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Electrorheological Fluid Based Brake for Active Physiotherapy Systems

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Abstract: The paper presents an electrorheological brake developed with the purpose to be used into the structure of rehabilitations wrist systems. A short overview of smart fluids used in systems for physiotherapy is presented to reveal the interest, at global level, for the possibilities of using electro-rheological fluids in such applications. The electrorheological fluid brake design is based on the hydraulic clutch equations and on the previous experimental results. After developing the brake it was tested with commercially available and laboratory developed electrorheological fluids. Results, the control modality and the implementation possibilities into a wrist exerciser are presented.

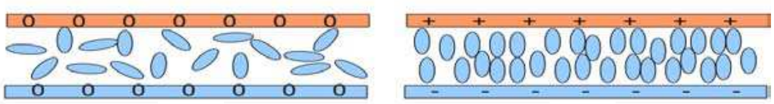
Keywords: electro-rheological fluids, rehabilitation systems, brake, clutch

1. Operation principle of electro-rheological fluids

The electro-rheological fluids (ERF) are characterized by fast, reversible and controllable changes in rheological properties upon the application of an electric field [1], [2], exhibiting a tunable transition from a liquid state to a solid state. Practically, ERF respond mechanically to an electrical stimulus. This specific behavior gives numerous applications of these fluids in several areas, such as active vibration suppression, motion control and robotic systems, and justifies their framing in the category of so-called smart materials.

Usually, the ERF are suspensions that contain an insulating fluid and particles from one-tenth to hundreds of microns in size, the volume fraction of the particles being from 20% to 80% [3]. According to Fig. 1, the particles arrange themselves as chains along the applied electric field lines, due to an induced dipole moment. As a consequence, the fluid viscosity and its yield stress change on the order of milliseconds.

The exterior applied electric field leads the transition from a Newtonian liquid (characterized by a linear relationship between shear stress and shear rate) to a non-Newtonian Bingham fluid (characterized by the fact that the yield stress is a function of the electric field) [4].



a b

Figure 1: Operation principle of electro-rheological fluids: a – without an applied electric field, b – when an electric field is applied (solid-like state)

Here following fluids are used as dielectric carrier liquid: mineral oil, castor oil, fluoro-silicone oil and silicon oil. The semiconducting solid particles are made of polymer particles, dried aluminosilicate powder, zeolites, $C_6H_{10}O_5$, TiO_2-CeCl3 and $SrTiO_3$/PANI (polyaniline) particles. The inter-electrode gaps are ranged from 0.25 mm to 2.0 mm and placed into an electric field with a strength in the range from 1 kV/mm to 4 kV/mm. This is limited by the breakdown of the dielectric characteristics of the fluid. Maximum yield stress magnitude is typically from 1 to 5 kPa [2].

The most remarkable advantages of ERF are low current density for activation, fast response, long life and wide temperature range of operation, nontoxic and nonpolluting components while the most important disadvantages are: nonlinearity of their behavior, complexity, high voltage to control an ERF based devices and thus high risk concerning safety, high cost and narrow variety of commercially available ERF.

The research of ERF has been in great progress, as well as their applications developed especially for damping and creation of resistive force. By a large variety of exercisers used in rehabilitation processes, the need of greatest interest consists in applying very high resistive forces and torques electrically controlled using small sized and low weighted brakes. The ERF based brakes respond quite well to these requirements.

2. Analysis of some intelligent rehabilitation devices

In order to provide an efficient rehabilitation process, *Rehabilitation Engineering,* that is a component of Biomedical Engineering, proposes simple devices or complex systems, such as prosthetic and orthotic devices, mobility aids, visual and hearing aids, rehabilitation robotics, and others, for a fast and as more fully reintegration of disabled in family and society [5]. Kinetotherapy is defined as an ensemble of procedures, which promote motion as a basic element of rehabilitation treatment. Often, this kind of rehabilitation approach (that includes walking, running, gym, games, training) must be aided by technical systems and requires different exercisers to support active and passive mobilizations of body segments. Thus, a lot of exercising devices were investigated and many of them are already in use. Some representative examples are presented below.

The device presented in *Fig. 2a* is an exerciser for hand rehabilitation. It is compatible with Functional Magnetic Resonance Imaging Systems (fMR) and uses an ERF brake in order to obtain variable resistance during the kinetic exercises [6].

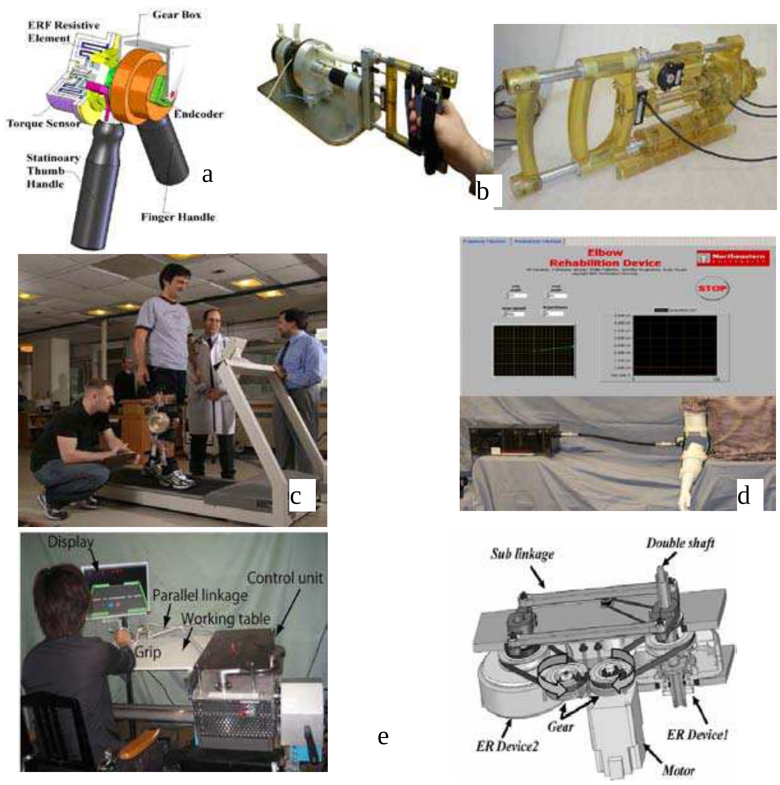


Figure 2: Smart fluids based rehabilitations\devices

According to [7], a hand rehabilitation system combines robotics and interactive gaming for repetitive exercises specific to patients with neurological motor deficits (*Fig. 2b*). It has two degree of freedom for forearm pronation-supination and prehension. Two ERF based actuators drive the system. One version of this rehabilitation system was developed in order to be fMR compatible [8].

Fig. 2c shows a knee orthotic-type, wearable exerciser equipped with an ERF based variable resistance brake. It is dedicated to iso-inertial, isokinetic and isometric exercising as well as gait retraining [9], [10]. The straps, rigid components, the central hinge mechanism with a connected gear systems and a variable damper are the main components in the structure of this rehabilitation exerciser. Based on the electrically controlled rheological properties of ERF, the brake supplies high resistive and controllable torques.

The transportable elbow rehabilitation device given in *Fig. 2d* responds to passive, active and bracing operation. A DC motor, gearbox, encoder, clutch and brake are located in a portable unit that is attached through a flexible shaft to the elbow brace. This device acts as a smart continuous passive motion machine as well as controlled active rehabilitation system due to the variable resistance applied using the brake based on smart fluids [11].

The active-passive rehabilitation system, called Hybrid-PLEMO is presented in *Fig. 2e* [12]. It is equipped with force sensors on the handle and incremental encoders to determine the handle position. Its user graphical interface enables a visual feedback.

3. Design of ER based brake

The hydraulic clutches are mechanical devices, which use the fluid shear stress in order to transmit rotational movement from the input to the output of the clutch. Basically the hydraulic clutch has two circular parallel discs with a fluid film between them. Depending of the fluid viscosity and the contact areas between discs and fluid, a specific torque can be transmitted. By using an ERF in such structures, the viscosity can be adjusted and with it the transmitted torque, without changing the mechanical structure (*Fig. 3*). New brake types can be designed; using hydraulic clutches structures and smart fluids. The basic configuration is done by fixing the clutch output shaft.

Regarding the practical construction and the torque maximization method, the most desirable structure of an ER fluid brake is the stack discs structure, (*Fig.3c*). The complex electrorheological phenomenon and the complex variable structure of an activated ERF do not permit a practically usable mathematical model. The most devices that imply ERF are developed by means of specific ERF experimental result.

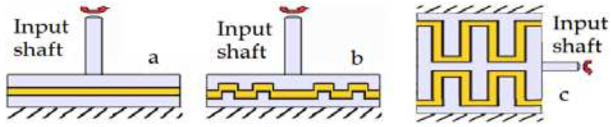


Figure 3: Hydraulic clutch construction types: a-simple discs, b-comb discs, c-stack discs

Assuming that the activated ERF viscosity, at certain field intensity, can be experimentally determined, we propose a simple method to determine the braking torque of a stack discs ERF brake type.

The structure of a stack discs ERF brake (*Fig. 4)* can be characterized by thickness h, inner radius R_0 and outer radius R_1. The calculus starts form the shear stress expression of a volume of fluid situated in the gap formed by two parallel plates, one fixed on the rotor and the other welded to the stator body:

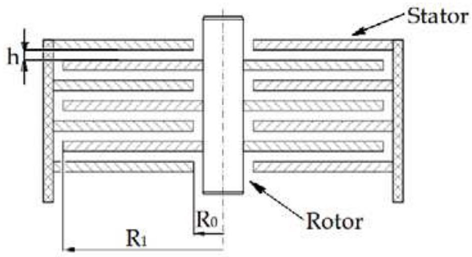


Figure 4: Stack ER fluid brake.

$$\tau = \eta \frac{dv}{dy} . \tag{1}$$

In the following calculus the hypothesis of the Newtonian fluid is accepted. The stream velocity at a radius ρ, $R_0 \le \rho \le R_1$, in dependence with the angular velocity ω can be expressed as $dv = \omega\rho$. Considering the disc gap $dy = h$ the formula (1) of the shear stress becomes:

$$\tau = \eta \frac{\omega\rho}{h} \text{, where} \tag{2}$$

η is the dynamic viscosity.

For an infinitesimal ring shaped area element built on the circle with the radius ρ, of width dρ, the elementary viscous force expression can be written as

$$\mathrm{d}F = \tau\,\mathrm{d}A = \eta\frac{\omega\rho}{h}2\pi\rho\,\mathrm{d}\rho = 2\pi\eta\frac{\omega}{h}\rho^2\,\mathrm{d}\rho . \tag{3}$$

With this, the elementary resistant torque developed by the fluid becomes:

$$\mathrm{d}M = \rho\,\mathrm{d}F = 2\pi\eta\frac{\omega}{h}\rho^3\,\mathrm{d}\rho\,. \tag{4}$$

Integrating (4) on the interval of common radiuses the fluid developed torque at one surface of the rotating disc will be:

$$M = \int_{R_0}^{R_1} 2\pi\eta\frac{\omega}{h}\rho^3\,\mathrm{d}\rho = \frac{\pi\eta\omega(R_1^{\,4} - R_0^4)}{2h}\,. \tag{5}$$

The average value of the dynamic viscosity can be found from the expression of shear stress (2):

$$\eta = \frac{\tau \cdot h}{\omega \cdot (R_1 - R_0)}\,. \tag{6}$$

The fluid torque developed by all structure theoretically can be computed by multiplying expression (5) with the double of the rotating discs. In the case presented in (*Fig. 3*) the number of surfaces is $2 \cdot 3 = 6$.

For a more general consideration equation (5) will turn into:

$$M_{total} = Y \cdot \frac{\pi\eta\omega(R_1^{\,4} - R_0^4)}{h} \tag{7}$$

where "*Y*" represents the number of discs in the structure [4].

For developing an ER fluid brake with possibilities to be incorporated into an upper limb exerciser some particularities must be considered:

- Used materials must be excellent dielectrics, in order to electrically isolate the exterior medium by the high voltage inside the brake;
- Miniaturization possibilities;
- The ER fluid brake chassis must be compatible with the exerciser;
- Brake structures must be oil sealed;
- The ER fluid activating electrodes are constituted from the stator discs and rotor discs;
- The rotor shaft is used as electricity charger for rotor discs;
- A boost converter is used as voltage generator in order to activate the fluid.

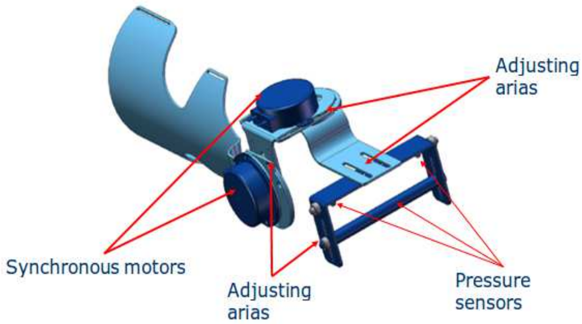


Figure 5: The previous developed wrist exerciser

In our previous work [13], we presented a developed wrist trainer exerciser, with anthropometric adjustment elements, actuated by two 24AC synchronous motors, angular sensors and force sensors (*Fig. 5*).

4. Implementation of the brake on a portable wrist exerciser

The ERF activation is obtained by placing it between two electrostatically charged electrodes. A common method to charge the electrodes is to connect them at a DC voltage source. The required intensity of the electrostatic field that activates the fluid is situated between 2-6 [kV/mm]. The required current depends on the stabilizers used at the fluid composition but because its dielectric nature the current needed has the order of tens of micro-Amperes. In case of overvoltage the fluid dielectric strength is reached, the current starts to flow through the fluid and the electrodes are discharging canceling the particles polarization phenomenon.

When designing voltage sources to activate the ERF some aspects must be considered:

- fluids breaking voltage;
- the electrostatic intensity needed to activate the fluid;
- the gap between the activation electrodes;
- the current should be always continuous;
- the electronic components should be well electric isolated between each other and from exterior medium.

In our previous work we presented a collection of voltage sources that can raise the voltage at the required ERF activation voltage [14].

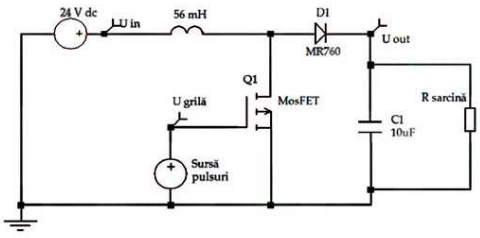


Figure 6: The Boost-Converter

Another modality to obtain the activation required voltage is the boost-converter (*Fig. 6*). This electric source is often utilized into the common step up sources or converters. The electronic components needed to make a boost-converter are: a coil, a power transistor, a high voltage diode and a high voltage capacitor. The components should be chosen for the needed specific voltage. A reliable advantage that boost-converter has it, is represented by the adjustment possibilities. This supply source can be adjusted by modifying the input voltage, the transistor input frequency or by modifying the transistor frequency duty cycle. The calculation of this device is not presented here because it is well treated in different bibliographic sources [15].

In order to control this circuit, between the control circuit board and the boost-converter a galvanic separation stage should be interpolated. This stage is an electronic board including a galvanic separated source, an optotransistor 6N136 and a power transistor driver. This stage is fully adapted for a Pulse Width Modulation control of the power transistor gate. *Figure 7* shows the results of the boost converter output voltage simulations realized in the following variants: adjusting the input voltage (*Fig. 7a*), the transistor frequency for a constant supply voltage (*Fig. 7b*) and the transistor frequency duty cycle also for a constant supply voltage (*Fig. 7c*).

In order to incorporate the structure of ERF brake described at the section 3 (*Fig. 4*) onto the developed exerciser (*Fig. 5*) some aspects were taken into account: the ER brake overall dimension should be compatible with the developed wrist exerciser; the maximum contact surface between the ERF and the activation electrodes should be at least 0.026 [m^2]; the distance between activation electrodes 2 [mm]; the outer brake shell must provide a galvanic separation; avoiding the fluid leakage onto the shaft bearings. The *Fig. 8a* presents an inside view of the developed ERF brake and *Fig. 8b* presents the experimental setup in order to measure the output ERF brake torque. The activation electrodes gap and the contact surface between the electrodes and the ERF were experimentally determined in our previous work by aid of a specially designed experimental stand for ERF study, [16].

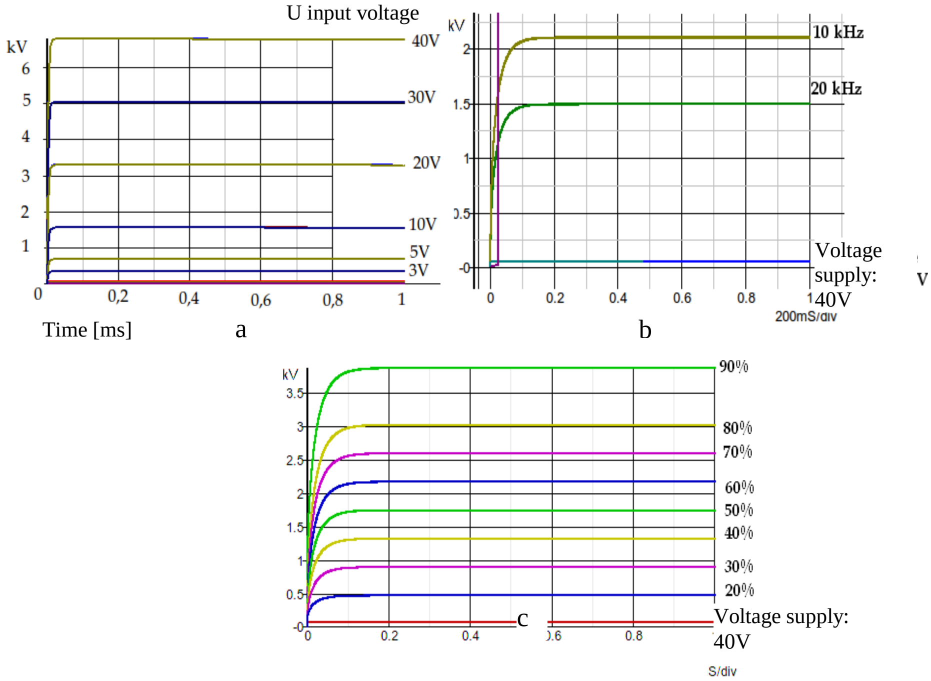
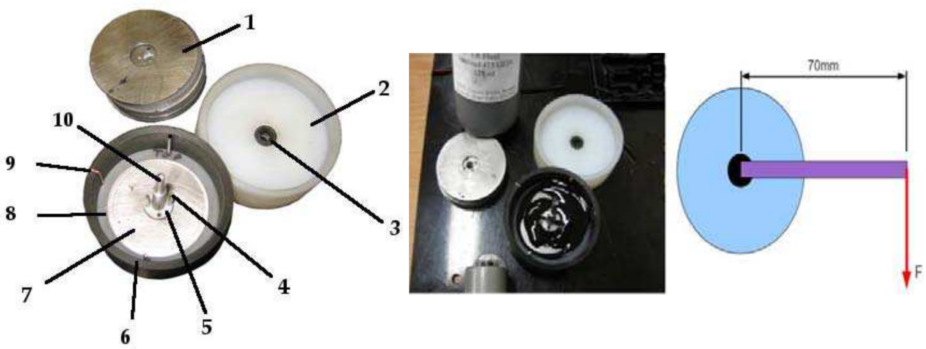


Figure 7: Output voltage by: a – modifying the input voltage; b – modifying the frequency; c – modifying the duty cycle



a b

Figure 8: a – The ERF brake: 1-fixed electrodes; 2-top cap; 3-lip sealing; 4-pin; 5-shaft; 6-body; 7-sinning electrodes; 8- fixed spacers; b – ERF brake testing setup

After the practical development of the ERF brake, it was filled with Reslinol 415/GE16 ERF and tested for determining the maximum available torque. The activation voltage was rised at 6.6 [kV], the force was measured with a force sensor and the experimental data was recorded.

The maximum braking torque determined form the measured force is 177.45 [mNm]. This value was compared with the medium torque developed for wrist flexion movement and it was found that the ERF brake torque is big enough to be used in rehabilitation purposes.

The ERF brake was tested also with laboratory developed ERF. These fluids were made up from corn starch and HLP46 hydraulic oil, in different concentrations and the output brake developed forces for different activation voltage were recorded as shown in Table *1*.

Following the forces measurement (*Fig. 9*) the torque was computed and for the 30% corn starch ERF the developed torque at zero field intensity is 45.6 [mNm] and the maximum torque obtained is 74 [mNm] for 1000 [V] activation voltage. For the 80% corn starch ERF the computed torque is 342 [mNm] for zero field intensity and 926 [mNm] for 900 [V] activation voltage, [4].

The developed wrist exerciser can be used in rehabilitation for passive exercises if its elements are actuated by the synchronous motors mounted on the structure or for active with resistance movements if the synchronous motors are replaced with the developed ERF brake *(Fig. 10)*. Because the input shaft is used to electrostatically charge the rotor disks it is necessary a galvanic separation between the wrist exerciser structure and the brake shaft. This galvanic separation consists from a dielectric coat that wears the metallic brake shaft.

Table 1: The brake measured values for different corn starch concentrations

Corn starch [%]	Voltage applied [V]	Output Force [N]	Corn starch [%]	Voltage applied [V]	Output Force [N]
30	0	0.8	80	0	6
	450	0.9		450	13.75
	600	1.3		600	16.25
	700	1		700	13.25
	830	1.2		830	15
	900	0.95		900	15.5
	1000	0.9		-	-

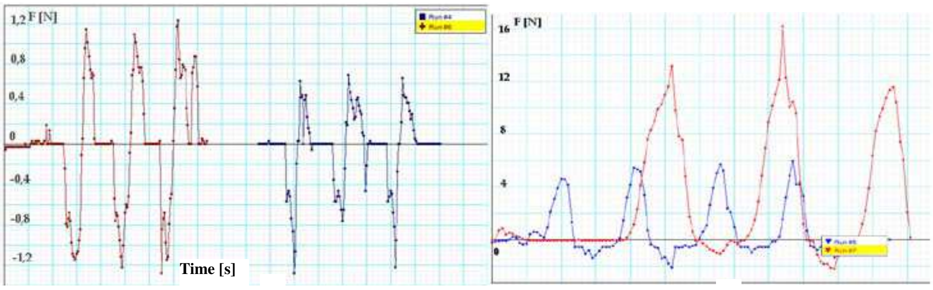


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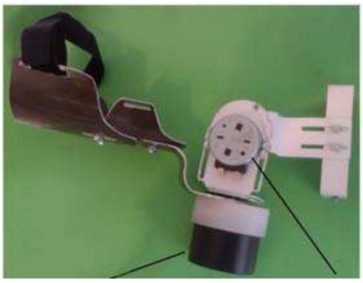
Figure 9: ERF brake output forces for: a-30%; b-80% corn starch fluid



ERF Brake AC Motor

Figure 10: The ERF brake compatibility with the wrist exerciser

5. Conclusions

Due to their property that consists of electroactive changing of their viscosity, the electrorheological fluids have attracted the interest of engineers. These fluids act as simple and rapid-response interfaces between electronic controls and mechanical hardware structures. Besides some explored commercial applications (shock absorbers, clutches, seat dampers, variable flow pumps, earthquake-resistant structures, positioning structures), innovative variable-resistance exercisers were investigated. There is a real need for smart exercising devices whose functional parameters can be rigorously controlled, what it can get through ERF based brakes.

Rotational ERF brakes are developed as the simplest structure of hydraulic clutches and by fixing one of the shafts. The benefit gained is that the ERF clutch or brake has a variable transmitted torque related with the activation voltage. These ERF clutches/brake stack structure can be easily dimensioned by aid of relations described if the ERF viscosity at different voltages and the maximum torque needed at the output shaft are known.

The most reliable method to control the ERF structures is by using a boost-converter as a power supply. Despite its simplicity this power supply has a control compliance that makes it easy to use for the ERF control.

Based on the described relations and on the previously ERF measurements an ERF brake was developed. The brake was tested with commercially available and laboratory developed ERF. In case of commercially ERF the braking torque domain is reaching the value of 177.45 [mNm] sufficient for wrist physiotherapy exercises. By using laboratory developed ERF the braking domain is smaller and is well influenced by the particles proportion. These laboratories developed ERF can develop necessary braking torques for rehabilitation exercises but need to be changed in accordance with the torque that can be achieve by the patient. The main advantage of the laboratory ERF is the cost price despite of their low torque domain. Usage of commercially ERF extends the torque domain but is more expensive.

ERF brake experimental results shows that the developed structure can be used for active with resistance exercises and its possibility to be incorporated into the structure of the previously developed wrist exerciser.

Acknowledgement

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