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Elbow Functional Compensation using a Lightweight Magnetorheological Clutch

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Abstract— **There are many applications for which a patient needs functional compensation due to motor disorders in daily activities. Classic research has focused on robotics solutions in terms of actuators or motors, but the point of this paper is to analyze new solutions combining both biological and artificial structures, in order to improve standard developments. Nowadays wearable Robots are taking an important role in rehabilitation purposes, due to this issue lots of new designs are emerging, but most of them are not still prepared to be used in terms of autonomy, weight, etc. Under the *Hybrid Neuroprosthetic and Neurorobotic devices for Functional Compensation and Rehabilitation* (HYPER) project, new actuator technologies have been developed in order to improve the adaptability and portability of rehabilitation devices. The designed device is based on a lightweight magnetorheological (MR) clutch which is able to transmit torque from a motor to the injured joint. Though it is intended to work in human upper limb (elbow mainly), other future designs will also be studied for other human joints. Simulation results using Simulink®, MSC Adams®and MSMS®are reported to illustrate the viability of the proposed device.**

Index Terms – **Functional compensation, Rehabilitation, Clutch, MR fluid, MSMS®, Co-simulation.**

I. INTRODUCTION

Exoskeleton is an external fixed structure with joints, which transmits torque from actuators to human attached limbs. The use of this kind of devices for rehabilitation purposes, as seen in recent literature [1], allow patients to recover or improve their motor functional capabilities [2], in an adaptable way. Defining different training exercises (depending on the specific injure/disorder) and improving the physical rehabilitation therapies, will permit the therapists to better attend their patients.

The use of typical industrial robot technologies, for rehabilitation purposes, has been proved to be a bad solution in terms of patients acceptability, usability, safety and dependability. Person-oriented robots thought to interact with user's limbs would be desirable. That is the concept of Wearable Robots (WRs) proposed by Pons [3]. The HYPER project, under the work presented in this paper has as main objective, the development of neurorobotic (NR) devices in close cooperation with the human body, both for rehabilitation and functional compensation of motor disorders in daily activities.

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Involuntary muscle contractions make the control strategy too complex for classic actuators. Spasms are really dangerous when wearing a medical robot, because of the inertias and opposition torques transmitted to the human joint. That is why a *smooth* and fast response of these devices is desired not only in terms of control software, but in the designed models.

Apart from these high requirements, the weight and dimension of a device, working in a wearable exoskeleton, should be as light and small as possible (as a general rule). That means that the most important variables are the force per kilogram or the force per volume of such device. These tricky constraints make the design of the actuators a difficult problem to solve but a challenge for most engineers just working to find the optimal actuator for biomedical applications [4].

A. MR fluids

MR fluids are non-colloidal suspensions of polarisable particles having a size on the order of a few microns in a carrier liquid. They change their viscosity instantly ($\sim$1ms) just modifying the magnetic field applied, by forming columnar structures parallel to it. These chain-like structures restrict the motion of the fluid, thereby increasing the viscous characteristics of the suspension.

The use of a fluid as a smooth transmission medium in actuators [5], allow freeing the joints instantly. Thus the physical response for an injured joint is suitable and robust for rehabilitation purposes, and it is also the principle of the proposed magnetorheological clutch [1].

B. Simulation software used

To accomplish the HYPER project goals, different types of software packages are being used. These include flexible mechanical structures development software (for the upper limb exoskeleton) and engineering specialized software to simulate complex material behaviour. Typically, the first mentioned area of work is accomplished using Computer Aided Design (CAD) ones, whose mainly consist of a friendly graphical interface with a huge amount of tools. During this project, two CAD style programs are being used; one of them is MSC Adams®, which work domain is the mechanical structural one, and it is used to develop the upper limb part with the elbow joint. The other CAD program used is MSMS®[6], which allows the possibility of building a musculoskeletal model of human limbs, and defining the muscles to be used. MR behaviour was simulated

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using Matlab-Simulink®, which is the most commonly used engineering software. It has its own scripting language, with lots of functional packages to construct robust control systems in both mixture of graphical interface and traditional text programming.

II. DESIGN OF A LIGHTWEIGHT MR CLUTCH

A. Proposed design

Remembering that the developed actuators need to be used in exoskeletons for human arms rehabilitation, HYPER project search for the best relation in transmitted torque and wearable comfort. Thus, the proposed clutch consists of a cylindrical shape as seen in Fig.1, similar to the one presented in [7]. The housing part is connected to the input shaft, and inside it there is/are the thin inner disk/s (connected to the output shaft) with little separation between them and the housing part. The MR fluid is found in the free space. The torque in the output shaft is obtained from the one applied in the input shaft and transmitted by the fluid. The viscosity of this fluid is changed by modifying the intensity of the magnetic field applied across the clutch. As a result, different clutch capabilities are obtained.

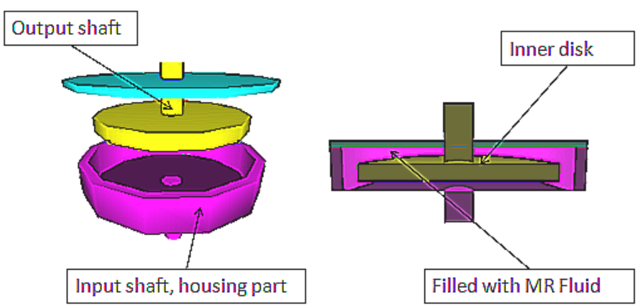

Fig. 1: MR clutch proposed design.

For better results the use of a bigger inner circular disk area is needed, within the imposed project limits. Also the magnetic field will be applied in the opposite way of other similar clutches [8]. This field crosses the inner disk in a perpendicular way to the circular areas of this disk. The transmitted torque to the output shaft depends directly on the contact area in the direction of magnetic field.

B. Calculations of the transmitted torque

The transmitted torque to the output shaft for a variable number of inner disks (n-disk) was calculated using the equations (1)-(3). This n-disk property is the main difference to the one presented in [9].

In order to simplify the calculations, some modifications are done considering that approximately the 95% of the inner disk area is effective in terms of transmitted torque to the output shaft.

$$\frac{T_d}{n-1} = \frac{\pi\eta\cdot|\Delta\omega|}{h_d}(R_2^4 - R_1^4) + \frac{4}{3}\pi(R_2^3 - R_1^3)\tau_B \quad (1)$$

$$T_h = \frac{\pi\eta\cdot|\Delta\omega|}{h_h}\cdot R_2^4 + \frac{4}{3}\pi\cdot R_2^3\cdot\tau_B \quad (2)$$

$$T_{tot} = T_d + T_h \quad (3)$$

In equations (1)-(3), the calculation is divided in two parts. T_d is the one corresponding to the transmitted torque due to the inner disks, and T_h is referred to the housing part. The total sum depends also on the number of inner disks n.

In the above expressions, η is the fluid viscosity with no magnetic field applied, and it is assumed to be a constant value of $0.3 Pa\cdot s$.

$|\Delta\omega|$ is the relative rotational speed between both input and output shafts.

h_d is the separation between two consecutive inner disks, and h_h is the separation between the closer inner disk to the housing part.

R_2 is the inner disk radio, while R_1 is the shaft radio that connects them.

τ_B is the yield stress of the fluid, for the magnetic field applied. For the rest of the work it is supposed that the fluid, when magnetized, is always at the same level, so this value is approximated to a constant, that for the rest of the calculations is supposed to be $5\cdot10^4 Pa$.

C. Simulation of the proposed device

Two different magnetic field sources will be used to evaluate which is better for the project purpose. One of them uses a magnetic field generated by an external current, using a coil. The other one uses permanent neodymium magnets, having the advantages of no electric energy used and less weight than copper coil. For simulations results, a constant value for the applied magnetic field is used instead of both proposed methods.

Before the prototype construction several simulations have been developed to understand the behaviour of MR fluids and the transmitted torque of the designed clutch (in different configurations). Due to the lack or complexity of CAD programs working directly with this fluids, Matlab-Simulink®has been used to simulate the behaviour of them instead of CAD programs. Several Simulink®blocks have been created, recreating this behaviour. The output of this Matlab-Simulink®model is connected directly to MSC Adams View/Controls®software in the way of a co-simulation as seen in Fig.2; that means a simulation carried out between several programs, each of them belonging to a different work domain. MSC Adams®can use as input the output of the previous explained Matlab-Simulink®model to move the elbow joint. With this technique the output torque for the joint is approximated to the one exerted by the MR fluid based clutch.

III. PRELIMINARY RESULTS

First experimental results were analyzed after a serial of fundamental measurements. An actuator scheme was analyzed several times, both in terms of transmitted torque of the MR fluid and the total weight of the clutch. The data

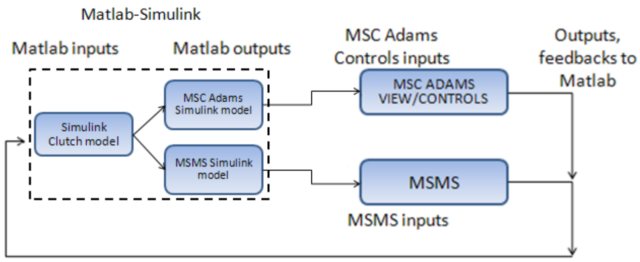

Fig. 2: Co-simulation basic scheme.

from trials is detailed in Table I where maximum transmitted torque was calculated based on the number and diameter of inner disks, and the diameter of the housing part. The weight is the result of the sum of clutch and both shafts. The selected material for every calculation was Al-Mg 5052 with $2.68g/cm^3$ density.

TABLE I: Transmitted torque for different clutch configurations, and total weight of the developed clutch

Number of disks	Inner disk ϕ (cm)	Outer housing ϕ (cm)	Max. torque (Nm)	Weight (g)
1	10	13	38.5	141
1	7	10	12	83
1	6	9	8	61
1	5	8	4.5	48
2	10	13	72	221
2	7	10	25	117
2	6	9	16	90
2	5	8	9	68
3	10	13	103	306
3	7	10	38	157
3	6	9	24	119.68
3	5	8	13	88

Since the required torque for lifting an adult arm is estimated at 3.3Nm (without load), thinking in terms of wearable comfort and maximum transmitted torque, for few loads, the best choice is the one with a single inner disk and with a housing part diameter of 10cm (83g) (see Table I). As said, this device has enough torque, and the size is proper for rehabilitation wearable applications (reaching up to 12Nm torque).

In addition, this device has an ultrasonic motor (the weight was not added in the table above), which provides the movement of the input shaft. Ultrasonic motors are particularly superior in high holding torque and speed/position responses, with low noise. These are unusual characteristics that justify the use of these types of engines in medicine. For the proposed clutch, it was selected the TRUMA USM-60-RA with a torque of 1.5Nm, weight 250g, and a rotational speed of 120rpm.

IV. Rehabilitation Exercise

The actuator is designed to recover the motor function of upper limb (elbow), lost after a stroke. Depending on the individual paralysis, the proposed device can help the patient with a desired torque percentage [10]. Also, a rehabilitation exercise can be designed for any of the patients. In the presented results this movement was sinusoidal in a range of $[0, \frac{\pi}{2}]$ rad.

Next simulation was performed using the clutch and the ultrasonic motor, Matlab-Simulink®, and a rehabilitation exercise with 70% assistance torque. The patient is supposed to be 1.80m tall and 80kg weight, with a load of 1kg added in the hand. The obtained results from such simulations are shown in Fig.3:

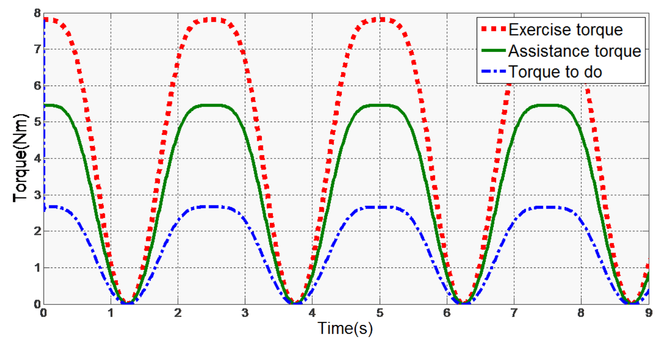

Fig. 3: Patient required torque with a 70% assistance.

The proposed clutch actuator has the great advantage of instantly connecting or disconnecting to the human joint. This is a basic requirement for a wearable exoskeleton as explained before, because the human joints cannot be forced to move. Involuntary muscle spasms or sudden contractions, are studied using a musculoskeletal modelling and simulation development software called MSMS®[6], [11]. This software is also used to simulate the contribution to the movement, exerted by the patient residual muscle capabilities, in order to define the required torque transmitted by the clutch actuator for all possible situations. Musculoskeletal models designed with MSMS®are able to be exported directly into a Matlab-Simulink®model, with this natively supported feature of MSMS®, a connection with Matlab-Simulink®is possible, as seen in Fig.4.

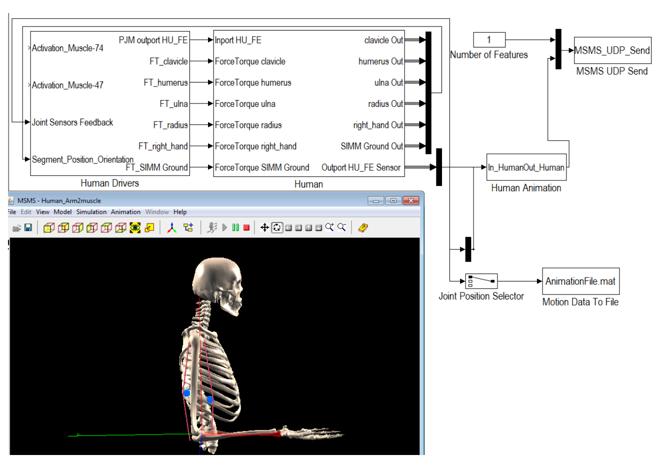

Fig. 4: Co-simulation between MSMS®-Simulink®.

Fig.5 shows the different computed variables of the rehabilitation exercise. These include angle position, angular velocity, angular acceleration and torque applied in the elbow joint for the configured human arm.

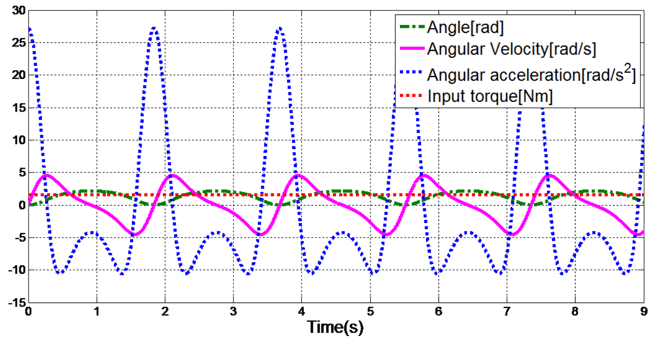

Fig. 5: MSMS®-Simulink®Dynamic simulation results with an input torque of 1.56Nm applied in the elbow joint.

Another interesting feature of MSMS®for biomedical research is the possibility of defining the parameters of the muscles and tendons, also the weight of the entire upper limb, which differs between patients. So, it is possible to analyze how these changes affect the functionality of the exoskeleton and the proposed MR based clutch actuator for the elbow joint. The defined muscles in MSMS®can have limits in their elongation and contraction capabilities, which make possible to simulate injured or wasted muscles. MSMS®uses a precise gravity and inertia implementation. With the full set of MSMS®features an accurate simulation of the upper human limb movement is achieved.

V. Advantages for Therapists

The main advantages are the possibility of having an exoskeleton for rehabilitation purposes, where the elbow joint is governed by a MR fluid based clutch. With the possibility of applying the treatment to more patients, and with the security of knowing that the exoskeleton cannot damage the patients muscles when a sudden spasm occurs, leaving the joint free of the rehabilitation imposed movements.

VI. Conclusions

The designed clutch, as seen in the presented results, is able to work under real conditions in terms of torque, weight and size required in a patients elbow. On the other hand, the critical response when involuntary contraction occurs (such as spasms) is accomplished because of the quick reaction of MR fluids.

The therapist will be able to set the assistance torque, for the desired proposed exercise, to each individual patient in a safe and easy way.

Depending on the application, other clutches devices could be designed for other human limbs, just determining the new requirements and constraints. Then, simulating the new configuration with the tools presented in this work, will give the viability of the new designed models.

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