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Pneumatic Muscle Actuated Rehabilitation Equipment of the Upper Limb Joints

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Abstract. Rehabilitation equipment of the upper limb joints holds a key role in passive physical therapy. Within this framework, the paper presents two such pieces of equipment developed for the rehabilitation of elbow and of wrist and knuckles, respectively. The presented and discussed equipment is actuated by pneumatic muscles, its benefits being a low cost, simple and robust construction, as well as short response time to commands.

1. Introduction

The mobility of the limbs is of essence for personal physical independence. For persons suffering from post-traumatic affections of the upper limbs, the lack of mobility creates barriers in carrying out day-to-day tasks, both personal and professional. In the wake of accidents and surgical treatment, patients are often subjected to a period of immobilisation of the limbs. Prolonged immobilisation cause muscle hypertrophy, dysfunctions of the circulatory apparatus and bone demineralization. For this reason a follow-up rehabilitation programme is always necessary.

The main objective of post-traumatic recovery is characterised by:

- maintaining the normal motion amplitude of the healthy segments that were not affected by trauma or surgical interventions;
- recovery of parts affected by trauma (muscle, bone, ligament, tendon tissue, etc.);
- regaining of the initial functions of the body, the affected segments, etc.

The most important method used for regaining the diminished functions and increasing joint mobility is physical therapy, that includes techniques focused on mobilising the targeted segment (active or static mobilisation techniques), as well as techniques that do not entail its motion (immobilisation and postural therapy). Physical therapy is efficient in the case of both minor and major trauma.

Physical therapy, together with kinetic prophylaxis are components of kinesiology, an interdisciplinary biological science that studies the movements of the human body, the functional elements that contribute to such movement and to the compensation modalities of reversible, partially reversible and irreversible disturbances [1].

On kinesiology nearly 5000 year old written information was discovered [2]. Thus Chinese documents dated 4700 years ago describe therapeutic postures and motions meant to ease pain. Also the Indian Vedas feature exercises recommended in rheumatism and other conditions. The true foundations of kinesiology, however, were laid by its founder Aristoteles in ancient Greece, followed by Hippocrates who observed that movement helps regaining muscle force (Fig. 1), while immobilisation leads to muscle atrophy.

Figure 1. Mobilisation of wrist and knuckles by traction (Hippocrates).

At present, in wrist and knuckle physical therapy, their mobilisation is achieved gently, the patient regaining the natural movements in a conscious manner. The alternative for patients unable to carry out the imposed motions consciously is passive mobilisation.

Continuous Passive Motion (CPM) is a therapeutic procedure that consists in applying a series of movements to the affected joint, without, however, entailing a contraction of the patient's muscles. This is achieved with the help of a physical therapist or by means of specially designed equipment.

Rehabilitation equipment plays an important role in passive physical therapy. Although passive physical therapy can be performed by the physical therapist without the help if such equipment, they are nevertheless deployed for moving the affected limb, thus easing the therapist's work.

The development of new mechanical rehabilitation methods of the upper limb joints has inevitably led to the conceiving of specific recovery equipment. A number of such pieces of equipment for the recovery of the shoulder, elbow or wrist, respectively, are produced by Rimec, Italy, [3]. Other manufacturers of rehabilitation equipment are Kinetec, France, KLC Services, USA and Ormed Medical Technology, India [4 - 6].

The conducted research has revealed that most rehabilitation equipment of the upper limb joints currently available on the marketplace is actuated by electric motors and has relatively high prices, of thousands of euros. For this reason at the National Research and Training Centre for Fluidic Drives and Automation at Transilvania University of Braşov, Romania such equipment – but pneumatically driven, were designed and developed. This paper presents two models of rehabilitation equipment that achieve continuous passive motion of the elbow, the wrist and the knuckles, respectively. These pieces of equipment are actuated by pneumatic muscles, the energy source generating force and motion being compressed air. The main advantages of the actuation system with pneumatic muscles are the low cost, simple and robust construction and swift reaction to commands. Due to the simple construction and reduced cost, the proposed equipment can be used in medical units by qualified personnel, as well as outside such entities by non-specialist personnel.

2. Wrist rehabilitation equipment

2.1. Rehabilitation motions and their limits

Pneumatically actuated wrist rehabilitation equipment is the object of several patents, some of which are described in [7] and [8].

The construction of such rehabilitation equipment starts from identifying the motions required for recovery, and of their respective amplitudes. The movements of the hand (the fist) are extremely complex and are facilitated by several joints, like the radiocarpal, the intercarpal or metacarpal ones. Flexion and extension of the fist, respectively, are carried out by the metacarpal joint as follows:

- Flexion of the fist or flexion of the palm – is obtained by rotating the palm in volar direction. The zero position is obtained when the forearm is flexed at 90º and in pronation (Fig. 2). The maximum rotation angle is of 90º according to [9].
- Extension of the fist or dorsiflexion – is obtained by rotating the palm in dorsal direction. The maximum rotation angle is of 70º according to [9] (Fig. 2).

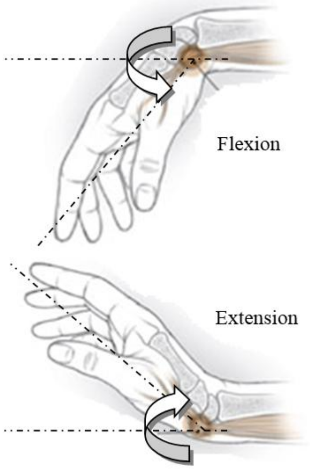


Figure 2. Flexion/extension movements of the fist.

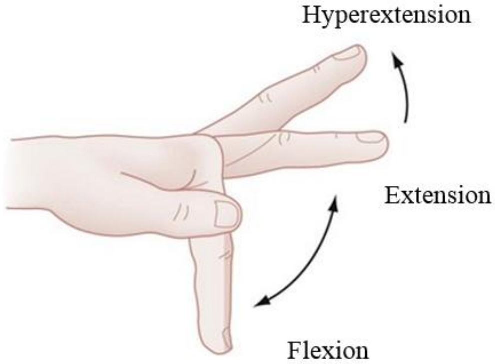


Figure 3. Flexion/extension movements of the fingers.

In the case of the knuckles, flexion – extension takes place within the following ranges:

- The flexion of the fingers increases from finger II to finger V from 90º to 100º, when fingers II, III, IV and V are flexed simultaneously (Fig. 3), according to [9].
- The extension of the fingers (Fig. 3) varies from individual to individual and can range from 0º to 90º (hyperextension), according to [9].

Fig. 4 features the proximal and distal inter-phalanx joints of phalanges II , III, IV şi V. Proximal flexion is the movement of the middle phalanx towards the inner palm, towards the proximal phalanx, until the limit of the movement is reached. The amplitude of this movement is of 100º, according to [9] or of 120º, according to [10]. Flexion has smaller values for fingers I and II, ad greater values for fingers IV and V.

Distal flexion is the movement of the distal phalanx towards the inner palm, towards the middle phalanx, until the limit of the movement is reached. In order to obtain the maximum value, the proximal joint needs flexing. The maximum value of this joint's flexion does not exceed 90º, according to [9] or 80º, according to [10].

Extension is possible only for the distal joints, the maximum amplitude being 20º, according to [9], it being present only in some individuals.

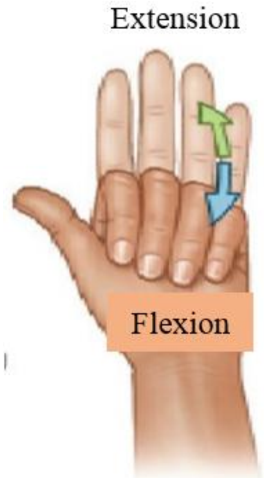


Figure 4. Proximal and distal flexion.

2.2. *The constructive solution*

Knowing the movements of the wrist and fingers, as well as their amplitudes, a rehabilitation device was conceived the motions of that are achieved by original bio-inspired systems based on the Fin Ray effect, specific for fish fins. There are similarities between the movements of the palm and fingers and the fishtail movement, as the flexion-extension of the palm is similar to the oscillatoy motion of the tail fin of some fish (Fig. 5). The bone structure of the hand and of the fishtail, respectively, is set into motion by muscle groups located on both sides of the skeleton and operating in countertime.

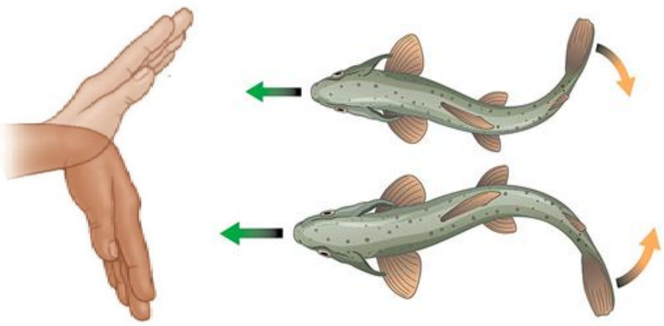


Figure 5. Flexion/extension of the hand vs. fishtail movements.

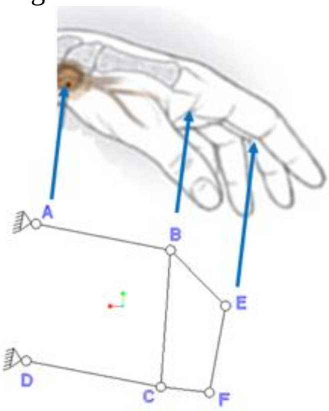


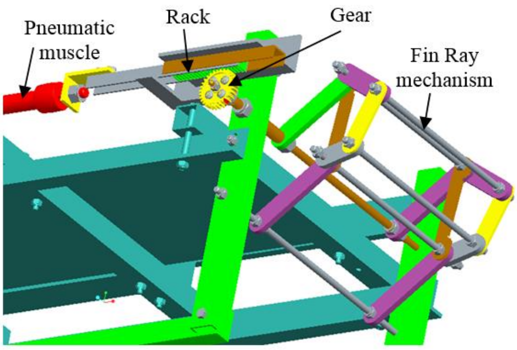
Figure 6. Structural diagrma of the rehabilitation equipment.

There are, however, also differences between the movements of the wrist and of a fishtail. One of these concerns the fact that the fishtail moves symmetrically by its resting position, while in the case of the palm and of the fingers the flexion-extension angles differ, their motion thus being not symmetrical.

Based on these observations a structural diagram of the wrist and fingers rehabilitation equipment was conceived, presented in Fig. 6.

The assembly that supports and mobilises the palm consists of two bar mechanisms connected by torsion springs, forming a Fin ray type structure. The length of segment AB is given by the distance between the fist joint (A) and the metacarpal-phalanx joints (B), and segment BE represents the length between the metacarpal-phalanx joints (B) and the proximal joints (E).

This bar system is set into motion at joint A, by a gear -rack mechanism, the latter's movement being imposed by a pneumatic muscle (Fig. 7).



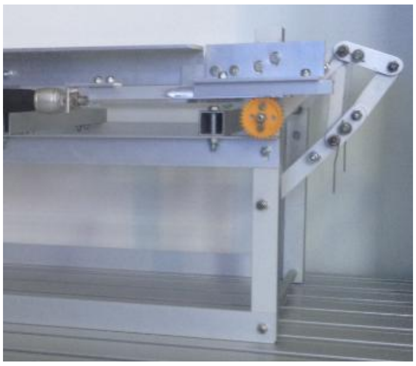


Figure 7. Actuation of the rehabilitation system.

The resting position of the system corresponds to the flexion of the hand and corresponds to the situation in that the pneumatic muscle is not fed air. Feeding air into the muscle causes the retraction of the rack and implicitly, the rotation of the bar system such as to achieve the extension of the hand.

Fig. 8. presents the positions of the hand on the bar system in the case of maximum flexion and extension of the hand.

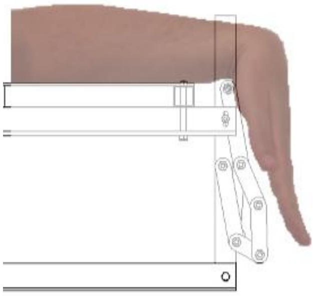
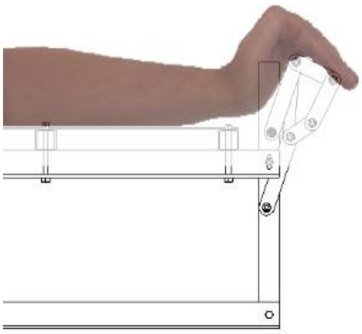



Figure 8. Flexion and extension of the hand.

Hand flexion and extension at various angles is obtained by corresponding commands of the pneumatic muscle stroke. A higher feeding pressure of the pneumatic muscle causes a greater rotation of the wrist in the direction of extension.

Table I presents a synthesis of the maximum angles achieved by the Fin Ray mechanism and of those found in literature.

Table1. Maximum flexion/extension angles.

	Flexion of the fist	Extension of the fist	Flexion of the fingers	Extension of the fingers
Found in literature	70°	80°	90°-100°	0°- 90°
Achieved by the mechanism	70°	80°	102°	9.67°

In addition to the fact that the equipment satisfies the functional requirements for the rehabilitation of the hand joints, its manufacturing cost is low, of only a couple of hundred euros.

Another benefit of this equipment follows from the fact that the other types of equipment available on the marketplace are specialised on either the rotation of the wrist or on the rotation of the fingers The proposed equipment, on the other hand, allows the simultaneous mobilisation of both hand and fingers.

3. Rehabilitation equipment of the elbow

3.1. Rehabilitation motions and their limits

The pneumatic actuation of elbow rehabilitation equipment has been the object of several research projects and patents have been granted to some Chinese universities [11 - 14].

In this case too, a prerequisite for constructing such rehabilitation equipment is identifying the movements required for recovery and their angular amplitudes.

The elbow is a complex and mobile joint, formed by the inferior part of the humerus and the superior part of the radius and cubitus (ulna). The elbow is a joint that ensures two degrees of mobility and allows flexion-extension and pronation-supination. Characteristic for flexion-extension is the humeroulnar, and for pronation-supination the radioulnar articulation.

Flexion, exemplified in Fig. 9a, is obtained by moving the forearm towards the arm, the maximum rotation angle being of 150°. Extension is obtained by moving the forearm away from the arm, its values ranging from 5° to 10° (hyperextension).

Pronosupination consists in the rotation of the forearm by its longitudinal axis (Fig. 9b), the amplitude of this rotation being of ±90º.

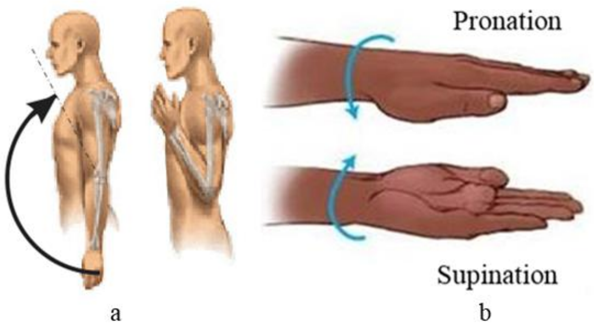


Figure 9. Elbow movements.

3.2. The constructive solution

The proposed rehabilitation equipment has two degrees of mobility, materialised by rotations conducted by two perpendicular axes. Each rotation is obtained by means of a pair of pneumatic muscles. Figures 10 and 11 show the diagrams of principle underlying these two movements.

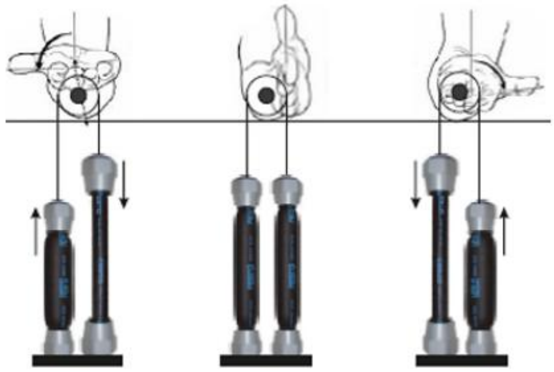


Figure 10. Generating pronosupination.

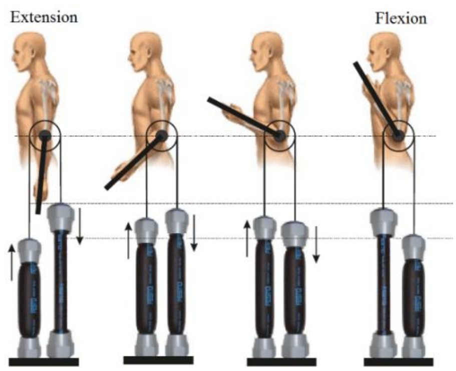


Figure 11. Generating flexion/extension.

It can be noticed that the two rotations are achieved similarly to the operation of human muscles, based on the agonist-antagonist principle, i.e. while a muscle contracts, the other one relaxes. For achieving zero position, both pneumatic muscles are fed the same pressure, upon which, in order to conduct rotation in one or the other direction, one of the muscles is inflated at the same time with the relaxation of the other.

Figure 12 shows the kinematic diagram of the proposed equipment next to a view of a joint.

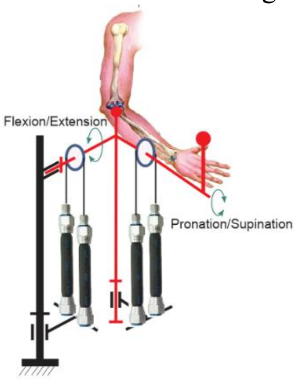


Figure 12. Diagram of principle of the rehabilitation equipment.

A thread is connected to the free extremities of each pneumatic muscle, stretched over a pulley and fixed in a specially conceived space. This constructive diagram allows the rotation of the pulley in one or the other direction, by the countertime inflation and deflation of the two muscles.

Initially the two pneumatic muscles are at a pressure of $p = 0$ bar, and hang freely from the pulley. In order to generate rotation in one or the other direction, the first step is the simultaneous pre-straining of the two muscles, by feeding them a pressure p_0 equal to half the maximum working pressure. This causes an axial contraction of the two muscles equal to half the maximum contraction generated upon inflating the muscles with a pressure $p = p_{max}$. Thus, when $p_0 = p_{max}/2$, the axial contraction of the two muscles is equal to $\Delta L_{max}/2$, the stroke of the inferior ends of the two pneumatic muscles being limited by a fixed stopper.

When a rotation by a certain angle is desired, one of the muscles will be fed additionally air up to a pressure $p_1 = p_0 + \Delta p$, and the second muscle will relax to a pressure $p_2 = p_0 - \Delta p$. By feeding the two muscles different pressures, their lengths will be modified in relation to their initial state as follows: the muscle inflated to pressure p_1 will shorten to a length of $L_1 = L_0 - \Delta L_{max}/2$, while the second muscle will expand to a length $L_2 = L_0 + \Delta L_{max}/2$. The countertime deformation of the two pneumatic muscles causes the rotation of the articulation, the angular amplitudes of the two axes being of $\pm 90°$.

In the case of the presented equipment, the rehabilitation motions by the two axes are conducted separately, in sequence, and not simultaneously.

4. Conclusion

Upper limb joint rehabilitation equipment actuated by pneumatic muscles becomes a viable alternative, capable of replacing successfully the electrically actuated variants. The developed prototypes prove the high capability and performance of the proposed rehabilitation equipment, the pneumatic muscle being eligible for becoming the adequate actuator of medical recovery systems.

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