Finite-element analysis of some pneumatically-actuated wrist-rehabilitation equipment

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Abstract. The paper presents some wrist-rehabilitation equipment, actuated by a pneumatic muscle. This one drives, through a rack-pinion mechanism, a Fin Ray-type mechanism, with a view to mobilizing the injured palm. Unlike other rehabilitation equipments, the one presented in this paper, ensures the movement of both palm and fingers.

1 Introduction

Passive motion is a part of the dynamic kinetic techniques for rehabilitation [1]. If the motion is made by means of muscle contraction, it is called active; and if the motion is made with external help, without muscle contraction, then it is called passive. Conscious motion, by muscle contraction, of the bodily segments, divides the kinetic techniques into active and passive techniques.

Disputes upon passive mobilization, have existed for a very long time; there being currently specialists opposing this technique, as well some others supporting it. Although these disputes date far back, passive kinetotherapy has been developing for centuries. This purpose is served by the wrist-rehabilitation equipment presented in this paper.

2 Wrist-rehabilitation equipments

On the medical-equipment market, there are several constructive types destined for hand rehabilitation [2]. According to the type of drive or actuation, they may be:

- with electric drive;
- with pneumatic actuation.

At this time, on the market, only electric-drive equipments are commercialized, as pneumatic actuation has not been yet sufficiently well studied and implemented in this system of applications.

According to their mobility, rehabilitation equipments are fixed and portable. In order to understand the operation of these rehabilitation systems, a few types of wrist-rehabilitation equipments will be presented in the following.

In figure 1, a portable equipment, with electric drive, produced by QAL Medical (former Otto Bock) [3] is presented. Because the equipment is placed on the patient's

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forearm, it belongs to the group of portable equipments. It is driven by means of an electric motor.

Fig. 1. W2 Wrist CPM.

Another portable equipment, produced by Kinetic Muscles Inc, is shown in figure 2. Paper [4] contains the description and operation of this equipment, called The Hand Mentor, actuated by a pneumatic muscle.

Fig. 2. The Hand Mentor.

Figure 3 presents a patent of the company Kinetic Muscle Inc [5], which is similar to the above equipment; but which, for actuation, uses two pneumatic muscles operating out of time.

Fig. 3. Patent US2010198115.

The rehabilitation equipment in figure 4 is fixed, with electric drive [6]. This is a more complex equipment, by which rehabilitation exercises for both wrists and finger joints, can be made. In order to perform these movements, the equipment is provided with several accessories, assembled as needed. This is a fixed equipment, driven by an electric motor.

Fig. 4. Kinetec Maestra.

A study conducted by the authors of this paper upon the motion of some fish species, has led to the conclusion there are similarities between the palm movement and, for instance the swinging in a horizontal plane of the caudal fin of the perch. The flexion-extension motion of the palm is similar to the swinging motion of the fish fin. In both cases, the bone structure is set in motion by muscle groups situated sideways from the skeleton and operating out of time.

Based on these studies, in paper [7] the authors proposed a new wrist-rehabilitation equipment (fig. 5), of a fixed type, actuated by a pneumatic muscle. The motion imprinted to the palm is similar to the one of the fish fin, and it is based on the effect known as Fin Ray.

Fig. 5. Wrist-rehabilitation equipment.

The equipment consists of a framework on which the forearm support, the palm support, the pneumatic muscle and the rack-pinion mechanism are assembled. The linear

advancement of the loose end of the pneumatic muscle is transformed into a rotary motion of the palm-supporting mechanism.

This is feasible by means of a rack-pinion mechanism. Unlike the other equipments presented above, this one enables the passive mobilization, at the same time, of both palm and fingers.

As follows, in this paper, the results obtained by a finite-element analysis upon the resistance of the whole equipment to the mechanical stresses undergone during operation, will be presented.

3 Verification at mechanical stresses of the wrist-rehabilitation equipment

For the verification at mechanical stresses, the forearm mass will be considered equal to 8 kg (approximately 80 N), and the palm mass 0,5 kg (approximately 5 N).

3.1 Calculation of the force necessary for palm-lifting

In order to determine the necessary force developed by the pneumatic muscle, with a view to lifting a force of 5 N, the support of the mechanism and the palm-support mechanism are imported from the software Pro/Engineer Wildfire 5.0 into Adams.

The palm-support mechanism is remade again, by means of the constraints in Adams, obtaining a new mechanism, shown in figure 6. In order to determine the value of the force, at rack level, two cases will be considered:

- in the former case, the torsional springs will not be considered;
- in the latter case, the torsional springs will be considered.

Fig. 6. Ensemble imported in Adams.

Palm weight was introduced in the calculations as a concentrated force, which acts in the middle of the bar supporting the palm (the circled area in figure 6). Following the simulations, the following force variations were obtained:

Fig. 7. Force variation at the rack (annulled springs; weight is considered in calculations).

Fig. 8. Force variation at the rack (springs and mechanism weight are considered in calculations).

The necessary force at the rack, with a view to lifting a body of 5 N in weight, can be briefly calculated, applying the law of levers. Noting with:

- F_c – force at rack
- r_c – pinion radius
- F – weight to be lifted
- r_f – distance between axes

This relation can be written:

$$F_c \cdot r_c = F \cdot r_f \tag{1}$$

It follows that:

$$F_c = \frac{F \cdot r_f}{r_c} \tag{2}$$

As $r_c = 15 \text{ mm}$, $r_f = 70 \text{ mm}$ and $F = 5 \text{ N}$, then $F_c = 23.3 \text{ N}$ is obtained, in case the gravitation is not taken into account.

If 200 g (mass of the ensemble in motion) are added to the force F , then the value of the force F_c calculated with the relation (2) is of 32.67 N.

In the case of the dynamic analysis made in Adams, if we consider the weight of the ensemble in motion and if we annul the two torsional springs, then we will obtain a maximal force value of approximately 33 N (figure 7). It is noticeable that the value theoretically obtained is confirmed by the simulation in Adams.

From figure 8, the force of 45N will be kept as a force for the future calculations.

3.2 Verification at strains of the equipment

The material of which the rehabilitation-equipment components have been made, is aluminium. According to [8], the mechanical properties of a few aluminium alloys can be found in Table 1.

Table 1. Mechanical properties of the aluminium alloys

Alloy	Temper	Tensile Strength (MPa)	Shear Strength (MPa)
AA1050A	H2	100	60
AA1050A	H4	115	70
AA1050A	H6	130	80

The verification at mechanical stresses was made with the finite-element analysis (FEA). In order to perform this analysis, the meshing and processing were achieved with the software Pro/Engineer Wildfire 5.0.

A first analysis was made considering the mechanical stress of the equipment by the weight of the forearm. Reckoning the forearm weight of 80 N, the force being uniformly distributed on the four legs, this means a leg is subjected to an axial load of 20 N. Following this load, the results in figures 9 and 10 are obtained.

Fig. 9. Tension variation in the leg.

Fig. 10. Leg deformation.

It is noticeable that the deformation in the leg of the equipment is very small, of only 0,0004 mm.

The palm-movement process mechanically stresses several components of the equipment. In figure 11, the components contributing to the motion of the palm, can be seen.

Fig. 11. Simplified ensemble.

The stressed elements are the legs of the equipment, the support in the fixed end of the pneumatic muscle, the support in the loose end of the muscle, the rack and the pinion, the shaft transmitting the rotary motion, the metallic plates which support the bar on which the palm rests.

The finite-element analysis was achieved for all components of the mechanical ensemble; all of which present loads below the yield point, and small deformations. In the following, for exemplification, the analyses afferent to the support in fixed end of the pneumatic muscle, to the rack and to the bar on which the palm rests, are presented.

In figures 12 and 13, the tensions and the deformations of the bar on which the palm rests, are noticeable.

Fig. 12. Tensions in the palm-supporting bar.

Fig. 13. Deformation of the palm-supporting bar.

It is noticeable that the maximal deformation in the case of the bar is of approximately 0,02 mm.

In the case of the rack, the maximal stress occurs when the contact between rack and cogwheel is made on one tooth. The maximal force which can stress the rack, according to figure 8, is of approximately 45 N. Figures 14 and 15 show the tensions and deformations appearing in the rack.

Fig. 14. Tension variation in a rack tooth.

Fig. 15. Deformation of the rack tooth.

Also in this case, the shift at the tooth tip is small, of approximately 0,01 mm.
The tensions and the deformations in the pinion are shown in the figure 16 and 17

Fig. 16. Tension variation in the pinion.

Fig. 17. Deformation variation in the in the pinion.

The maximal deformation of the pinion is 0.04 mm.
The support in the fixed end of the pneumatic muscle, because of the great distance between the embedment plane and the force-application point, presents higher stresses. Figures 18 and 19 show the variation of the tensions and the deformations in the support.

Fig. 18. Tension variation in the fixed support of the pneumatic muscle.

Fig. 19. Deformation variation in the fixed support of the pneumatic muscle.

All of the above point to the fact that the maximal deformation of the components does not exceed 0,2 mm, the tensions therein not exceeding the yield point.

4 Conclusions

The wrist-rehabilitation equipment is original, resisting the stresses and strains for which it was designed. The deformations in the components of the equipment are small, not influencing its operation. Achieving the three-dimensional model enabled verifying the equipment at mechanical stresses and making thereby the physical model.

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