An Exercise Device for Upper-Extremity Sensory-Motor Capability-Augmentation Based on a Magneto-Rheological Fluid Actuator

Roman KAMNIK, Jernej PERDAN, Tadej BAJD, Marko MUNIH

Abstract: Resistance exercise has been widely reported to have positive rehabilitation effects for patients with neuromuscular and orthopaedic disorders. This paper presents the design of a versatile rehabilitation device in the form of a rotation joint mounted on the adjustable arm support that provides a controlled passive resistance during the strength training of hand muscles. The resistance is supplied by a rotational magneto-rheological actuator controlled by the force-feedback information. The device provides both isometric and isokinetic strength training and is reconfigurable for different usage conditions. The experimental evaluation results show that the usage of the magneto-rheological actuator is advantageous for electrical motors in cases of passive-resistance-based exercise.

Keywords: rehabilitation, exercise device, magnetorheological fluid

1 Introduction

In rehabilitation and sports medicine, computerized active-exercise devices have been shown to be suitable for providing the clinical delivery of training of the required intensity [1]. An especially challenging aspect is the recovery of the hand's function. We have recently developed a novel system for hand sensory-motor augmentation [2] that is designed to allow the force tracking training of finger flexors and extensors and to provide objective data on training performance in isometric conditions. Incorporated functional electrical stimulation adds to reduced finger-force generation due to injury, thus motivating the user to perform better. The system consists of a visual feedback display, the hand-force measuring device, and the closed-loop controlled electrical stimulator. The results of a pilot therapy study in incomplete tetraplegic subjects showed that the augmentation of voluntary grip force control with the presented system is possible. However, the training performed in isometric conditions in which at various angular positions the external resistance applied to the joint is always equal to the force applied by the patient is not considered to be the most efficient.

The isotonic and isokinetic exercises are considered to be more efficient. The isotonic exercise is performed dynamically over a predefined range of motion. The resistance applied to the joint is either constant or follows a

Prof. dr. Roman Kamnik, univ. dipl. inž., Jernej Perdan, univ. dipl. inž., prof. dr. Tadej Bajd, univ. dipl. inž., prof. dr. Marko Munih, univ. dipl. inž.; Laboratory of Robotics and Biomedical Engineering, Faculty of Electrical Engineering, University of Ljubljana

predefined pattern as a function of the joint's angular position. This mode of exercise is motivated by the length tension relationship of the skeletal muscle in which the largest force is generated when the muscle fibers are at their optimal length. The force-producing capacity of a muscle changes across the range of joint motion and is typically highest in the mid range of joint motion. Muscle force generation during concentric exercise is also influenced by the contraction velocity, as described by the hyperbolic model relating the force and velocity during contractions. As the contraction velocity increases, the muscle force decreases. From this relationship the isokinetic exercise is motivated, which is also performed dynamically, but in that case the resistance is applied to the joint only if a predefined angular speed is reached by the joint in order to avoid the joint exceeding this speed value. This particular exercise mode is the only one that enables dynamic training at the maximum muscle force over the entire range of motion.

Most force-feedback devices that are capable of regulating joint motion according to the needs of a particular patient and take muscle and limb dynamics into consideration rely on electric motors, pneumatics, or some other conventional power-producing method.

In this paper we present a semi-active exercise system based on magneto-rheological fluid (MR fluid) actuator [3]. This semi-actively controlled device can be considered as one that has properties that can be adjusted in real time, but cannot input energy into the system being controlled. Such devices typically have very low power requirements and offer the reliability of passive devices, while maintaining the versatility and adaptability of fully active systems [4], [5]. In the second section of the paper the principle of the operation of the MR fluid actuator is presented. The third section presents the design of the exercise device based on the MR fluid actuator, while the fourth section outlines the experimental results.

2 Principle of operation of the MR fluid actuator

MR fluids are materials that respond to an applied magnetic field with a change in rheological behavior. Typically, this change is manifested by the development of a yield stress that monotonically increases with the applied field. The MR fluid typically consists of micron-sized, magnetically polarizable particles dispersed in a carrier medium, such as mineral or silicone oil. When a magnetic field is applied to the fluids, particle chains form, and the fluid becomes a semi-solid and exhibits viscoplastic behaviour. The MR fluid can be readily controlled with a low voltage (e.g., 12-24 V), current-driven power supply outputting only 1-2 A.

The behaviour of MR fluids is often described as a Bingham plastic model having a variable yield strength, which depends upon the magnetic field B. At fluid stresses below the yield stress the fluid acts as a viscoelastic material exhibiting Newtonian-like behavior. At fluid shear stresses above the field-dependent yield stress $\tau_{yd}(B)$ the fluid flow is governed by the Bingham plastic equation [9]. This behaviour is described by (1):

$$\tau = \begin{cases} G\gamma & \tau < \tau_{yd} \\ \tau_{yd}(B) + \mu_p \dot{\gamma} & \tau > \tau_{yd} \end{cases} \tag{1}$$

where B is the magnetic field $\dot{\gamma}$ is the fluid shear rate and μ_p is the plastic viscosity (i.e., the viscosity at $B = 0$), G is the complex material modulus (which is also field dependent). τ_{yd} in equation (1) is a function of the magnetic field B and exponentially increases with respect to the magnetic flux density. The relationship is given by:

$$\tau_{yd}(B) = kB^{\beta} \tag{2}$$

where the proportional coefficient k and the exponent β are intrinsic values of the MR fluid, which are functions of various factors such as the magnetic field, the particle size, the particle shape and concentration, the carrier fluid, the temperature and the magnetic saturation. The applied magnetic field B is produced within the actuator when a current i is supplied to the electromagnet encircling the MR fluid, i.e.,

$$B = k_k i \tag{3}$$

True MR fluid's behavior exhibits some significant departures from this simple model. Perhaps the most significant of these departures involves the non-Newtonian behavior of MR fluids in the absence of a magnetic field.

In general, the MR devices involve either disc-type or valve-type designs. In valve-type designs, the fluid is pushed through a narrow channel where the magnetic field is applied to control the flow rate, and hence the applied force. Typically, these designs resemble a cylinder-piston assembly with the coil on the piston shaft. In disc-type designs, the fluid is in a narrow gap between a rotating disc and a fixed outer casing [6], [7]. The coil is positioned close to the outer edge of the disc. When the magnetic field is applied, the increased yield stress of the fluid creates a braking torque on the disc.

The braking torque T_b developed by the MR fluids in the disc-type actuator can be determined as:

$$T_b = 2\pi \int_{r_w}^{r_z} \tau \, r^2 dr = 2\pi \int_{r_w}^{r_z} (\tau_{yd} + \mu_p \dot{\gamma}) r^2 dr \tag{4}$$

where r_z and r_ω are the outer and inner radii of the actuator disk, respectively; and $\dot{\gamma} = r\omega/h$ where ω is the angular velocity of the rotating disk and h is the thickness of the MR fluid gap [10]. Following (2), the equation (4) can be rewritten as:

$$T_b = 2\pi \int_{r_w}^{r_z} \left(\mu_p \frac{r\omega}{h} + kB^{\beta}\right) r^2 dr \tag{5}$$

Integrating (5) and substituting with (3) the braking torque developed by the MR fluids can be calculated:

$$T_b = \frac{2\pi}{3} k k_k^{\beta} \left(r_z^3 - rw^3\right) i^{\beta} + \frac{\pi}{2h} \mu_p \left(r_z^4 - rw^3\right) \omega \tag{6}$$

Equation (6) shows that the braking torque developed in the circular plate MR fluid actuator can be divided into a magnetic-field-dependent induced yield-stress component T_b and a viscous component T_μ:

$$T_b = T_B + T_\mu = k_i i^\beta + k_\omega \omega \qquad (7)$$

3 MR fluid actuator experiments

For actuating the exercise device, a rotary MR fluid actuator produced by Lord Corporation, USA was used [8]. The Lord TFD Device RD-8043-1 is capable of producing up to 12 Nm of axial torque while it is driven by a current-driven power supply with current capabilities of up to 1.5 A. The device has a position feedback sensor integrated, which outputs a PWM signal with duty cycle varying between 5 and 95%, according to the position of the axis.

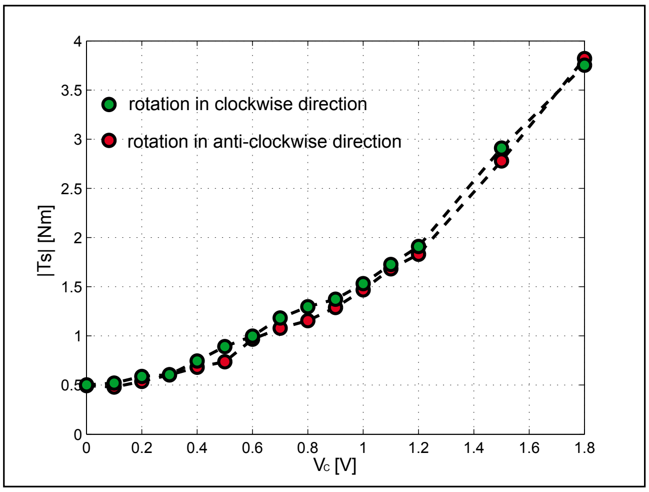

Figure 1. *Static torque threshold values versus the MR fluid excitation*

The torque output was measured using a test setup with a load cell, a lever arm, and a data-acquisition system. The braking torque experiment started with measuring the static torque threshold while manually rotating the actuator axis, first in the clockwise and then in the anti-clockwise direction. The threshold torque, which is actually the sum of the static friction and the magnetic-field-dependent induced yield-stress component T_B, was assessed in several repetitions with different input voltages. The graph in *Figure 1* presents the absolute values of the acquired threshold torque T_S with regards to the input voltage V_C. From the results a nonlinear relationship can be observed.

In the second experiment, the dynamic characteristics of the MR fluid actuator were measured, evaluating the dependence on the motion speed. The braking torque was assessed during the motion in the forward and backward directions, moving with a different rotation velocity and with a constant MR fluid-actuator input. A family of curves was obtained that is presented in *Figure 2*. Each curve represents a typical characteristic of the braking torque. The presented values sum the yield stress component T_B , the viscous component T_μ, and the static friction. From the acquired results a nonlinear torque-velocity relationship with a hysteresis loop can be observed [11].

4 Exercise device for upper-extremity sensory-motor capability augmentation

The conceptual scheme of the training system for upper-extremity sensory-motor augmentation is presented in *Figure 3*. The system is designed to train the finger or wrist flexor and extensor muscles by performing the position-tracking task. The reference and actual positions are displayed on a visual display as two rotational pointers. The MR fluid actuator is used as a braking torque modulating device that allows exercise under isometric, isotonic or isokinetic conditions. The core of the system is a personal computer (PC) that is used for reference generation, actual hand-force acquisition, visual presentation of the reference and actual position, and control of the MR fluid actuator. The software application for controlling the system was developed in the Mathworks Matlab-Simulink programming environment and it runs in the xPC real-time operating system.

A close-up view of the exercise device is shown in *Figures 4* and *5*. The device is constructed from aluminium strut elements. On the construction, the MR fluid actuator is mounted, and on its axis an adjustable lever arm with a JR3 force/torque sensors (50M31A-I25; JR3, Inc., Woodland, CA, USA) and a finger fixation are fixed. The fingers are fixed to the force sensor by means of a finger support and a Velcro strap. The finger fixation and the force sensor enable the acquisition of the hand forces. To ensure the proper position and to prevent the arm from moving during the training, the forearm is fixed to the arm support by Velcro straps. The position of the force sensor, the actuator and the forearm support is adjustable, allow-

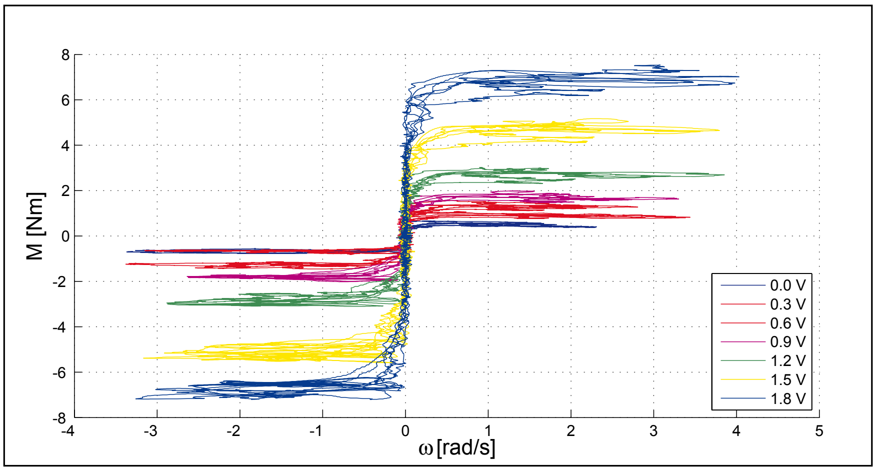

Figure 2. *Dynamic characteristics of the MR fluid actuator*

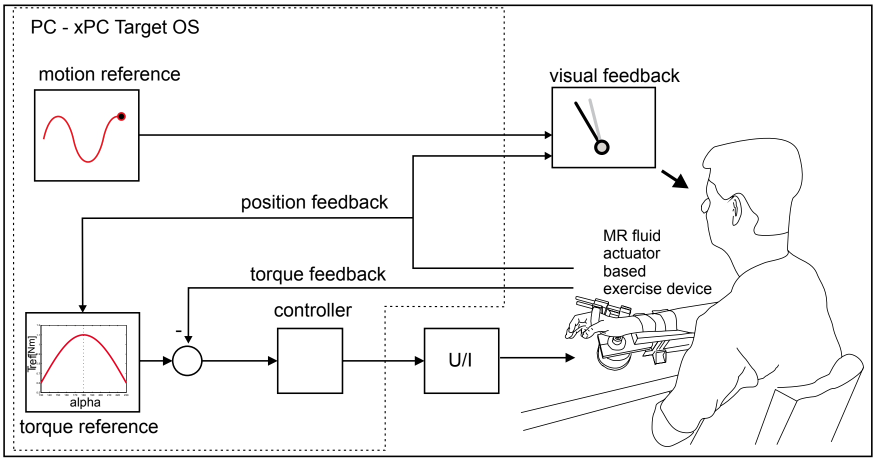

Figure 3. *Conceptual scheme of the training system showing its main components: exercise device with force sensor and MR fluid actuator, visual feedback, and closed-loop controller*

$$T_{ref} = \pm 0.6 \pm 0.5 * \sin(1.8 * (\alpha - 2.269)) \quad (8)$$

in which the parameter α indicates the current position of the actuator axis in radians, and the sign ± is changed regarding the rotation direction (clockwise/anticlockwise). According to the term above, the braking torque had the highest value at the finger-extended position, while it diminished with the displacement from it.

The actual torque was measured while the MR fluid actuator activity was controlled by a PI controller with a feed-forward term according to the difference between the actual and the

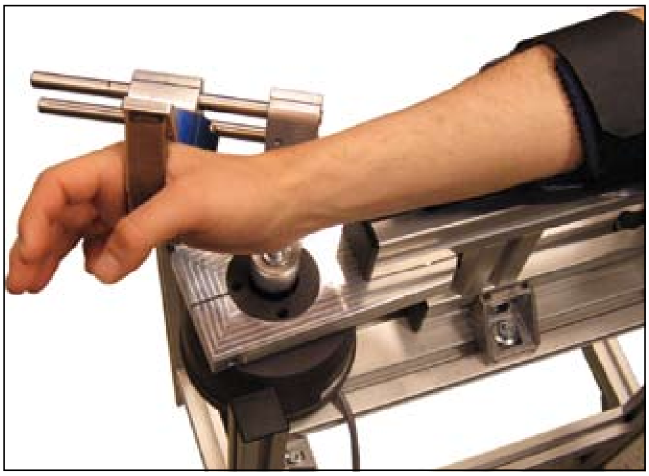

Figure 4. *Close-up view of the exercise device from the left side*

Figure 5. *Close-up view of the exercise device from the right side*

ing the accommodation of the measuring setup to each individual, as well as to assess either the right or the left hand. Two PCI boards were used for data acquisition from the force and position sensors, and to generate the control voltage for the MR fluid actuator.

5 Experimental evaluation

To demonstrate the performances of the developed exercise device an experimental evaluation was made. In the position tracking experiment a healthy subject was asked to follow the reference position, which was altered linearly in the range of ±30° from its center (fingers extended) position at 180°. During the motion, the braking torque was modulated by the MR fluid actuator according to the term:

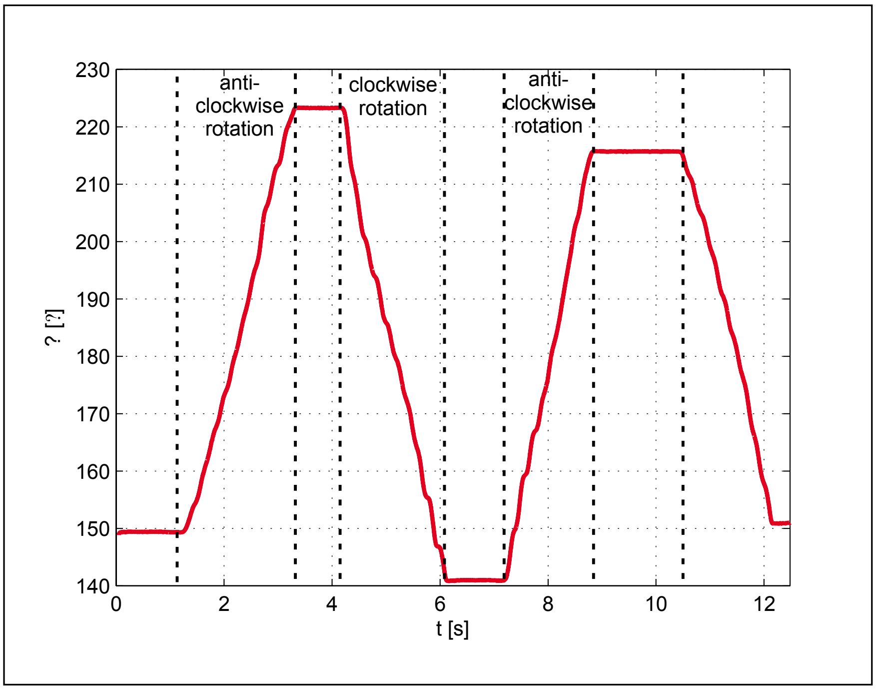

Figure 6. *Motion trajectory in the experimental evaluation*

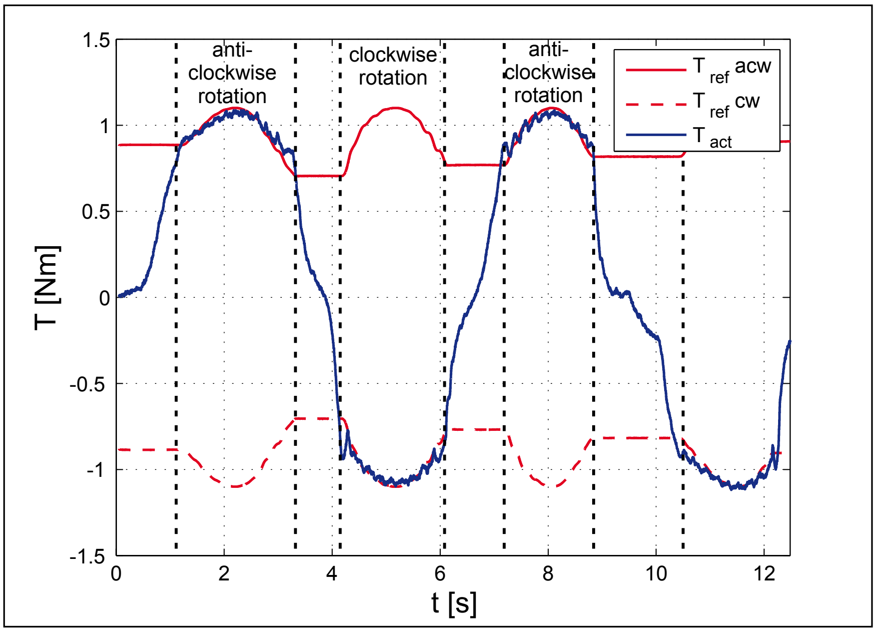

Figure 7. *Reference torque tracking of the MR fluid actuator*

reference values. Figure 6 presents the actual motion trajectory achieved during the experimental evaluation. In Figure 7 the reference T_{ref} and actual T_{act} torques are shown.

6 Conclusion

The paper presents the development and experimental evaluation of a semi-active exercise device for upper-extremity sensory-motor capability augmentation. The device is built on the basis of the rotational magnetorheological actuator that allows resistive torque modulation. The frame of the device is constructed to allow a flexible change of the configuration, while the controller is implemented in the Mathworks Matlab/Simulink environment and the real-time xPC Target operating system.

The experimental results show that the MR fluid actuator is suitable for application in exercise devices as a semi-active element providing braking-torque modulation. On this basis, several exercise modes can be achieved. In comparison to electric motor actuators the power-to-weight ratio and the need for a power amplifier is advantageous in the case of MR fluid actuator usage. On the other hand, the control is more complex since the MR fluid actuator is a highly nonlinear device.

The proposed areas of application for exercise devices based on MR fluid actuators are in rehabilitation and sports training.

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Naprava za vadbo roke na osnovi mehanskega člena z magnetoreološko tekočino

Razširjeni povzetek

Vadba z gibanjem proti uporu je uveljavljena v rehabilitaciji in športu. Prispevek predstavlja sistem za krepitev senzomotoričnih sposobnosti gornjih ekstremitet, ki je razvit na osnovi člena za zagotavljanje upora s pomočjo magnetoreološke tekočine. Sistem je namenjen vadbi fleksorjev in ekstenzorjev prstov z izvanjanjem naloge sledenja pozicije. Naprava je zgrajena kot prilagodljiva mehanska konstrukcija na katero sta nameščena opora za podlaht ter člen za zagotavljanje upora z vpetjem za prste in senzorjem sile. Med vadbo je upor gibanju zagotovljen glede na povratno informaciji o sili s pomočjo rotacijskega aktuatorja, ki vsebuje magnetoreološko tekočino. Magnetoreološka tekočina (ang. magnetoreological (MR) fluid) je tekočina, ki ima spremenljive reološke lastnosti glede na vpliv magnetnega polja. MR tekočino tvori osnovna nemagnetna tekočina v kateri se nahajajo mikronsko veliki delci, ki se pod vplivom polja polarizirajo. V odsodnosti magnetnega polja se ti delci prosto gibljejo, ko pa je tekočina izpostavljena magnetnemu polju, se delci začno povezovati v verižne strukture. Verižne strukture spreminjajo viskozne karakteristike pretoka, hkrati pa je zaradi njih od magnetnega polja odvisna tudi meja tečenja (ang. yield stress). S pomočjo mehanskega člena, v katerem se nahajajo rotor v obliki diska, MR tekočina in električna tuljava, je mogoče na osi ustvariti moment upora, ki je voden z električnim signalom. S pomočjo zaprtozančnega vodenja glede na informacijo o navoru in pomiku pa je lahko tovrstni MR člen uporabljen za zagotavljanje vadbe v izometričnih, izotoničnih ali izokinetičnih pogojih.

Rezultati vadbe s pomočjo razvite naprave in MR člena kažejo, da je pri zagotavljanju pasivnega upora MR člen možno uporabiti kot enakovredno zamenjavo električnim, hidravličnim ali pnevmatskim aktuatorjem. Prednosti uporabe so varnost, majhne dimenzije in teža ter velika energijska učinkovitost. Kompleksnejše je vodenje, saj je MR člen aktuator z nelinerano karakteristiko.

Ključne besede: rehabilitacija, naprava za vadbo, magnetoreološka tekočina

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