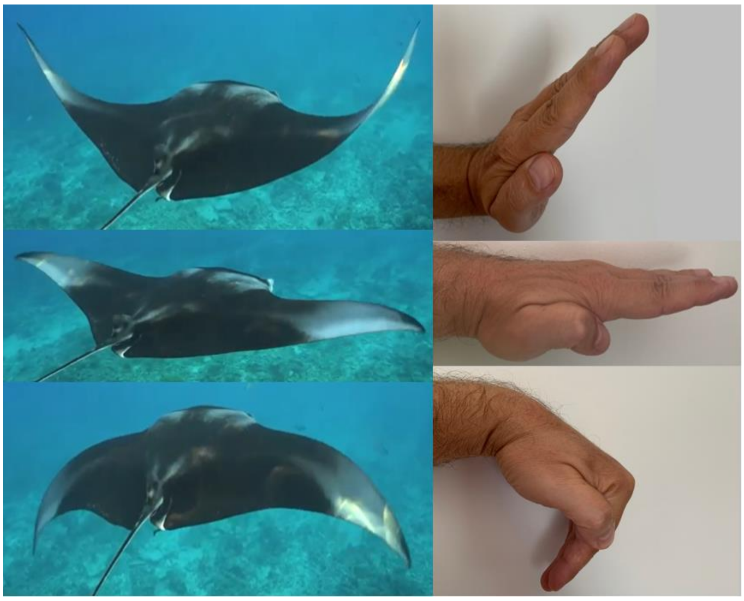


Fig. 5. Similarity between the motions of the manta ray fin and human palm

Based on these insights, the design of the palm support resembles the flexible structure of a manta ray, giving the rehabilitation equipment distinctive mobility features. A key advantage of this design is its ability to facilitate the simultaneous exercising of multiple joints.

Table 1 presents an overview of the motions and indicates the maximum speeds that can be achieved by rehabilitation equipment available at present.

Table 1. Limits of the hand and finger joint motions

Joint		Motion	Rotation angle [°]	Rotation speed [°/min]
Wrist		Flexion	0 to 80	30 to 180
		Extension	0 to 70	
Joints of the fingers	Metacarpal - phalangeal	Flexion	0 to 90	55 to 440
		Extension	0 to 90	
	Proximal	Flexion	0 to 120	
	Distal	Flexion	0 to 90	
		Extension	0 to 90	

Figure 6 presents the principle of the equipment. For a comfortable positioning of the hand on the equipment, the structure consists of two identical Fin-Ray-type mechanisms positioned in parallel and connected by distancing elements [9].

The Fin-Ray-type structure consists of two identical series-connected bar mechanisms, ABCD and BCFE. The motion of lever AB is generated by causing the rotation of joint A. The whole assembly is activated through a rack and pinion mechanism, the actuator being a pneumatic muscle. Figure 7 shows the rehabilitation equipment in start position and Figure 8 shows the pneumatic control diagram of the rehabilitation system.

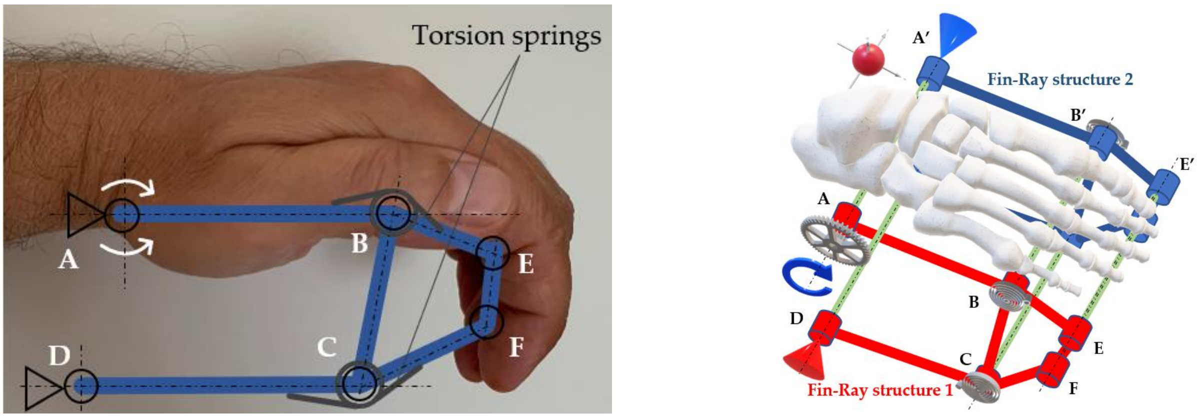


Fig. 6. Principle of the hand support based on the Fin-Ray effect

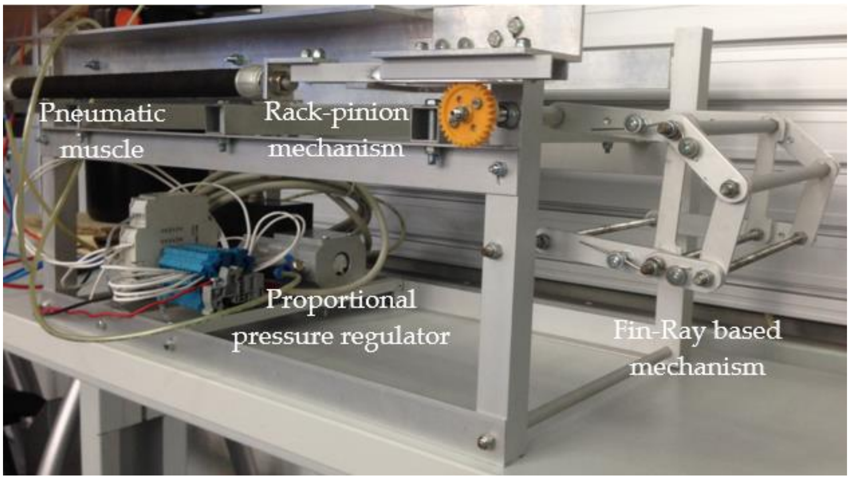


Fig. 7. Construction of the rehabilitation equipment

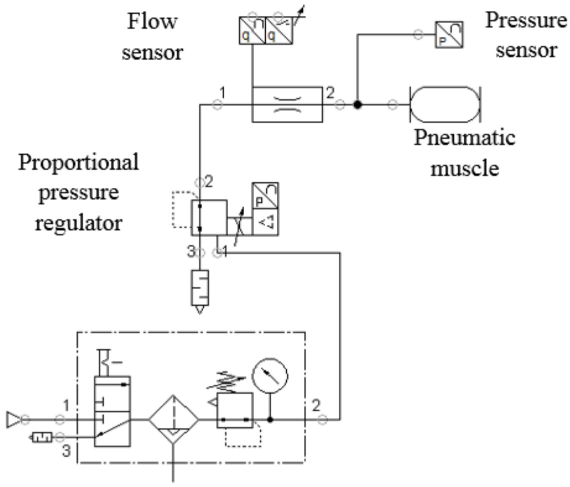


Fig. 8. Control of the rehabilitation equipment by a proportional pressure regulator

Experimental research conducted on the prototype of the rehabilitation equipment showed that its motions meet the requirements laid out in Table 1.

2.3. Elbow rehabilitation equipment

The elbow is one of the most sensitive joints of the human body, as it is heavily strained due to its position between shoulder and the wrist. The functional significance of the elbow is evident, as a lesion at this level could hinder the function of the entire upper limb. The functional analysis of the elbow capsule reveals two distinctive rotation couples: one for flexion and extension, and one for pronation and supination. The variation range of the angles that have to be achieved for flexion-extension is form -90° to +50°, while for pronation-supination the interval is of ±90°.

Starting from the input values a prototype of the elbow rehabilitation equipment actuated by pneumatic muscles was designed and manufactured. Figure 9 presents the proposed principle and Figure 10 shows the geometric model.

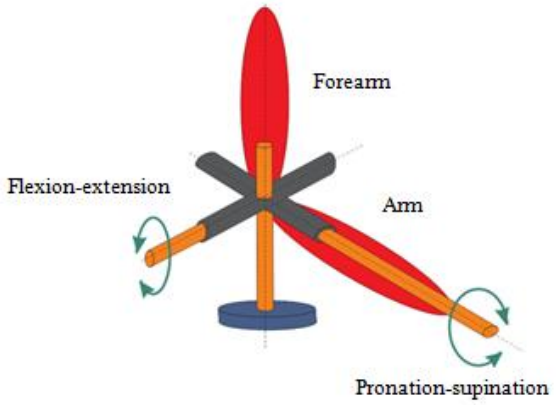


Fig. 9. Principle of the rehabilitation equipment

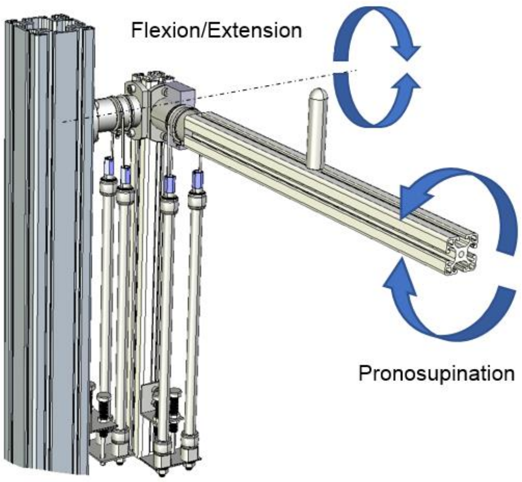


Fig. 10. Geometric model of the rehabilitation equipment

Figure 10 shows the positioning of the muscles referred to the human arm, in order to enable rehabilitation exercising. One pair of muscles generates flexion-extension, while the other pair positioned by a perpendicular axis ensures pronation-supination. The two rotations of the hand support are obtained by the antagonist operation of the pneumatic muscles (while one muscle is charged, the other is discharged). The neutral position is obtained when both muscles are fed the same pressure. The two types of motion are performed non-simultaneously, each separately and in sequence.

Figure 11 shows an image of the prototype, and Figure 12 presents its actuation diagram [12, 13].

Fig. 11. Prototype of the rehabilitation equipment

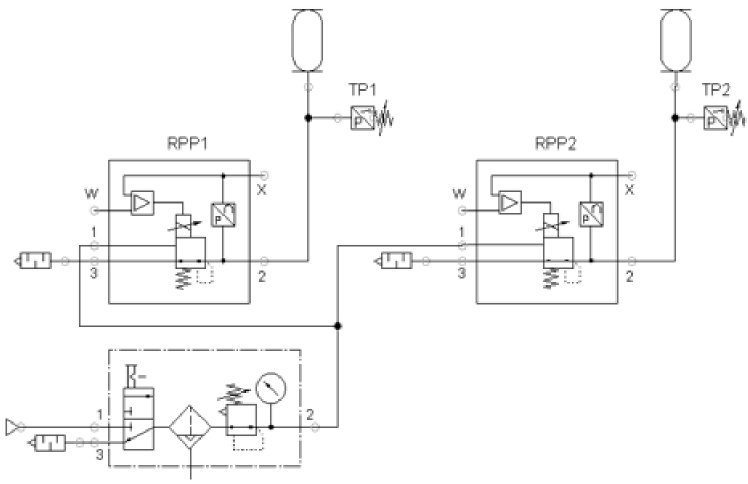


Fig. 12. Diagram of the pneumatic actuation

The two pneumatic muscles are charged with air via two proportional pressure regulators (RPP1 and RPP2) MPPES-3-1/4-6-010 (Festo). Each pressure regulator is equipped with a sensor that monitors air pressure at the exhaust of the device. An electronic control unit compares this pressure to a preset reference value. If the exhaust pressure of the regulator does not match the reference value, the control unit generates correction analogue electric signals until the two values become identical.

Testing of the equipment confirmed that it meets its proposed purpose, as the rotation angles reach the imposed values.

2.4. Neck joint rehabilitation equipment

The dysfunctions caused by neck joint trauma have a high recovery rate and afford patients significant chances of rapid reintegration into everyday activities and home life. An essential component of the general strategy devised for swift patient recovery is deploying rehabilitation equipment for the complex neck joint.

The neck joint enables motions in the three anatomic planes: frontal, sagittal and transverse. In the frontal plane, the neck performs lateral left/right flexion with maximum angles of ± 45°. In the sagittal plane maximum flexion is of 50°, and the extension of 60°. In the transverse plane, the neck joint carries out left/right rotations with angular amplitudes of ±80°. Starting from these data a rehabilitation equipment was conceived the kinematic diagram of which is shown in Figure 13.

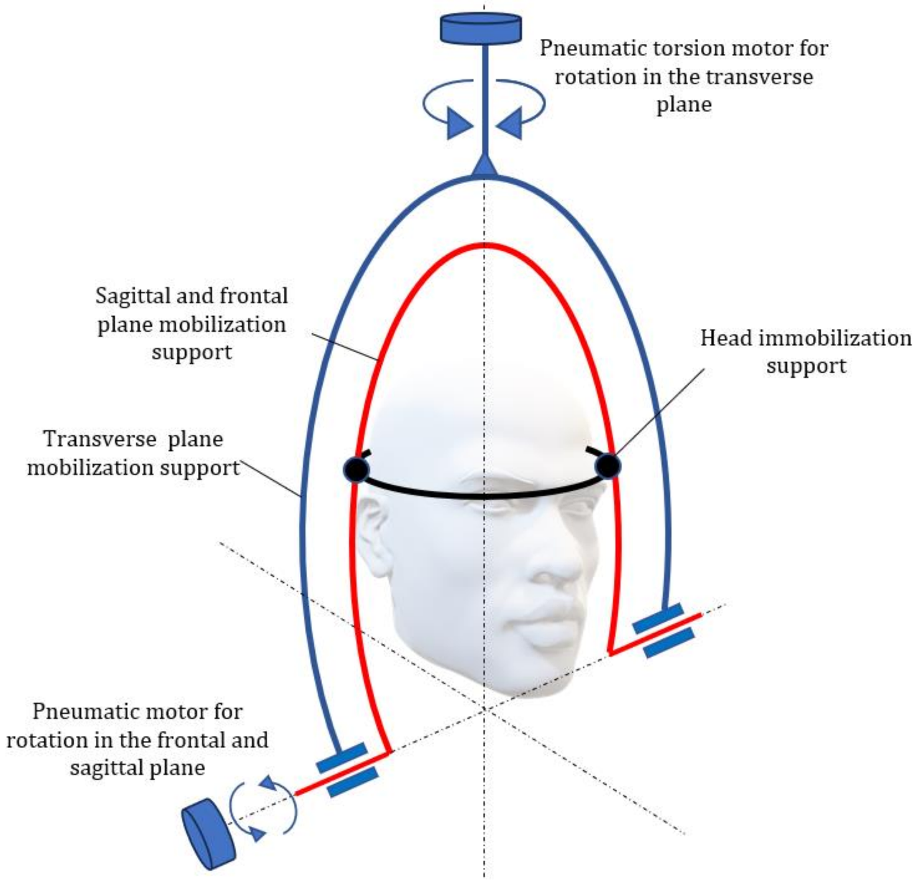


Fig. 13. Principle of the neck joint rehabilitation equipment

The patient’s head is immobilized in a cylindrical support and is rotated in the three anatomic planes by means of two pneumatic motors. A torsional pneumatic motor actuated by two antagonistic pneumatic muscles generates the neck’s rotation by the vertical axis. By their antagonistic operation the muscles generate rotation of ±80° amplitude, and ensure the equilibrium of any certain intermediary position of the actuated system [14]. The motions in the other two planes (sagittal and frontal) are generated via a single pneumatic motor, materialized by a pneumatic muscle.

The prototype of the equipment is shown in Figure 14.

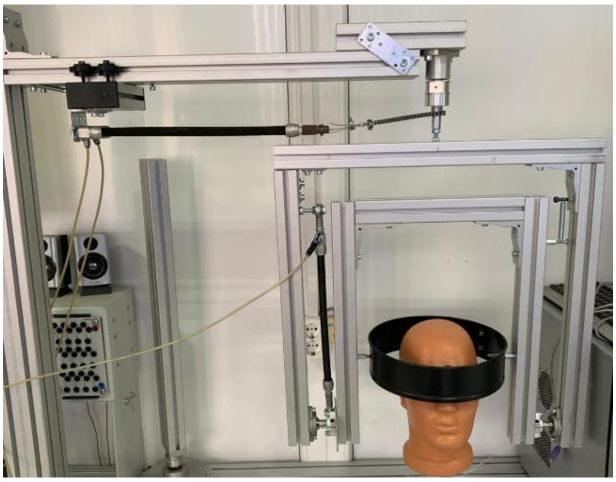


Fig. 14. Prototype of the rehabilitation equipment

The neck rehabilitation equipment meets two operational requirements simultaneously: high positioning precision and high adaptability to the patient's pain threshold. The latter requirement calls for an adjustable compliance of the actuation system. The deployment of actuation systems benefitting from this feature allows minimizing high forces generated during collisions (shocks). Such systems are able to store and release energy by passive elastic elements and ensure safe interaction with the user. Due to the adjustable compliance of the pneumatic muscles the equipment swiftly adapts to the patient's state and more specifically to the patient's pain threshold. The experiments conducted on this equipment demonstrated that the rotations meet the imposed limits.

2.5. Soft gripper system for assembling operations

One of the most important requirements of an industrial gripper systems is structural rigidity. This can be ensured by conceiving a system with a small number of degrees of mobility, achievable at low costs. Unlike industrial grippers, mechanical hands mimic the behaviour of natural systems and thus have a complex structure. Their compliant behaviour and high dexterity render them adequate for more delicate applications, like grabbing fragile and/or deformable objects, or automated assembling. Compliant gripper systems can be developed with pneumatic muscles as actuators. The use of pneumatic muscles is recommended due to their inherently compliant operational characteristics. This compliance arises from the compressibility of air and can be adjusted by varying the working pressure.

Such a gripper system was designed, manufactured and tested by the authors. Its principle (Figure 15) shows a parallel system with two mobile jaws and a rack-and-gear power transmission mechanism [15]. The pneumatic muscle is positioned asymmetrically in order to fit the proportional pressure regulator that controls the motor's motion into the metal casing of the system.

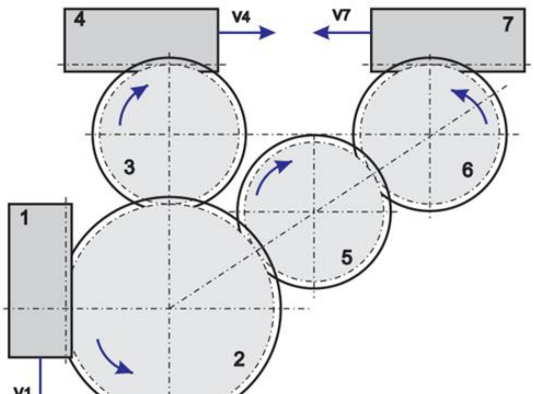


Fig. 15. Principle of the gripper system

The developed gripper system uses a pneumatic muscle manufactured by FESTO AG & Co: MAS-10-45N-AA-MC-O-ER-EG, with an interior diameter of 10 mm and an active part of 45 mm length (Figure 16).

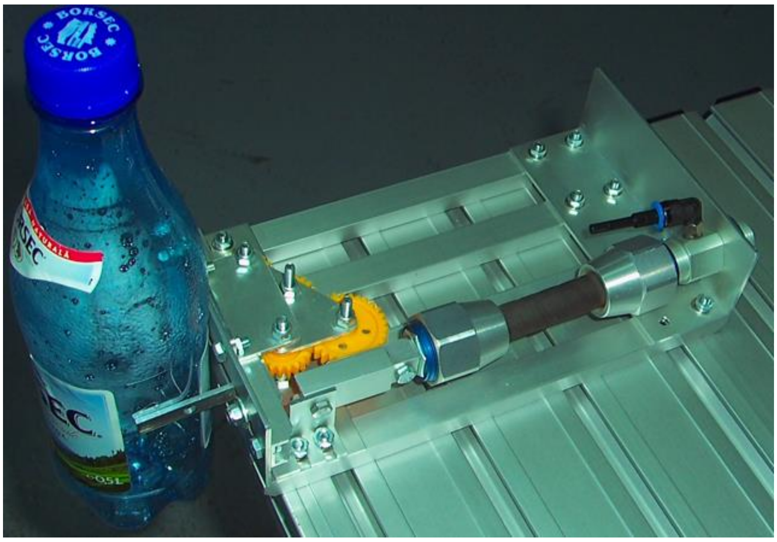


Fig. 16. Construction of the gripper system

Experimental research conducted on this gripper system revealed a non-linear relationship between the force developed by the jaws and their displacement. This suggests that the system displays a compliant behaviour, adequate for assembling operations. Specifically, when two parts to be assembled are misaligned, the compliant system offers the benefit of adaptability to the circumstances, enabling assembling without damage to either component.

5. Conclusions

Pneumatic muscles made from of elastomers reinforced with aramid fibres offer a novel solution for applications in industry or medical rehabilitation. They serve as a viable alternative to traditional pneumatic cylinders. Pneumatic muscles offer significant flexibility, high force output, and an excellent energy-to-mass ratio. Furthermore, pneumatic muscles represent a practical option for rehabilitation systems due to their lightweight design, portability, safe operation, reliability, adaptability, and ease of integration into wearable assistive technologies.

References

1. Chou C.-P., Hannaford B. (1994): *Static and dynamic characteristics of McKibben pneumatic artificial muscles*. Proceedings of the 1994 IEEE International Conference on Robotics and Automation, ROBOT 1994, Vol. 1, pp. 281-286, https://doi.org/10.1109/ROBOT.1994.350977
2. Caldwell D.G., Tsagarakis N., Medrano-Cerda G.A. (2000): *Bio-mimetic actuators: polymeric Pseudo Muscular Actuators and pneumatic Muscle Actuators for biological emulation*. Mechatronics, eISSN 1873-4006, Vol. 10, iss. 4-5, pp. 499-530, https://doi.org/10.1016/S0957-4158(99)00071-9
3. Zhang Z. (2012): *Modeling, Analysis, and Experiments of Inter Fiber Yarn Compaction Effects in Braided Composite Actuators*. PhD Thesis, Virginia Polytechnic Institute and State University, Blacksburg, USA, https://vtechworks.lib.vt.edu/server/api/core/bitstreams/359901c0-acdf-42f6-b497-2a585fc9c4ea/content
4. Shadow Robot Company: *Shadow 30 mm Air Muscle – Specification*. https://www.shadowrobot.com/downloads/datasheet_30mm_sam.pdf. Accessed 2020-06-14
5. Festo: *Precisely to the point: membrane technology*. https://www.festo.com/cms/en_corp/14047.htm. Accessed 2020-06-15
6. *Membrane technology flexes its muscle – precisely*. http://www.pneumatictips.com/3970/2015/05/featured/membrane-technology-flexes-its-muscle-precisely/. Accessed 2024-12-23
7. Deaconescu T., Deaconescu A. (2017): *Echipament destinat antrenării şi reabilitării articulaţiilor portante ale membrului inferior prin mişcare continuă pasivă* (*Equipment meant to train and rehabilitate the weight bearing joints of a lower limb by passive continuous motion*). Patent RO 126094 B1 (in Romanian)

8. Petre I., Deaconescu A., Rogozea L., Deaconescu T. (2014): *Orthopaedic Rehabilitation Device Actuated with Pneumatic Muscles*. International Journal of Advanced Robotic Systems, eISSN 1729-8814, Vol. 11, is. 7, https://doi.org/10.5772/58693
9. Filip O., Deaconescu A., Deaconescu T. (2021): *Mechanical Design of a Bioinspired Compliant Robotic Wrist Rehabilitation Equipment*. Applied Sciences, eISSN 2076-3417, Vol. 11, is. 3, 1246, https://doi.org/10.3390/app11031246
10. Kniese L. (1999): *Load carrying element with flexible outer skin*. Patent EP 1040999 A2
11. *EvoLogics BOSS - Manta Ray*. https://evologics.de/projects/boss. Accessed: 2020-09-15
12. Vetrice G. (2022): *Cercetări privind echipamentele de reabilitare a articulației cotului acționate cu ajutorul mușchilor pneumatici* (*Research concerning the elbow rehabilitation equipment actuated by pneumatic muscles*). PhD thesis. Transilvania University of Brașov, Romania (in Romanian)
13. Vetrice G., Deaconescu A. (2017): *Development of elbow rehabilitation equipment using pneumatic muscles*. Proceedings of the 8th International Conference on Manufacturing Science and Education – MSE 2017, MATEC Web of Conferences, Vol. 121, art. 01017, https://doi.org/10.1051/matecconf/201712101017
14. Mareş S., Deaconescu A., Deaconescu T. (2024): *Pneumatically Actuated Torsion Motor for the Transverse Rehabilitation of the Neck Joint*. Actuators, eISSN 2076-0825, Vol. 13, art. 363, https://doi.org/10.3390/act13090363
15. Deaconescu T., Deaconescu A., Negrea D. (2019): *Sistem de prehensiune paralel cu două bacuri, asimetric, acţionat cu muşchi pneumatici* (*Parallel asymmetrical prehension system with two wedge grips, actuated by pneumatic muscles*). Patent RO 130331 B1 (in Romanian)
16. Negrea D., Deaconescu A., Deaconescu T. (2014): *Actuation by Pneumatic Muscles of a Parallel Asymmetric Gripper System*. Applied Mechanics and Materials, eISSN 1662-7482, Vols. 548-549, pp. 943-947, https://doi.org/10.4028/www.scientific.net/AMM.548-549.943