Applications of Pneumatic Muscles Developed within the Festo National Fluid Actuation and Automation Training Centre in Braşov

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Abstract
Pneumatic muscles are increasingly used for the actuation of robot or general industrial systems due to their benefits compared to pneumatic cylinders. The deployment of pneumatic muscles in rehabilitation equipment developed for the upper and lower limbs has been a concern of the Festo National Fluid Actuation and Automation Training Centre at Transilvania University of Braşov. The paper presents and discusses a number of constructive solutions devised for such rehabilitation equipment designed to ensure a swift and cost efficient social and workplace reintegration of the patients. The rehabilitation equipment discussed in this paper achieve the mobilisation of the lower limb bearing joints, as well as of the wrist, knuckles and elbow by continuous passive motion. The diagrams of principle and of actuation of such equipment are presented, the developed prototypes and their performance. The absolute novelty brought by such equipment consists in the utilisation of the pneumatic muscle as actuator, what ensures a light and highly compliant structure that satisfies the safety requirements related to interaction with humans.

Keywords
Pneumatic muscles, rehabilitation equipment, continuous passive motion

1. Introduction

The Festo National Fluid Actuation and Automation Training Centre at Transilvania University of Braşov was established in 2006, first as a regional entity, upgraded to National Centre status in 2016. The main objectives of the centre are ensuring the necessary training of personnel from industry nationwide in the field of pneumatic and hydraulic actuation and automation, as well as the training of students in view of enabling their smooth integration into the labour market. The National Centre together with FESTO SRL of Bucharest also organises periodically presentations of the most recent technical achievements of FESTO AG & Co KG.

Benefitting from permanently updated high performance apparatus, the Centre's activity has also included research, financed from contracts secured by national or international competition or with industry nationwide. The research has been focused on the utilisation of pneumatic muscles – novel elements developed by FESTO AG & Co KG – for achieving medical rehabilitation equipment or for industrial robot systems. The results of the conducted research also materialised in a number of completed PhD theses.

This paper presents a series of the research results, namely rehabilitation equipment of the lower limb bearing joints, as well as of the wrist, knuckles and elbow, all actuated by pneumatic muscles. The diagrams of principle and of actuation of such equipment are presented, as well as the developed prototypes and their performance.

2. Pneumatic Muscles

The functional morphology of living beings has always represented a permanent source of inspiration for identifying innovative solutions for high-tech constructions. In this regard, since the 1960s a new branch of science has emerged and grown, namely bionics (biomimetics), which combines concepts from biology, mathematics, medicine and engineering. Bionics is based on biological intuition and engineering pragmatism such as to adapt nature's projects to the requirements of modern technology. Nature is but the starting point for innovation, it merely offers hints as to what can be used in a mechanism [1].

Regarded as a process, bionics can be approached from two perspectives, namely top-down (analogy bionics) and bottom-up (abstractive bionics). Analogy bionics identifies technical solutions based on natural models; thus the concept of pneumatic muscles emerged from analysing the movement of living beings. If in the case of natural systems the forces required for motion are developed by the muscles, in industrial systems forces are generated by motors. The pneumatic muscle appeared within this context, a bio-inspired system analogous to the muscles of humans and animals (Fig. 1).

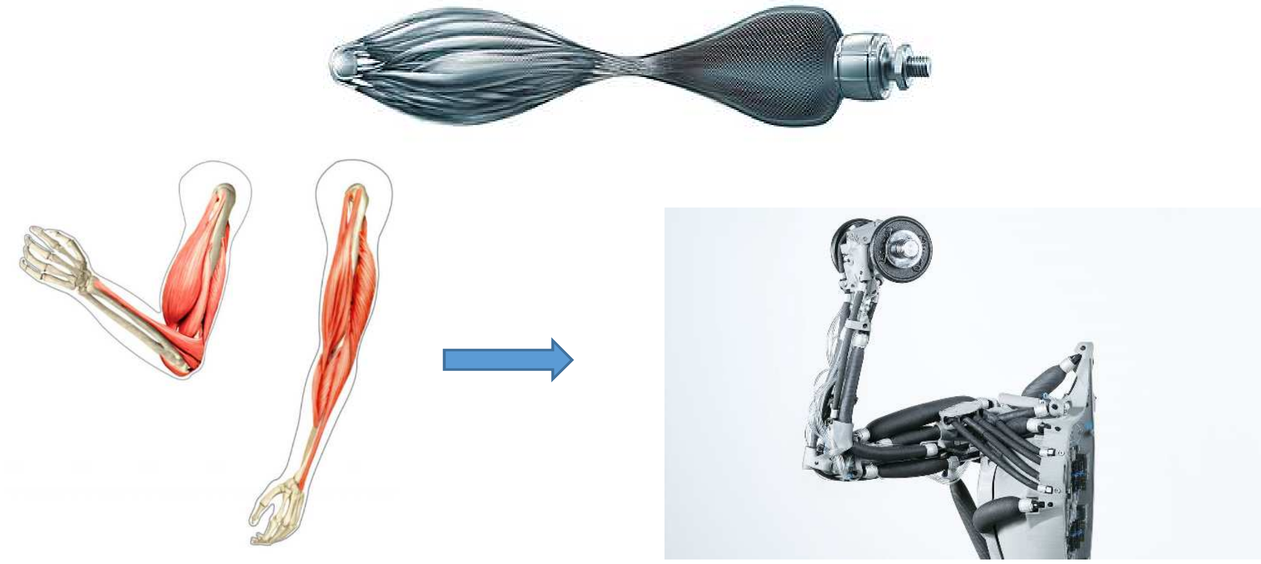

Fig. 1. Transition from the human to the pneumatic muscle

Pneumatic muscles are contracting actuators similar to single acting linear motors fed with compressed air. The driving effect of such actuators is achieved by controlled deformation, the length of the stroke depending on the fed pressure.

The pneumatic muscle is a system based on a contracting membrane and whose operating principle is similar to that of the human muscle; thus displacement is caused by the muscle changing its geometric form under pressure. Being made from an elastomer tube reinforced with synthetic fibres, the pneumatic muscle contracts rapidly and generates pulling forces when fed compressed air. As the compressed air penetrates the muscle, the traction force generated along its longitudinal axis causes the muscle to shorten proportionally to the increase of the internal pressure. The pneumatic muscle generates the maximum of its pulling force as soon as its contraction starts, while at the end of the stroke the developed force is zero [2, 3].

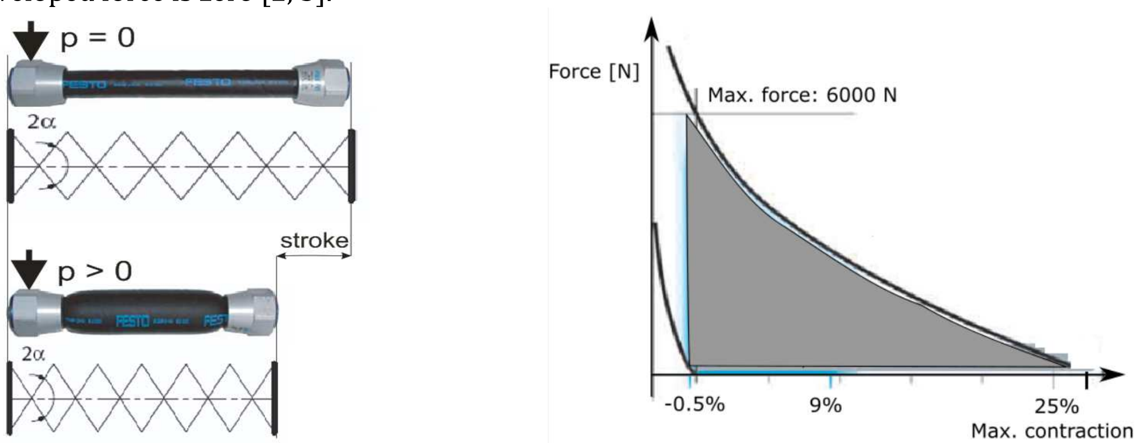

Fig. 2. Working principle and limits of the pneumatic muscle

To date the utilisation of pneumatic muscles has not spread widely because of insufficient knowledge of their performance, as well as because of certain disadvantages related to the control of the systems actuated by these. Many variants are available for the control of these systems, such as PID conventional control [4], adaptive control [5], control based on the computed torque method [6], neural networks [7], sliding mode control and implementation [8], etc.

At the Festo National Fluid Actuation and Automation Training Centre several applications of pneumatic muscles have been designed and tested, conceived mostly for continuous passive motion based rehabilitation equipment of the upper and lower limbs. Further on the paper presents a series of these achievements.

3. Rehabilitation Equipment for the Lower Limb Bearing Joints

Continuous Passive Motion (CPM) is a method of post-surgical rehabilitation in the case of operations of the lower limb bearing joints. After such interventions the tissues surrounding the wound become rigid, thus significantly diminishing the mobility of the joint. As the natural recovery of the mobility could last in certain cases even several months, recovery exercising is called for.

The utilisation of continuous passive motion entails the mechanised mobilisation of the wrist that has suffered surgery, without straining the patient's muscles. This is achieved by means of specially conceived equipment, capable of applying to the joint the optimum motions for rehabilitation.

Research has proved that the deployment of such equipment significantly reduces the period of recovery, and the patients resort to smaller quantities of pain medication. Thus the total cost of healing is consistently diminished.

The rehabilitation equipment for continuous passive motion currently available on the marketplace is in most cases actuated by electric motors. As an alternative to this the idea emerged of conceiving equipment actuated by pneumatic muscles, yielding a smaller manufacturing cost of the devices.

Such a piece of equipment actuated by pneumatic muscles was designed at the National Training Centre. Figure 3 shows the kinematic diagram underlying its functioning, the structure of its positioning system and views of the entire rehabilitation system [9].

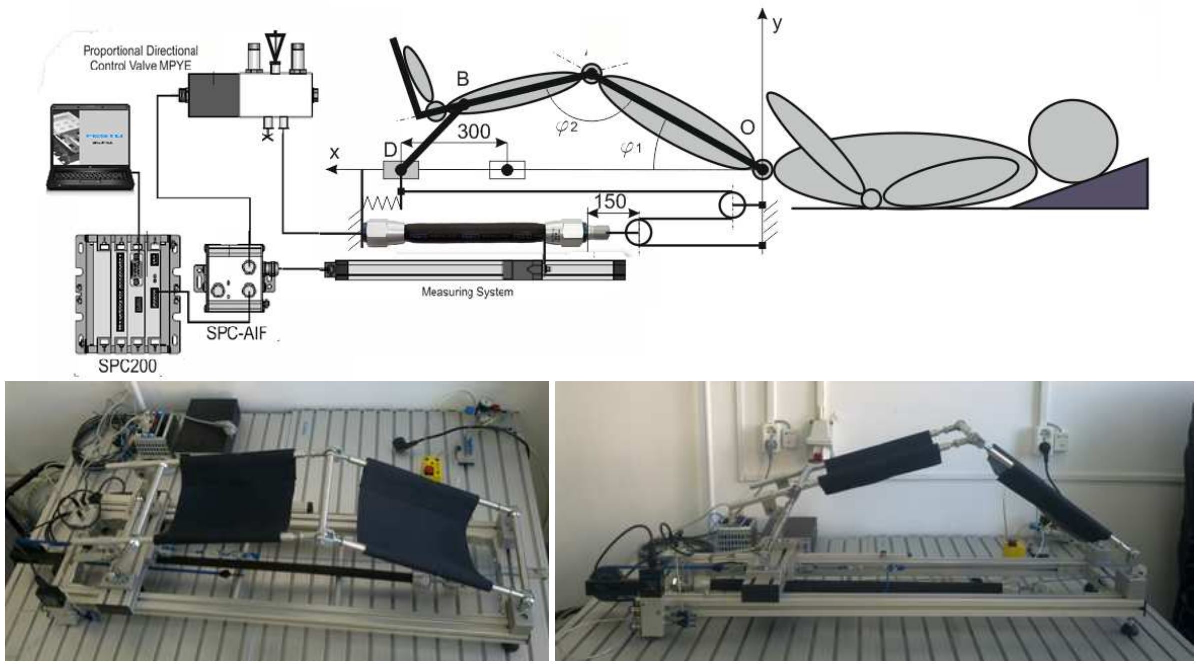

Fig. 3. Rehabilitation equipment of the lower limb bearing joints

The continuous passive motion is generated by a single pneumatic muscle of 20 mm interior diameter and 750 mm initial length, which displaces a slide by a stroke up to 300 mm. In order to carry out the rehabilitation motions, the slide is linked to a bar mechanism supporting the affected leg. As the maximum possible stroke achievable by the free end of the muscle is of approximately 20% of its initial length in relaxed state (*i.e.* 150 mm), a mobile pulley mechanism is placed between the muscle and the slide, such as to amplify the slide's displacement up to the required length.

The positioning system includes the following components: a resistive position transducer attached to the slide; a SPC 200 controller for programming and saving the working positions, the types of motion and their sequence; programming, operation and diagnosis of the controller are achieved by WinPISA software. The control variable is the displacement relative to the origin of the system and is measured by a transducer. The device allows the programming of single or multiple cycles of exercises, depending on the degree of recovery of the affected joints.

An example of utilisation of the equipment is the hip rehabilitation exercise presented further on, consisting of a sequence of movements described in figure 4. Starting from an initial angle of 35°, the angular positions of 45°, 55°, 50°, 55° are achieved successively, and eventually the initial position (35°) is regained [10].

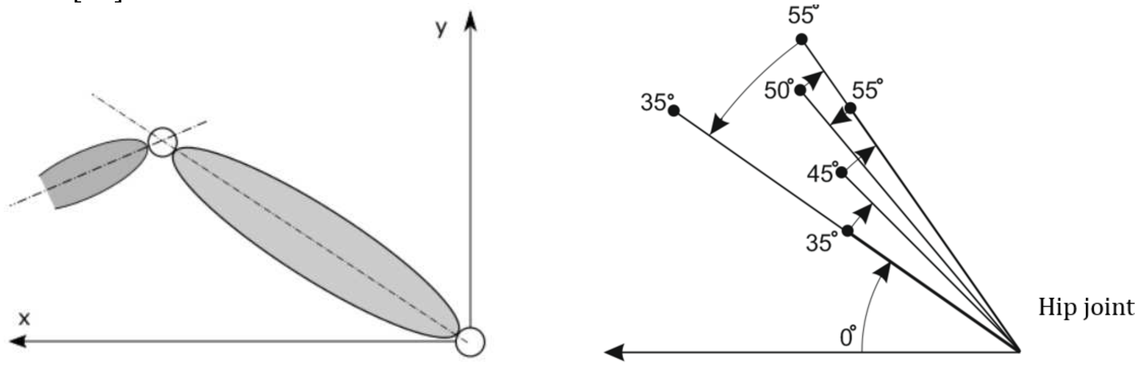

Fig. 4. Sequence of movements for hip rehabilitation

The graphs of Figure 5 illustrate the motions of the slide versus time.

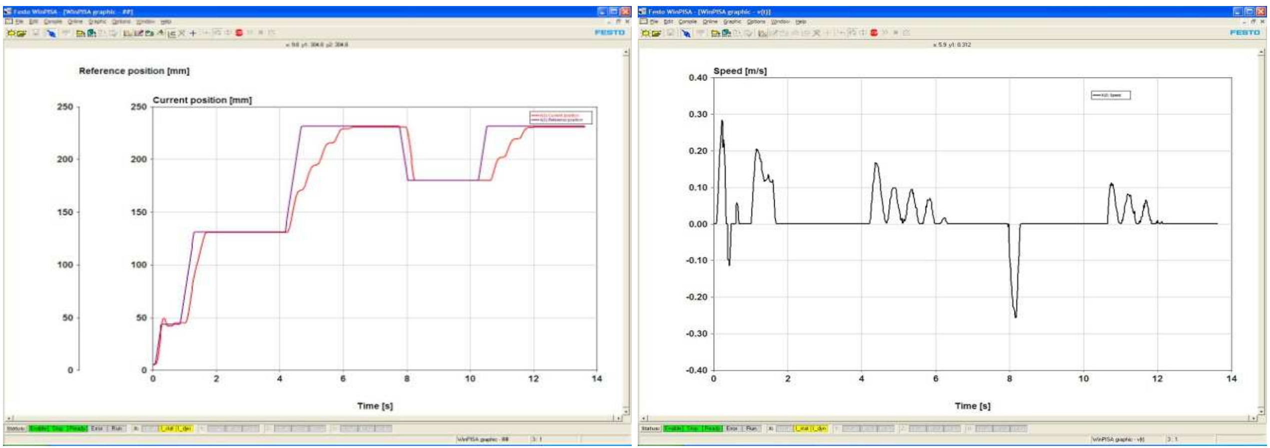

Fig. 5. Slide displacement and velocity versus time

The numerous tests conducted on this pneumatic muscle actuated equipment have led to the conclusion that the motion limits of the slide and implicitly the variation intervals of the lower limb joint rotation angles correspond to the requirements of the rehabilitation exercises. Also, the positioning precision of the slide as programmed is satisfactory for the requirements of this type of equipment, while the direction of motion is reversed shock-free, proving the compliant behaviour of the pneumatic muscle.

4. Rehabilitation Equipment for the Wrist and Knuckles

The motions of the equipment designed for the rehabilitation of wrist and knuckles are achieved by original, bio-inspired self-adaptive systems based on the Fin Ray effect, specific to the fins of fish. In this case too, pneumatic muscles were used as motion generators.

Fishes move with the help of their fins, which ensure stability and propulsion. Similarities could be observed between the motions of the human palm and fingers and the motions of a fish fin; thus the flexion-extension of the palm is similar to the oscillatory movement of the tail fin of fishes. In both cases the bone structure is set into motion by muscle groups located on either side of the skeleton working counter-time.

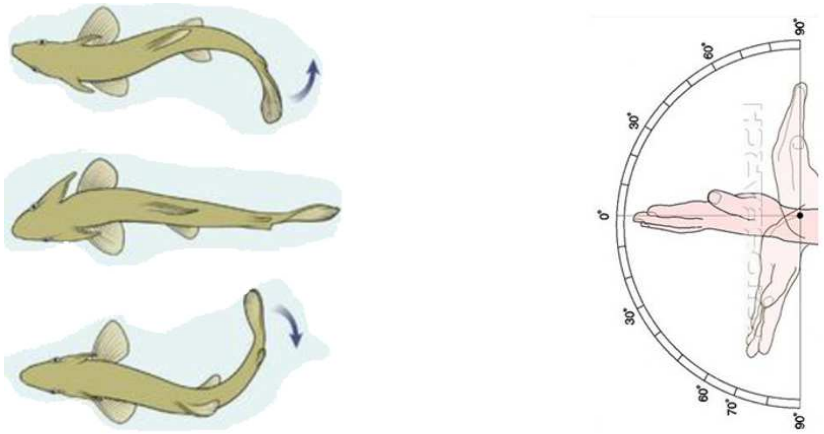

Fig. 6. Angular amplitudes of the fish tail find and of the palm

Certain differences exist, however, between the movement of the palm and that of the fish tail, which need to be taken into consideration in designing the palm rehabilitation equipment. One of these differences consists in the fact that the fish tail moves symmetrically in relation to its position at rest, while the flexion-extension angles of the palm have different values yielding a non-symmetrical movement. Another difference relates to the fact that the amplitude of finger movements is significantly greater than the of the tail fin tip of the fish; in flexion, the fingers turn the palm into a fist.

Fish fins are elastic structures including thin bony fibres, their makeup yielding the Fin Ray effect. In engineering a Fin Ray effect structure is obtained by series-connecting several four-bar mechanisms. For the entire mechanism to function as a fin, the four-bar mechanisms have to be arranged in a reverse, apex-down pyramid.

Based on these considerations a piece of rehabilitation equipment was conceived, the structural schematic of which is shown in Figure 7 [11]. Figures 8 and 9 illustrate the position of the hand on the mechanism for the maximum flexion and maximum extension of the fist, respectively.

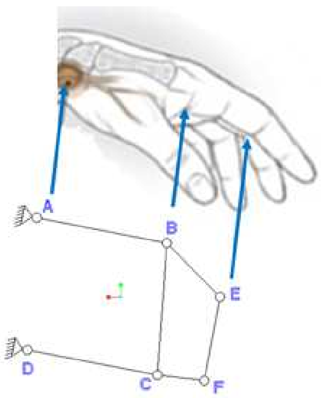

Fig. 7. Structural schematic of the rehabilitation equipment

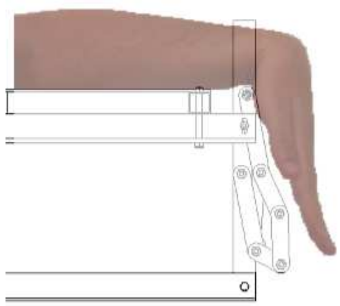

Fig. 8. Maximum flexion

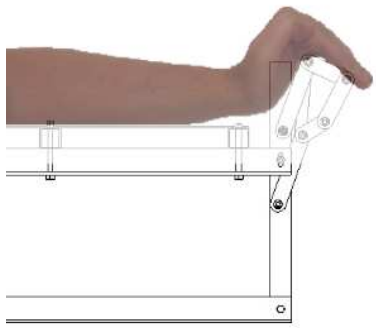

Fig. 9. Maximum extension

The assembly responsible for supporting and mobilising the palm consists of two four-bar mechanisms connected by means of torsion springs, thus forming a Fin Ray type structure. The length of lever AB is determined by the distance between the wrist and the metacarpophalangeal joints, while distance BE is the length between the metacarpophalangeal joints and the proximal joints. The maximum flexion of the palm is obtained with extended fingers, and the maximum extension of the palm is achieved with flexed fingers. The proposed system follows this natural movement of the palm, as the upward rotation of lever AB determines the rotation of lever BE in the opposite direction.

Figure 10 presents views of this equipment, with several positions of the palm supporting and mobilisation system.

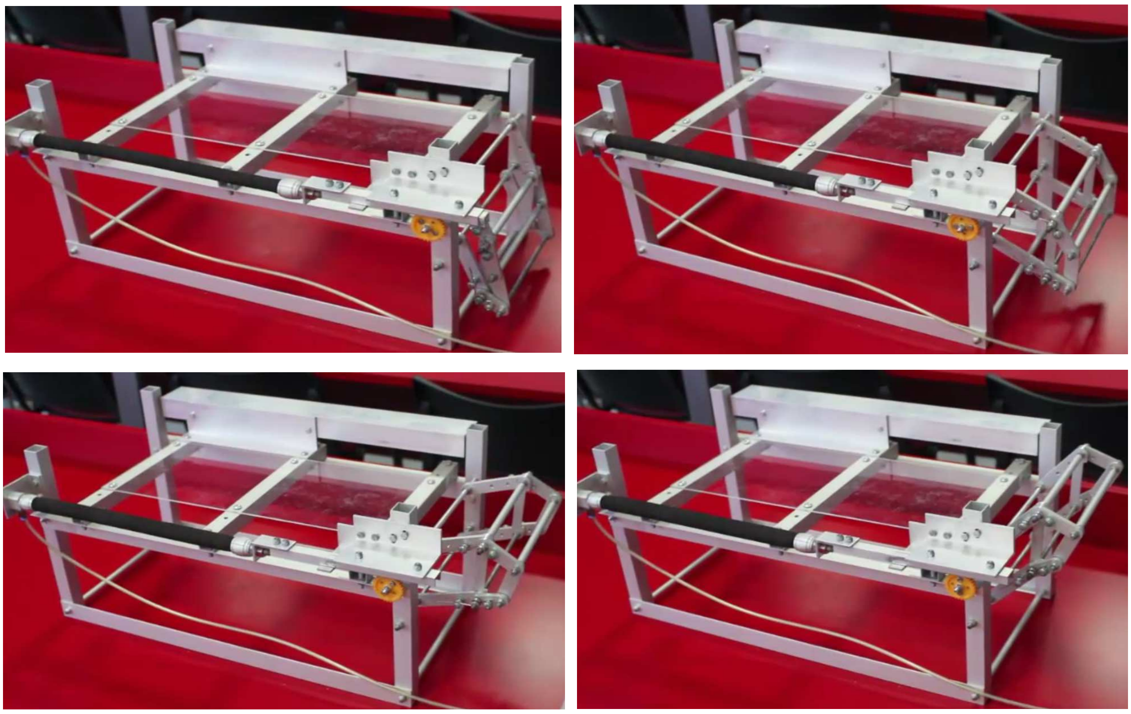

Fig. 10. Positions of the palm mobilisation system

The rehabilitation equipment for wrist and fingers is currently undergoing a test phase, the results of which will be the object of future publishing.

5. Rehabilitation Equipment for the Elbow

The elbow allows two motions: flexion-extension and pronation-supination. Flexion is achieved by lifting the forearm towards the arm, while extension means moving the forearm away from the arm. Pronation is the inward rotation of the forearm, the thumb moving towards the body, while supination is the outward rotation of the forearm, the thumb moving away from the body.

The rehabilitation equipment designed at the Festo National Training Centre is actuated by two pairs of pneumatic muscles, a pair for each movement carried out by the elbow joint. Figure 11 exemplifies the operation of the muscles for pronation-supination [12]. It can be noticed that the rotation of the joint is achieved similar to the functioning of human muscles, based on the agonist-antagonist principle, meaning that while one-muscle contracts, the other relaxes.

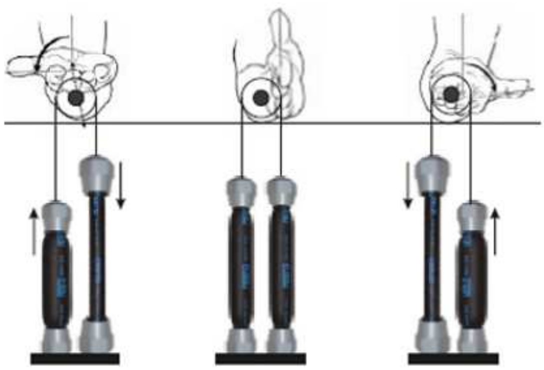

Fig. 11. Generating prono-supination

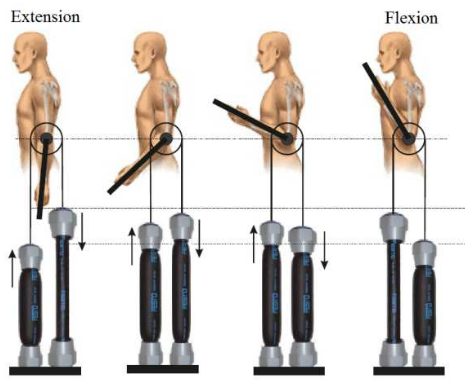

Fig. 12. Generating flexion - extension

The same principle underlies also flexion-extension (Fig. 12). For achieving the initial neutral (zero) position, both muscles are fed the same pressure; subsequently, motion is generated by further feeding one of the muscles at the same time with deflating the other.

Figure 13 shows the kinematic diagram of the proposed equipment, the positioning of the muscles in relation to the human arm in view of conducting the motions required by the rehabilitation exercise. Further views of the proposed equipment are shown.

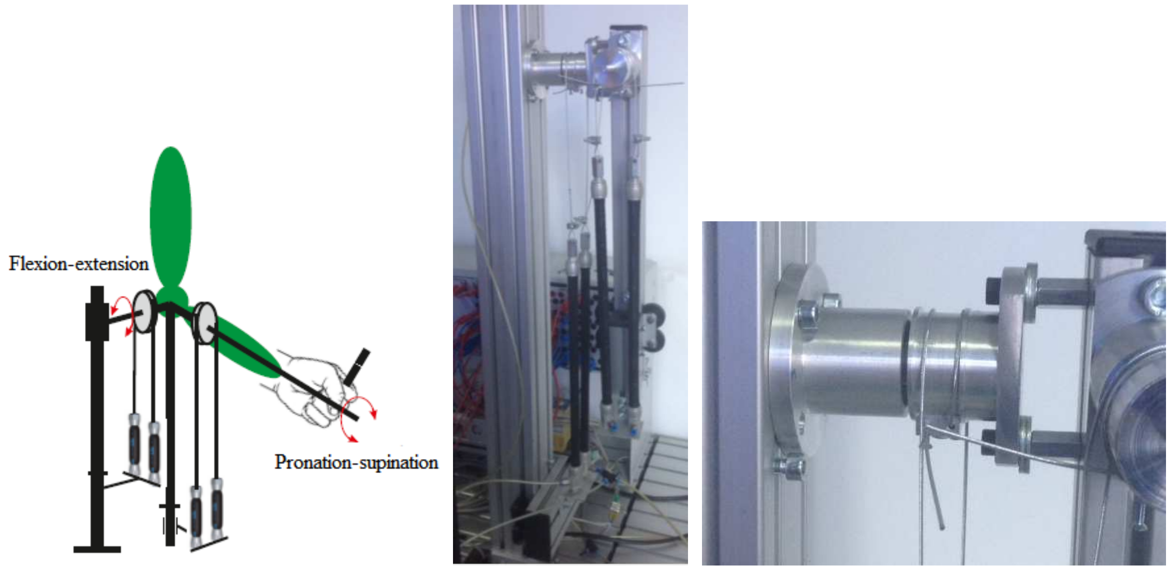

Fig. 13. Elbow joint rehabilitation equipment

A rotation couple corresponds to each of the two motions, actuated by a pair of pneumatic muscles. For one of the rotation couples two flexible steel cables are connected to the upper ends of the two pneumatic muscles; the steel cables are wound over a pulley by a 270° angle and fixed on it, thus allowing the rotation of the pulley in either direction by counter-time inflating and deflating of the two muscles.

The rehabilitation equipment too is currently undergoing a test phase, the results of which will be the object of future publishing.

6. Conclusions

The paper has presented a series of the achievements of the Festo National Fluid Actuation and Automation Training Centre at Transilvania University of Braşov, namely rehabilitation equipment for the lower limb bearing joints, as well as for the wrist, knuckles and elbow, all actuated by pneumatic muscles. The mechanical structures of the equipment were presented, their actuation and positioning systems, as well as their operational characteristics. A special emphasis was placed on describing the pneumatic muscles that benefit from optimum features for being included in the structure of medical equipment devised for the continuous passive motion based recovery of patients.

As a general conclusion to the research reported in this paper it can be asserted that the obtained results prove the capability and high performance of the proposed rehabilitation equipment, the pneumatic muscle being eligible as an adequate actuator for medical recovery systems.

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