MR-Tech: a portable smart wrist rehabilitation device

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Abstract. The purpose of this paper is to present a novel patent-pending, computer controlled, MR-brake actuated, muscular rehabilitation and evaluation device that can be carried to and used at patient’s home (without the immediate assistance of the physiotherapist), offering similar functionalities as existing stationary devices that can be found in hospitals (i.e. isometric, isotonic and isokinetic exercise modes). The first part of the paper describes in more details these various exercise modes. The second part is devoted to the design of the machine and the third part to its control. The last part presents preliminary results obtained for the wrist pronation/supination motion.

1. Introduction
The handling of patients with joint muscular dysfunctions requires the intervention of a practitioner who currently mainly exercises his skills with the assistance of large, heavy, expensive and stationary rehabilitation devices (e.g; BIODEX, HUMAC NORM, CONTREX…) that force the patient to perform exercises in clinics or medical private practices. The objective of the device presented in this paper is precisely to make this technology available for home exercises of the wrist joint.

Muscular rehabilitation and evaluation is usually carried out by performing three main types of exercises namely isometric, isotonic and isokinetic [1]. The isometric exercise is performed statically (without any rotation of the joint) at various angular positions. The external resistance applied to the joint is always equal to the force applied by the patient. The isotonic exercise is performed dynamically over a predefined Range Of Motion (ROM). The resistance applied to the joint is either constant or follows a predefined pattern as a function of joint angular position (e.g. parabolic…). The isokinetic exercise 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 exceeds this speed value. This particular exercise mode is the only one that enables dynamic training at the maximum muscle force over the entire ROM (figure 1) since the isotonic exercise (even with a parabolic profile) does not adapt its force profile to the exact muscular capacities of the user.

![Figure 1. Performances comparison for the isotonic and isokinetic exercise modes](image_url)
2. Description of the device

2.1. System components
As can be seen on figure 2, the rehabilitation device is composed of three major subsystems: mechanical hardware, embedded electronics and user interfaces.

![Figure 2. Schematic view of the system components](image)

The mechanical hardware is mainly composed of a MR-brake (described in details in section 2.2.) connected to its support through two bearings. A rotational MR-brake actuation was preferred over other technologies (commercial devices use DC-motors and other authors have used ER-brakes [2][3] or linear MR damper [4]) mainly due to its high torque/volume ratio and safety of operation (more details can be found in [5]). The brake rotation relatively to its support is blocked by a load cell providing a measurement of the reaction force applied to the brake stator when a torque is applied on the rotor of the brake. An encoder is connected to the rotor of the brake providing position and speed measurements.

Embedded electronics are composed of a TI TMS320F2812 microcontroller used for control and data acquisition purposes. It is linked to an electronic board that drives the MR-fluid brake (through a PWM current drive) and implements the interface with the sensors and the user interfaces (through Bluetooth or wired connections).

Two user interfaces are provided with the device. The first one is a laptop used by the physiotherapist to set exercise parameters and to analyse data collected during the exercise. The second one is a PDA that provides a simplified visual feedback to the patient when he is using the device and that stores exercise results for further analysis by the physiotherapist (following a data transfer between the PDA and the physiotherapist laptop).

2.2. Details on the MR-brake design
A previous study has shown the advantages of T-shaped rotor brakes over conventional drum brakes in terms of compactness [6]. Indeed, such a configuration enables to concentrate the action of the fluid as far as possible from the output axis, leading to a high output torque while maintaining a reasonably compact design (figure 2). The magnetic circuit of the brake as been optimized (using electromagnetic FE analysis) in order to achieve a maximum output torque of 28Nm while minimizing its volume and mass with the following constraints: maximum external diameter: 120mm, thickness of the MR-fluid gap: 0.4mm, thickness of the rotor T-shaped extremity: 2mm and maximum current in each coil: 0.5A.

Experiments conducted on the prototype that was built based on the previously mentioned specifications have shown a maximum output torque of 22.5Nm combined with an off-state torque of...
0.4Nm. The difference between predicted and measured torque could be explained by a non-optimal filling of the fluid gap. This hypothesis seems to be confirmed by the fact that measurements of the magnetic induction field in the gap of the stator (without fluid) exhibit good correspondence with FE simulation results. The achieved torque still being compatible with physiological requirements, the brake has been kept in that state due to difficulties to clean and refill it.

3. Control strategy

A control strategy, inspired by [4], composed of three overlapping control loops, is used to control the device. The first control loop is a current loop used to compensate for the electrical time delay related to the use of coils to generate the magnetic field inside the brake. The second control loop is a torque loop used to compensate for the imperfections of the relation between the current applied to the brake and its output torque (non-linearity, hysteresis, remanence). The third loop is a motion loop used to control the motion of the shaft of the device according to the selected exercise mode (isometric, isotonic or isokinetic)(figure 3).

![Figure 3. Control scheme of the rehabilitation device](image)

For the isometric mode, the control is based on a position controller that implements a hard stop if the measurement position is reached and if the patient applies a force in the right direction. For the isotonic mode, when the patient moves within the measurement ROM, the reference torque, used as input of the torque loop, is simply set to a constant value or to a value varying with the angular position (following the pattern selected by the physiotherapist). For the isokinetic mode, the control is based on a speed controller that provides a reference torque to the torque loop. It should be noted that, as the speed of motion is quite slow (<180°/s), the quality of the speed signal derived from the encoder measurements is quite poor. In order to alleviate this problem, control is not based on a speed measurement but on a position measurement that is compared with a reference signal consisting of a ramp signal (corresponding to a constant speed). The difference between these two values is used as input of a PID controller. The reference position signal starts to increase/decrease from the current position as soon as the motion is initiated. The slope of the ramp signal is adjusted according to the speed to be achieved. For both isotonic and isokinetic modes, virtual end-of-motion stops have been implemented in order to limit the motion of the user to the specified ROM.

4. Experimental results

Dedicated electronics and user interfaces are still under development. Preliminary tests have however already been conducted by linking the mechanical hardware to a dSPACE PC-based acquisition board used in combination with the Control-Desk software package emulating the future user interface. Control has been implemented using MATLAB Simulink.

All the results presented here are for the wrist pronation/supination motion but similar results have been obtained for the two other wrist motions. Results obtained for the isometric exercise show that the user is perfectly blocked at the various measurement positions (0°, 30°, 60°, 90°) and that he is able to leave these positions with a very limited sticking force (figure 4). Performances of the isotonic mode have been evaluated by applying a parabolic and a constant resistive torque profile (with various
maximum values: 2, 4, 6Nm) against the pronation and supination motion respectively (figure 4). A perfect behaviour can be observed. The torque peaks at the end of the ROM are due to the fact that the user motion is suddenly limited by the virtual end-of-motion stops.

**Figure 4. Torque vs position for the isometric and isotonic exercise modes**

Results obtained for the isokinetic mode show that the angular speed of the pronation/supination motion can be kept almost constant whatever the torque applied by the user (figure 5), for various values of the reference speed (50°/s, 100°/s, 150°/s). Future work will be mainly focused on the statistical analysis of the reproducibility of the measurements made with the machine and of the agreement with measures obtained with existing commercial devices.

**Figure 5. Speed & torque vs position for the isokinetic exercise mode**

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