

Fin-Ray effect® based structure for the passive mobilization of the hand joints

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Abstract. In medical rehabilitation and physical therapy practice it has been proved that the passive mobilization of the hand joints as part of rehabilitation exercises improves the recovery period and also diminishes the rehabilitation costs by about 50%. In order to facilitate the practice of passive mobilization exercises in both medical units and patient homes the development of new adequate rehabilitation equipment has become a necessity. It is within the context of this requirement that the paper puts forward and discusses a novel solution of rehabilitation equipment that makes possible the simultaneous exercising of the radiocarpal, metacarpophalangeal and interphalangeal joints. The first novelty proposed by this equipment is using the Fin-Ray effect® in the construction of the hand support and mobilization structure. A further novelty is the utilization of a pneumatic muscle as the motor that drives the equipment. The paper presents the construction of the equipment and discusses range of motion generated by it compared to the corresponding motion limits of the human hand, as identified in literature.

1 Introduction

The human hand is a complex articular structure that includes bones, tendons, nerves, ligaments and tissue forming an assembly that allow the hand to conduct motions with a certain dexterity and force required for everyday tasks. It is this very complexity of the hand that entails high risk of accidents which may affect the ability of performing even the simplest of tasks.

As the integrity of the hand is absolutely essential for its daily functioning, following trauma accurate diagnosis and adequate rehabilitation are required in order to prevent long-term impairment and possible permanent disability. Numerous motion-based rehabilitation techniques are available for this purpose, aimed at diminishing the consequences of the injury and swift recovery of all functions of the hand.

Rehabilitation methods based on the mobilization of the hand joints offer patients the chance of a swift recovery of their capacity to perform everyday tasks at home and at work.

Continuous passive motion (CPM) is a rehabilitation method that lends itself to exercising the hand after surgical interventions. The period of rest that typically follows surgery favours the tissue surround the wound become rigid. Thus, the mobility of that joint is significantly

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diminished and the natural recovery of the normal functions may take as long as several months.

Passive continuous motion entails the mechanised mobilisation of the joint that has undergone surgery, without stressing the patient's muscles. The motions of the affected joints can be carried out by either a specialised person (a physical therapist) or by specially conceived equipment. Passive mobilisation has to adapt to the clinical state of the patient its main control parameters being stroke, velocity, acceleration, and duration of the motion as well as frequency and magnitude of the applied force. As the intensity of recovery exercising varies in time depending on the degree of healing of the joints, rehabilitation equipment has to allow the adjustment between certain limits of all above mentioned parameters. While various manoeuvres can be carried out during passive mobilisation, typically slow progressive motions of different amplitudes are applied. The force applied by the rehabilitation equipment at maximum amplitude has to be adapted to the patient's pain threshold. Such desideratum requires actuation systems benefitting from adjustable compliance.

An analysis of the currently available range of available hand rehabilitation equipment for the joints of the hand has revealed that the majority uses electric motors for motion generators; electric motor-based drives do not ensure a compliant behaviour, that is the system's sensitivity and adaptability to the patient's pain threshold. The analysis further revealed that existing equipment is designed for the exercising of merely a single joint, and cannot be used for the simultaneous mobilisation of several areas of the hand [1]. Starting from these observations the paper presents a novel concept of a device for the simultaneous rehabilitation of the radiocarpal, metacarpophalangeal and interphalangeal joints. This is possible by conceiving an innovative support system of the hand based on the Fin-Ray effect®. The compliance of the entire assembly is ensured by the deployment of a pneumatic muscle as a motor, which due to air compressibility has an inherently compliant behaviour.

2 Biomechanics of the joints of the hand

Conceiving a novel rehabilitation device requires knowledge of the anatomy of the hand and of the biomechanics of the respective joints. In this respect an analysis of joint motion is required consisting in establishing the maximum rotations of the joints in the three planes of reference, transversal, frontal and sagittal. Figure 1 shows the main bones and joints of the hand.

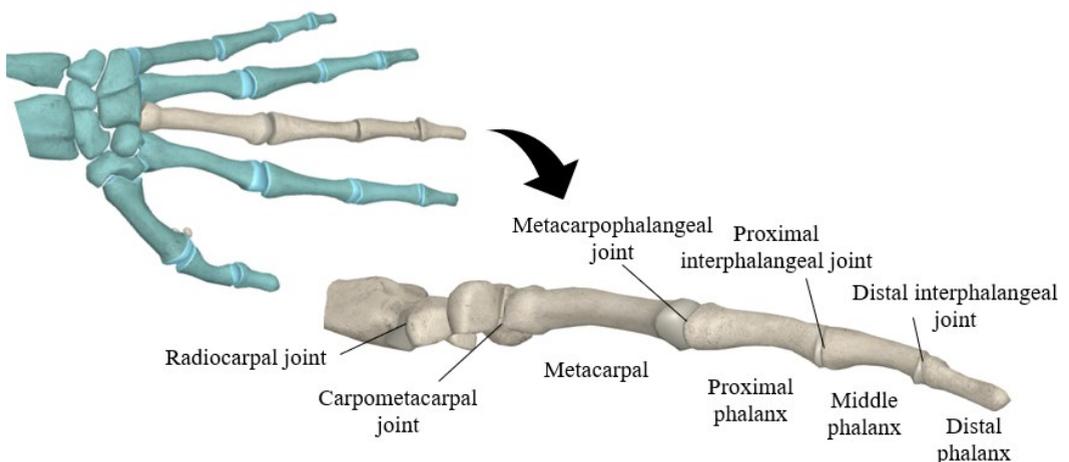


Fig. 1. Bones and joints of the hand.

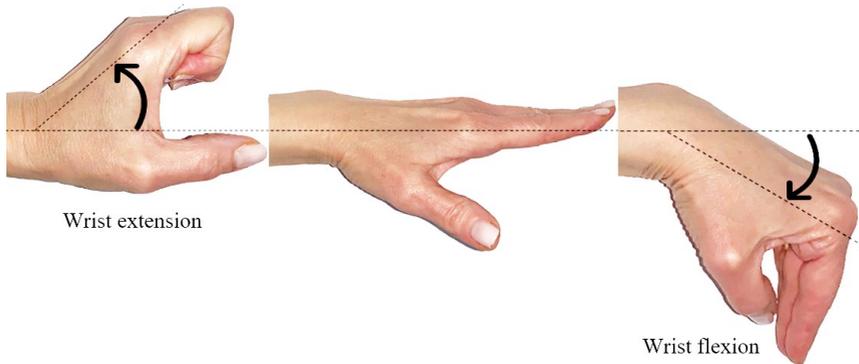


Fig. 2. Flexion/extension of the wrist and joints of the fingers.

Of interest for the rehabilitation equipment proposed in this paper are the flexion and extension motions of the radiocarpal, metacarpophalangeal and interphalangeal joints. In order to design the rehabilitation equipment, the limits between that the motions of the various joints of the hand are conducted have to be known. A literature search carried out for this purpose yielded the maximum values of the rotation angles of the palm and of the finger joints.

The radiocarpal joint makes the flexion and extension of the palm possible (Figure 2). Palm flexion is obtained by its rotation in volar direction around the zero position that corresponds to the forearm flexed at a 90° degree. The maximum palm flexion angle is of 80° [2]. Palm extension or dorsiflexion is obtained by rotating the palm in dorsal direction, the maximum rotation angle being of 70° [2].

The metacarpophalangeal joints allow flexion/extension of $\pm 90^\circ$, while typically extension has smaller values [3]. The proximal interphalangeal joints facilitate only flexion up to 90° , and the distal interphalangeal joints flexion of maximum 90° and extension of up to 20° (only in some individuals) [3].

3 Construction of the rehabilitation equipment

The system that supports and mobilises the hand was conceived based on the observation that palm flexion and extension are conducted by trajectories similar to the movements of the fins of certain fish (manta ray) (Figure 3) [4].

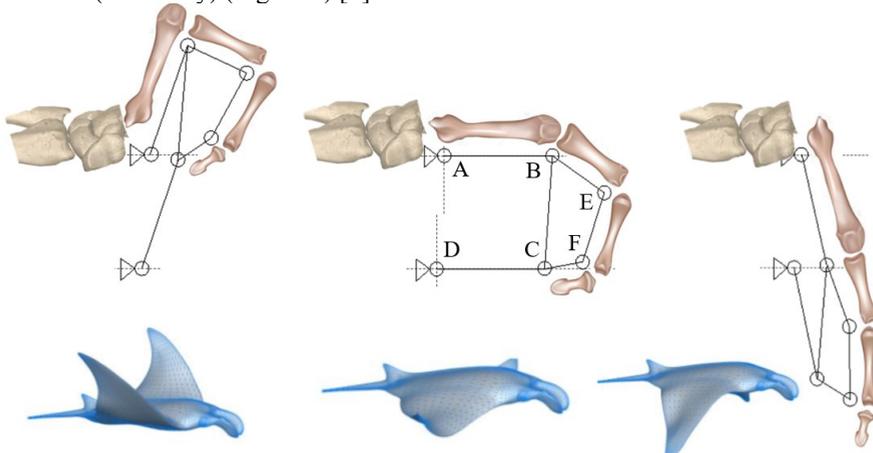


Fig. 3. Flexion/extension of the rehabilitation equipment and of the wrist and joints of the fingers.

The motions of fish fins were studied by Leif Kniese who defined the Fin-Ray effect concept that has underlain the development of Fin-Ray® structures [5]. A structure of this type consists of two elastic struts displayed at an angle and connected by transversal ribs. This way several bar mechanisms arranged in a pyramid are series connected in the descending order of their sizes (a V-shape). The links of the struts and ribs are flexible and allow relative motions and deformations of the component mechanisms (Figure 4).

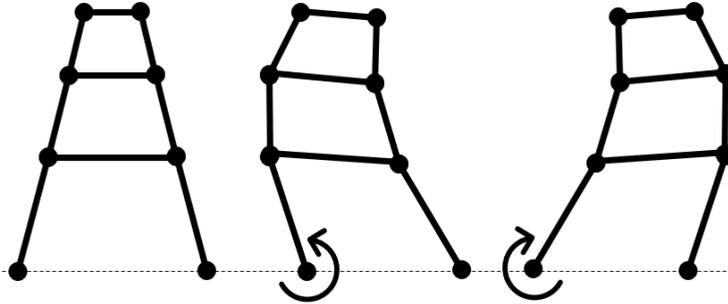


Fig. 4. Fin-Ray effect-based structure

The construction of the rehabilitation equipment was based also on another similarity observed between the motions of fish fins and those of the hand. In both cases displacement is generated by the muscles on either side of the skeleton working antagonistically.

There exists, however, also differences between the movements of the hand and that of fish fins. In the case of fishes, the fin moves symmetrically in relation to its resting position, while the flexion angles of the hand are greater than the extension angles, standing for an asymmetrical motion [6].

The dimensions of the rehabilitation equipment were established based on the lengths of the bone segments that make up the hand. In [7] J.W. Littler asserts that the movements of the fingers follow an equilateral spiral due to the fact that the ration of phalanx lengths relates to the Fibonacci sequence. Each number in this sequence is the sum of the preceding two numbers ($x_n = x_{n-1} + x_{n-2}$).

Applying the principles of mathematical statistics to the data obtained by measuring the lengths of the bones of the hand revealed that the interarticular distances between the distal, intermediary, proximal and metacarpal phalanges follow a Fibonacci sequence of form 18; 26; 44; 70 [8]. Figure 5 shows the dimensions (in mm) of the middle finger taken as reference for building the rehabilitation equipment.

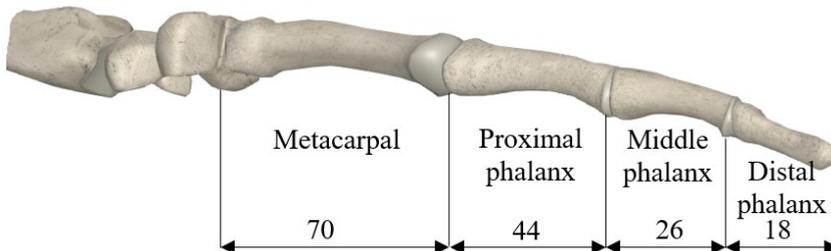


Fig. 5. Distances between the joints of the middle finger.

The schematic diagram of the rehabilitation equipment developed for the joints of the hand consists of two series connected bar mechanisms ABCD and BCFE, where flexion and extension are generated by introducing a rotation through joint A. Reducing the degree of

mobility of this bar mechanism from two to one requires attaching two torsion springs to joints B and C, respectively (Figure 6).

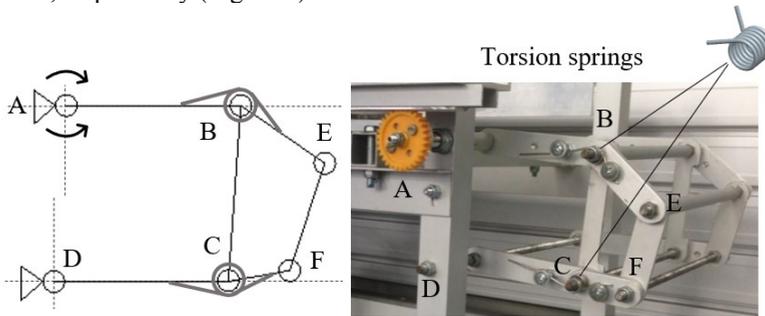


Fig. 6. Reducing the degree of mobility by attaching torsion springs.

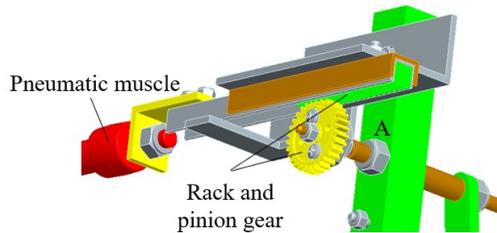


Fig. 7. Mobilisation of the rehabilitation equipment.

The rotation in joint A is generated by means of a rack and pinion gear, whereby the former component is set into motion by a pneumatic muscle (Figure 7). The maximum force that the pneumatic muscle is required to develop is determined by simulation of the mechanical system's operation by means of Adams software.

Under static conditions, by loading the Fin-Ray structure with 5 N (the weight of the palm) and knowing the geometrical parameters of the entire rehabilitation equipment, a 23.3 N force to be generated by the pneumatic muscle is calculated. Taking into account also the moving masses of the hand support and the influence of the two torsion springs, the value of the necessary force at the rack is determined as approximately 47 N. Figure 8 shows the variation of force to be developed by the pneumatic muscle versus the flexion/extension angle of the radiocarpal joint (determined by means of Adams software).

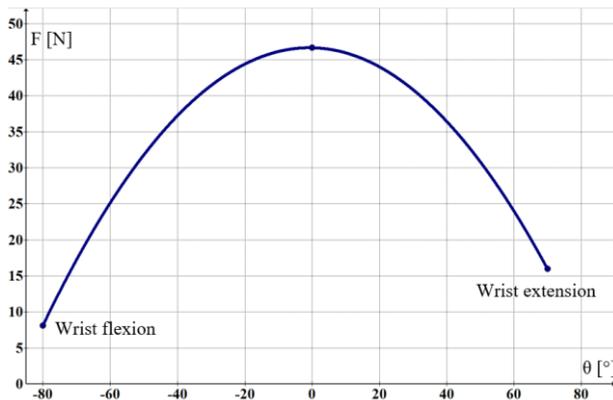


Fig. 8. Variation of the force to be developed by the pneumatic muscles versus the rotation of the hand support.

Based on these results a DMSP-10-300N-AM-RM pneumatic muscle manufactured by Festo, Germany was selected for the actuation of the equipment. The muscle has a diameter of 10 mm, the length of the active part is of 300 mm and the maximum achievable stroke is of 60 mm. In order to obtain a rotation angle of the hand support of 150° ($-80^\circ \dots +70^\circ$), the displacement of the free end of the muscle (and implicitly of the rack) is of 39.25 mm. For this value of the displacement the force that can be developed by the pneumatic muscle is of 136.5 N, greater than the maximum force required for the actuation of the rehabilitation equipment.

The testing of the rehabilitation equipment yielded that the flexion and extension motions of the radiocarpal joint register small deviations of the respective angles' limit values from those obtained theoretically. For maximum flexion the measured angle is of 78.2° (smaller than the theoretical 80°), and for maximum extension the measured angle is of 67.3° (smaller than the theoretical 70°). These deviations are due to the presence of the two torsion springs that prevent reaching the initially proposed ends of stroke. For the metacarpophalangeal joints the obtained angles are of -87.6° for flexion, and of 8.3° for extension.

4 Conclusions

The paper presents the construction of a rehabilitation device of the hand joints, designed for the simultaneous recovery exercising of the radiocarpal, metacarpophalangeal and interphalangeal joints. One of the novelties brought by this equipment is the solution conceived for the construction of the hand support and mobilisation system based on a Fin-Ray® type structure developed by bio-mimetics starting from the movements of fish fins. Compared to devices currently available, the equipment ensures the simultaneous mobilization of the wrist and the finger joints. Another element of novelty is the utilisation of a pneumatic muscle as the actuation motor of the equipment.

The conducted experimental research showed that the rehabilitation equipment ensures the flexion and extension of the radiocarpal, metacarpophalangeal and interphalangeal joints within the angular limits typical for a healthy hand, while the small registered deviations do not affect recovery exercising. The next stage of research envisages extending tests - that so far have been conducted on healthy persons - to clinical tests on informed and consenting patients.

References

1. O. Filip, T. Deaconescu, RECENT **18**, 2 (2017)
2. E.L. Sidenco, *Ghid practic de evaluare articulară și musculară în kinetoterapie*, Editura Fundației „România de Mainé”, București (2009)
3. T. Sbenge, *Kinetologie profilactică terapeutică și de recuperare*, Editura Medicală București, (1987)
4. I. Petre, A. Deaconescu, F. Sârbu, T. Deaconescu, Strojniški vestnik – J. Mech. Eng. **64**, 6 (2018)
5. L. Kniese, EP1040999A2. Patent (1999)
6. T. Deaconescu, A. Deaconescu, RECENT **17**, 4 (2016)
7. J.W. Littler, *The Hand*, **5**, 3 (1973)
8. P. Ben-Tzvi, Z. Ma, IEEE Trans. Neural Syst. Rehab. Eng., **23**, 6 (2015)