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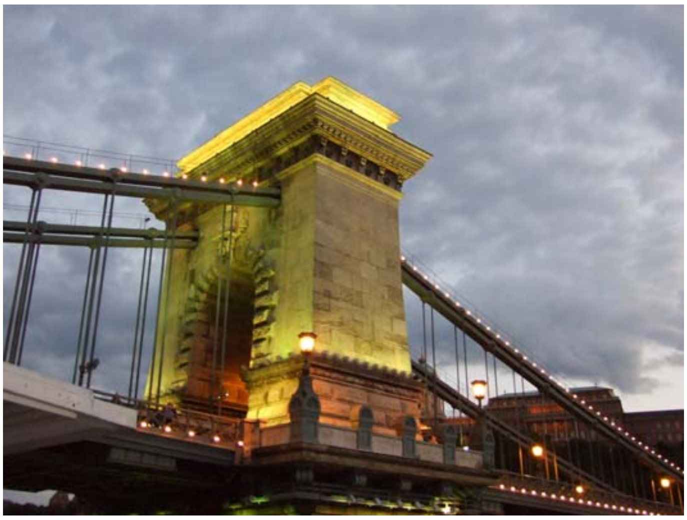

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EXERCISE DEVICE FOR UPPER-EXTREMITY SENSORY-MOTOR CAPABILITY AUGMENTATION BASED ON MAGNETO-RHEOLOGICAL FLUID ACTUATOR

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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 strength training of hand muscles. The resistance is supplied by a rotational magnetorheological actuator controlled with regards to 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 magnetorheological actuator is advantageous to the electrical motors in the cases of passive resistance based exercise.

Keywords: rehabilitation, exercise device, magnetorheological fluid

1 INTRODUCTION

In the 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]. Especially challenging aspect is the recovery of hand function. We have recently developed a novel system for hand sensory-motor augmentation [2] which is designed to allow 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 for better achievements. The system consists of a visual feedback display, the hand force measuring device, and the closed-loop controlled electrical stimulator. The results of pilot therapy study in incomplete tetraplegic subjects showed that augmentation of voluntary grip force control with 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 as most efficient.

As more efficient, the isotonic and isokinetic exercises are considered. The isotonic exercise is performed dynamically over a predefined range of motion. The resistance applied to the joint is either constant or follows a predefined pattern as function of joint angular position. This mode of exercise is motivated by the length tension relationship of skeletal muscle in which largest force is generated when 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 midrange of joint motion. Muscle force generation during concentric exercise is also influenced by the contraction velocity as described by a hyperbolic model relating the force and velocity during contractions. As contraction velocity increases, 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 that the joint exceed this speed value. This particular exercise mode is the only one that enables

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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 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 magnetorheological fluid (MR fluid) actuator [3]. This semiactive 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 maintain the versatility and adaptability of fully active systems [4], [5].

In the second section of the paper the principle of operation of MR fluid actuator is presented. The third section presents the design of exercise device based on MR fluid actuator, while the fourth section outlines the experimental results.

2 PRINCIPLE OF OPERATION OF MR FLUID ACTUATOR

MR fluids are materials that respond to an applied magnetic field with a change in rheological behaviour. Typically, this change is manifested by the development of a yield stress that monotonically increases with applied field. The MR fluid typically consists of micron-sized, magnetically polarizable particles dispersed in a carrier medium such as mineral of 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 the fluid flow is governed by the Bingham plastic equation [9]. This behaviour is described by (1):

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

where B is the magnetic field, $\dot{\gamma}$ is the fluid shear rate and μ_p is the plastic viscosity (i.e., 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 magnetic flux density. The relationship is given by:

$$\tau_{yd}(B) = \kappa B^{\beta} \qquad (2)$$

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

$$B = k_k i \qquad (3)$$

True MR fluid behaviour exhibits some significant departures from this simple model. Perhaps the most significant of these departures involves the non-Newtonian behaviour 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 haft. 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 Tb developed by the MR fluids in the disc- type actuator can be determined as:

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

where r_z and r_w 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:

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

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

$$T_b = \frac{2\pi}{3} \kappa\, k_k^{\beta}\; (r_z^3 - r_w^3) i^{\beta} + \frac{\pi}{2h} \mu_p (r_z^4 - r_w^4)\omega \qquad (6)$$

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 to produce up to 12 Nm of axial torque while it is driven by current-driven power supply with the 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 $5 - 95\%$ according to the axis position.

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 a static friction and a magnetic field dependent induced yield stress component T_B was assessed in several repetitions with different input voltages. The graph on Figure 1 presents the absolute values of acquired threshold torque T_S with regards to the input voltage V_C. From the results a nonlinear relationship can be observed.

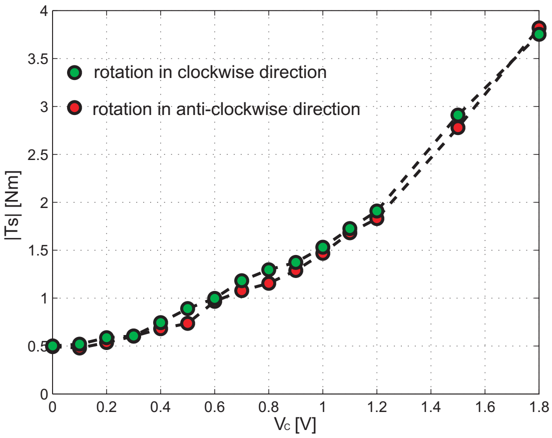

Figure 1 Static torque threshold values with accordance to the MR fluid excitation.

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

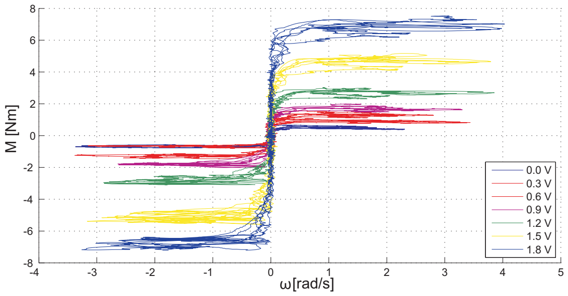

Figure 2 Dynamic characteristics of MR fluid actuator.

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 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 which 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 xPC real time operating system.

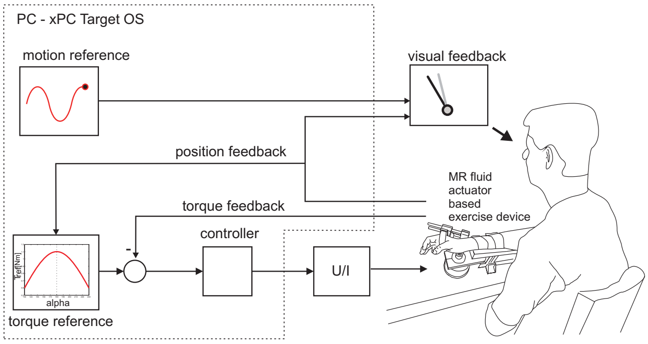

Figure 3 Conceptual scheme of the training system showing its main components: exercise device with force sensor and MR fluid actuator, visual feedback, and closed-loop controller.

The close view of the exercise device is shown in Figures 4 and 5. The device construction is made of aluminium strut elements. On a 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 force sensor enable the acquisition of the hand forces. To ensure the proper position and to prevent the arm from moving during training, the forearm is fixed to the arm support by Velcro straps. The position of force sensor, the actuator and forearm support is adjustable, allowing the accommodation of 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 MR fluid actuator.

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

Figure 5 Close view of the exercise device from the right side

5 EXPERIMENTAL EVALUATION

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

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

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

The actual torque was measured while the MR fluid actuator activity was controlled by a PI controller with a feedforward term according to the difference between actual and reference value. Figure 6 presents the actual motion trajectory accomplished during experimental evaluation. In Figure 7 the reference T_{ref} and actual T_{act} torques are shown.

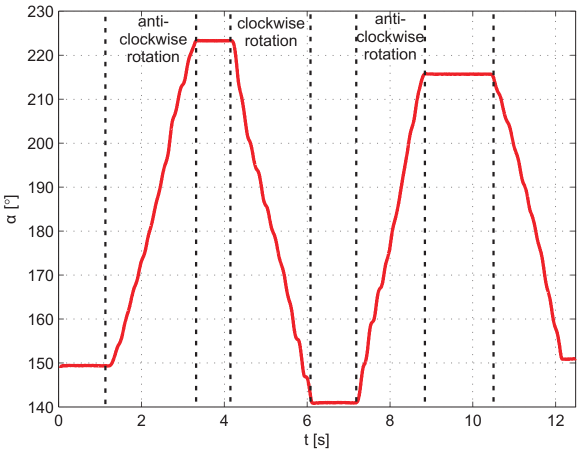

Figure 6 Motion trajectory in experimental evaluation.

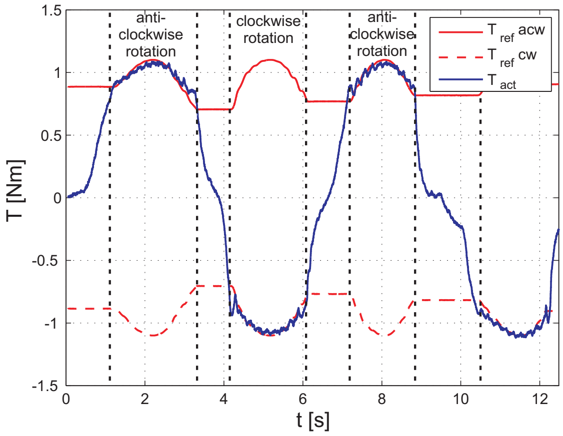

Figure 7 Reference torque tracking of MR fluid actuator.

6 CONCLUSION

The paper presents the development and experimental evaluation of semi-active exercise device for upper-extremity sensory-motor capability augmentation. The device is built on the basis of the rotational magnetorheological actuator which allows resistive torque modulation. The frame of the device is constructed to allow flexible change of configuration, while the controller is implemented on a Mathworks Matlab/Simulink environment and 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 its basis, several exercise modes can be achieved. In comparison to electric motor actuators the power to weight ratio and need for power amplifier is advantageous in the case of MR fluid actuator usage. On the other side, 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 the MR fluid actuators are in rehabilitation and sports training.

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