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ReGrasp, a Robotic Tool to Investigate Fine Motor Control and Track Therapy-Induced Neuroplasticity

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Abstract— **The neural mechanisms of fine motor control and recovery, e.g. after a stroke, are not fully understood, nor how these are influenced by different types of motor therapies, leaving potential for optimization of current rehabilitation strategies. This paper presents the development and evaluation of a novel robotic tool for fMRI-based neuroscience studies allowing to investigate the neural mechanisms of dynamic precision grip and track therapy-induced neuroplasticity. In this proof of principle study we investigate the feasibility of high-fidelity haptic interaction with human motion using remote sensing and actuation. A cable-spring mechanism transmits force to the thumb and index finger in an unconstrained manner, actuated over a stiff cable transmission. Characterization of the prototype with a transmission length of two meters revealed good dynamic performance including a 16 Hz open loop force bandwidth and a maximal output force of 28 N. Combined with a remote and shielded conventional electromagnetic actuator, this device could be used to investigate the neural correlates of precision grasping as well as the effect of different hand function therapies on the neural correlates of motor recovery after stroke.**

Fig. 1. *ReGrasp*, a robotic tool for precision grasp studies involving opposition of the index finger against the thumb in conjunction with functional brain imaging.

I. Introduction

Stroke is one of the leading causes of disability, affecting more than 15 million people every year worldwide. About 60 to 70% of stroke survivors suffer from upper limb paresis, severely limiting their independence and ability to perform activities of daily living (ADL), such as grasping and manipulating objects. Stroke patients can expect spontaneous recovery during the first few months following stroke as a result of increased neuroplasticity, i.e. structural and functional reorganization to compensate for the neuronal networks damaged by the stroke. Nudo et al. demonstrated cortical reorganization in monkeys while they retrained hand function after a focal infarct in the motor cortex. Rehabilitation prevented the reduction of the hand area adjacent to the infarct, a phenomenon that normally occurs following the injury. Furthermore, an expansion of the hand area into the area generally occupied by the shoulder and elbow was observed in some cases [1]. Structural neuroplasticity has also been observed in humans. Studies using transcranial magnetic stimulation (TMS) demonstrated an increased excitability of the hand area in the motor cortex after intensive rehabilitation, e.g. Constraint-Induced Movement Therapy (CIMT) [2], [3].

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Nevertheless, the neural mechanisms underlying fine motor control and cortical reorganization, e.g. after stroke, are not yet fully understood, nor how these are influenced by different types of motor therapies, leaving potential for optimization of current rehabilitation strategies. By providing high spatial resolution and whole-brain coverage, functional Magnetic Resonance Imaging (fMRI) can provide insights into the neural underpinnings of the functionally highly relevant precision grip and the effect of different rehabilitation therapies on cortical reorganization. By combining fMRI with robotics, it becomes possible to render repeatable and well-controlled sensorimotor tasks, and to make a direct comparison with the evolution in behavioral parameters that can be objectively recorded by the robot [4]. Tracking cortical reorganization after brain injury and potentially influencing it through customized training with a robotic device could redefine current neurorehabilitation strategies by reshaping the brain to maximize recovery after injury, or even enhancing sensorimotor skills in healthy subjects [5].

This paper presents a proof of principle study that investigates the feasibility of highly dynamic haptic interaction over a cable transmission with remote sensing and actuation, adapted to future use in an MR environment. A cable-spring mechanism located at the output allows unconstrained movement during precision grip, i.e. opposition between thumb and index finger, a basic function required in most prehensile tasks in ADL, and among those stroke survivors desire to

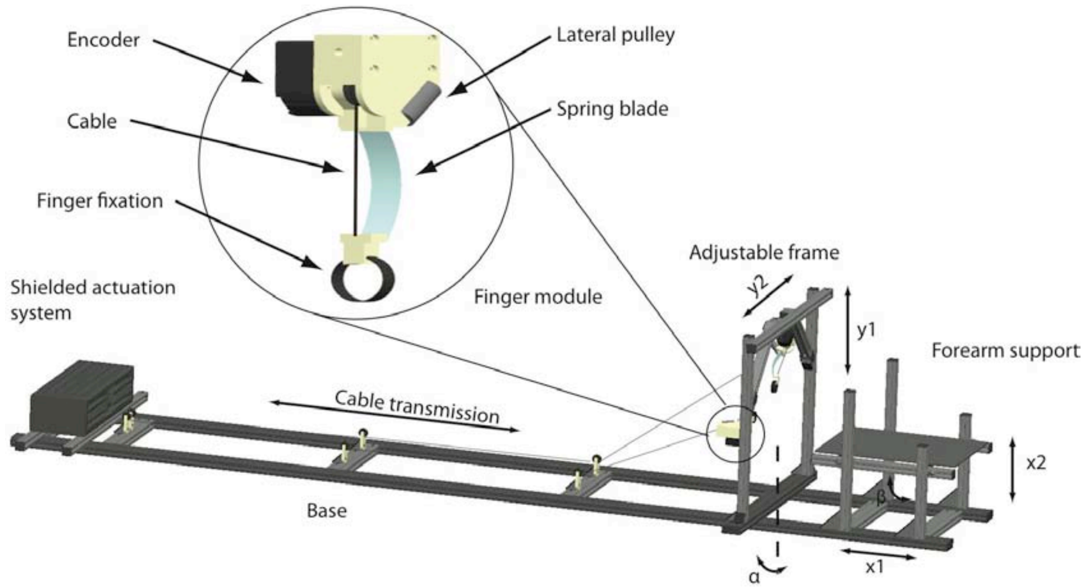

Fig. 2. The *ReGrasp* consists of two finger modules actuated over a stiff cable transmission, an adjustable frame to which the finger modules are fixed and an adjustable forearm support. Actuated over a remote unit containing a shielded conventional electromagnetic actuator [6], it can become a powerful neuroscience tool in conjunction with fMRI.

recover the most. Combined with a shielded actuation unit containing a conventional electromagnetic actuator, *ReGrasp* (Fig. 1) could become a powerful neuroscience tool that can provide high quality dynamic interactions during well-controlled and repeatable fine motor finger tasks as well as during rehabilitation therapy. In conjunction with fMRI, this would enable a detailed investigation of sensorimotor processes in the brain during such tasks, and during cortical reorganization, e.g. after stroke.

The structure of this paper is as follows: Section II presents the design of the proof of principle prototype, Section III details the implementation of the system, while Section IV describes the dynamic performance and discusses MRI compatibility. Finally, Section V summarizes our conclusions and gives an insight on future work.

II. Concept

A. MRI-Compatible Robotics

The magnetic resonance (MR) environment imposes severe safety and electromagnetic compatibility constraints on the development of mechatronic devices [7], [8]. The major limitations are:

- the high magnetic flux density, typically ranging from 1.5 T to 3 T for functional imaging, with up to 9.4 T for research, making the use of ferromagnetic components impossible in the close proximity of the magnet.
- the powerful radio-frequency pulses and the sensitivity of the receivers could result in mutual interference with electronic circuits located within the MR room.
- the limited workspace within the scanner bore, with a typical diameter of 60 *cm*, imposes additional constraints on the development of mechatronics devices to be used by the subject while lying in a supine position.

The majority of MR-compatible robotic systems have been developed for various interventional MRI (iMRI) applications [8]–[10]. While several MR-compatible haptic systems for interaction with arm and wrist movements have been proposed [11]–[14], only few have been developed for the purpose of investigating brain activity during fine precision hand and finger movements, or rehabilitation. Khanicheh et al. developed a hand rehabilitation device based on an electro-rheogolocial fluid (ERF) brake to generate haptic feedback during grasping movements [15]. An extension of the PHANToM premium 1.5 (SensAble Technologies Inc., USA) was proposed by Hribar et al. to investigate brain activity during upper limb movements in a virtual environment [16]. However, none of these devices can achieve dynamic action with fine finger movements. This paper presents a novel device allowing high-fidelity haptic interaction during precision grip studies, to overcome the nonlinearities of the hydrostatic transmission used on a previous system [4].

B. ReGrasp to Investigate and Train Precision Grip

To investigate neuroplastic processes during the learning or recovery of a fine motor task, a versatile, low impedance and high bandwidth device capable of dynamic interaction with humans performing movements is required [8]. This device should be optimized with regards to a specific application. Precision grip or pinch, i.e. the opposition of the thumb against the index finger, is fundamental for any prehension activity required for ADL, and is often impaired after stroke. The stability in a pinching task is given by the forces applied by the fingers and the mechanical and surface properties of the manipulated object, requiring fine motor control and coordination to avoid slipping of the object, while at the same time avoiding undesired object deformation. This requires precise control of both force and impedance. Such a fine finger task is a functionally relevant task to train, could easily be influenced by a robotic device capable of dynamically interacting with the fingers and only requires minimal movement from the user in the scanner. Further, the cortical representation of the hand is well explored, and several studies have already been performed to investigate the neural correlates of fine motor control [17]–[19].

The *ReGrasp* takes advantage of the cable-spring mechanism proposed by Dovat et al. [20], which can assist or resist the motion of the thumb and index finger without spatially restraining the movement. Remote sensing and actuation over a cable transmission promise good dynamic performance and MRI-compatibility. The interface consists of the following four main parts (Fig. 2):

- *MRI-Compatible Actuation System and Cable Transmission*

A crucial point in the development of MRI-compatible robotic devices is the actuation system. Most MRI-compatible robotic systems developed to date are actuated by ultrasonic motors, or use conventional actuators placed outside the MR room, combined with a pneumatic or hydrostatic transmission [4], [13], [21]. None of these can achieve the performance of a direct-drive torque motor, as it is commonly used in haptic interfaces. With this in mind, we use a cable transmission to place conventional electromagnetic actuators as well as sensing and control hardware away from the magnet, outside the 20 *mT* line. Such a transmission has been used in several MRI-compatible devices [22]–[24], and, in contrast to pneumatic or hydrostatic transmissions, does not require long, sealed hoses, has minimal transmission delay as well as low friction and inertia. The cable transmission consists of one cable for each motor, guided by three pulleys to increase the bandwidth of the system (Fig. 2).

The actuation system used for the *ReGrasp* consists of two standard DC motors, one to actuate each finger. The motors are placed in a shielded box electrically and magnetically isolating the actuators from the MR environment and vice versa. This actuation box can then be placed about 2 *m* away from the edge of the magnet without interfering with the imaging. Detailed compatibility tests previously performed in a 1.5 *T* scanner with a similar system confirmed that the shielded actuation system can be safely introduced into the MR room [25]. The actuation system developed for the *ReGrasp* and its placement relative to the scanner are shown in Figure 3.

- *Finger module*

Two finger modules, each composed of a cable-spring mechanism, interact with the thumb and index finger of the user. The cable-spring mechanism works in a push-pull manner; the cable actuated by the motor pulls in one direction (finger extension), and a plastic spring blade preloads the system in the opposite direction (finger flexion), in order to maintain tension in the cable and allow the generation of small forces in the direction of finger flexion. This cable-spring mechanism allows the fingertip to move out of the vertical plane defined by the cable for more natural finger movement [20]. The finger modules are fixed to an adjustable frame and can slide along the frame to adjust the finger orientation during typical exercises, or to adapt to different hand sizes.

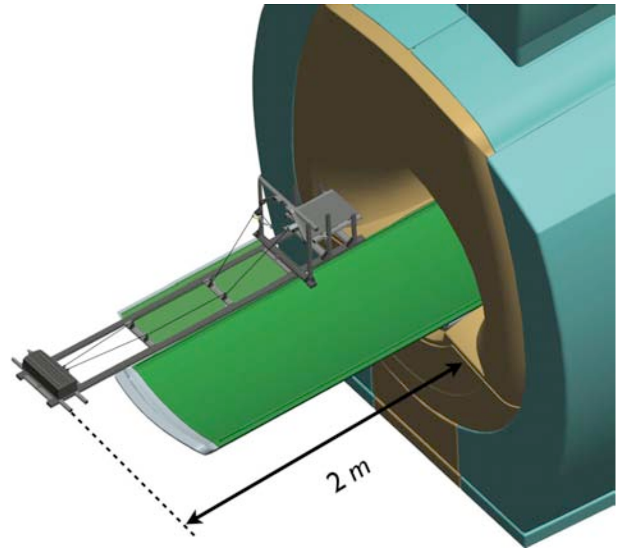

Fig. 3. Schematic of the *ReGrasp* placed within an MR room. The actuation system is placed about 2 *m* away from the edge of the magnet, and contains all sensing and control hardware, eliminating the need for electronic components close to the magnet. Motor torques are transmitted to the finger modules over a cable transmission.

The finger modules are composed of an inner pulley to guide the cable to the fingertip of the user, a finger fixation consisting of an adjustable Velcro® loop fixed at the end of the spring blade, an encoder attached to the inner pulley shaft to measure the fingertip position during system characterization, and two lateral pulleys in the back to reduce friction and guide the cable for different angles of the finger module.

The fingertip workspace consists of a truncated cone of 5 *cm* radius and 10 *cm* height defined by the length of the spring blade. It corresponds to a finger flexion/extension angle range of 0-90° and an abduction/adduction angle range of ±20° at the metacarpophalangeal (MCP) joint.

- *Adjustable frame*

The frame on which the finger modules are fixed is located on the opposite end of the actuation system, close to the subject. The height of the frame can be shifted by ±20 *cm* (y_1 in Fig. 2), the width by ±8 *cm* (y_2) and the orientation can be adjusted for different wrist angles (±30°, α). This maximizes comfort of use, especially in the limited area available inside the scanner, and in order to accommodate for left or right hand use.

- *Forearm support*

During finger tasks, the forearm of the user should be fixed in order to isolate the hand from other body movements, and to ensure a comfortable support. The support developed for the *ReGrasp* can be adjusted in height (± 16 *cm*, x_2 in Fig. 2), orientation ($\pm 45°$) and distance to the frame (± 10 *cm*, x_1) in order to provide a comfortable training position for each subject.

III. Implementation

A. Materials

Materials for the *ReGrasp* were chosen for their MRI-compatibility. Aluminum profiles were selected for the frame and the adjustable forearm support, i.e. the non-moving parts, to assure sufficient stability. Pulley supports and finger modules were manufactured using rapid prototyping material (Objet Materials, FullCure 720). The eight pulleys used to guide the cable are made of Derlin®. Plastic spring blades (APSOplast®) with a thickness of 0.4 *mm* have been selected to maintain sufficient tension in the cable-spring mechanism.

Polymer cables were selected primarily for good MRI-compatibility, high elasticity modulus (110 *GPa*) and ultimate strength (3500 *MPa*), reduced friction around the pulley and low creep [23]. The cable used on the *ReGrasp* is made of Dyneema®, with a diameter of 0.6 *mm*.

B. Actuation & Control

The actuation system used for the characterization consists of two conventional DC motors (RE 40, 150 *W*, Maxon Motor, Switzerland), one for each finger (i.e. thumb and index finger), controlled by two servoamplifiers (4-Q-DC servoamplifier ADS 50/5, Maxon Motor, Switzerland). The system is controlled by a program written in Microsoft Visual Studio 2008 that runs on a PC (Intel Core 2 Duo 4.4 *GB* RAM, 2.33 *GHz*) and uses the resolution of the PC clock for timing. The motor and finger module encoders as well as the motor currents are sampled by a data acquisition card (NI PCI 6221, National Instruments), which also sends the torque commands to the servoamplifiers. The control program for the system identification uses a sampling frequency of 330 *Hz*.

IV. Performances

A. General Features

Table I summarizes the key features of the realized prototpye. The external dimensions of *ReGrasp* are 200 *x* 50 *x* 46 cm^3, which allows the placement of the actuation system about 2 *m* away from the entrance of the scanner (Fig. 3).

B. Friction Identification

Knowledge of the friction in the system is essential to model the system dynamics and for control. The friction force in the cable transmission of the *ReGrasp* has been identified by measuring the difference of motor torque required to move a load fixed to the finger fixation at a constant velocity. This measurement was performed with different loads in the range of 1–3 *N*. The friction force is proportional to the load, showing that mainly dry friction occurs in this system. Figure 4 shows that friction in the transmission is below 1.5*N*.

TABLE I

Specifications of the *ReGrasp*.

maximal force generated at the fingertip (extension)	28 *N*
maximal force generated by the spring blade (flexion)	1.5 *N*
control frequency	330 *Hz*
force bandwidth in open loop control	16 *Hz*
force bandwidth in close loop control	18 *Hz*
transmission friction force	<1.5 *N*
moving mass	9 *g*
elastic modulus of the transmission cable	110 *GPa*

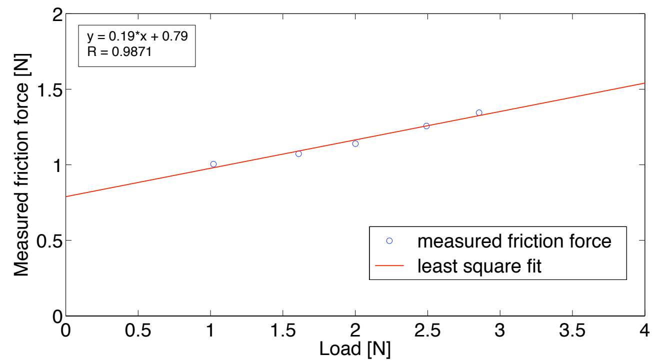

Fig. 4. Friction force in the cable transmission is measured for different loads applied at the finger fixation. Friction force is proportional to the load showing that mainly dry friction occurs in this system.

C. Dynamic Behavior

To determine the dynamic behavior of the system, a sinusoidal force command was imposed on the motor, using a PD force controller in open- and closed loop. The finger fixation was attached to the frame over a force sensor (ELFF-T2M, 50 *N*, Measurement Specialties, USA) for system characterization and the closed loop measurements. The frequency of the sinusoidal force profile was varied from 0.05 to 50 *Hz*; measurements were performed at 0.05, 0.1, 0.2, 0.5 and 1.0 *Hz*, then in steps of 2 *Hz* from 2 to 20 *Hz*, and then in steps of 10 *Hz* up to 50 *Hz*. Data was acquired during 40 *sec* for each frequency, leaving out the first 15 *sec* and the last 5 *sec*. The mean value was subtracted from the input and output signal before calculating the Fast Fourier Transform (FFT) of the input and output signals. Amplitude and phase were obtained from the division of FFT signals. Figure 5 shows the frequency response of the system when controlled by a PD force controller in open and closed loop. The system has a resonance frequency at around 12 *Hz* and a bandwidth of around 18 *Hz* in closed loop control and around 16 *Hz* in open loop control for 2 meters of cable transmission. Further tests showed that the lag and offset between the motor encoder and the encoder placed on the slave module was negligible within the performance range of the system, allowing to remove the slave encoder and place all electronic components in the shielded actuation box.

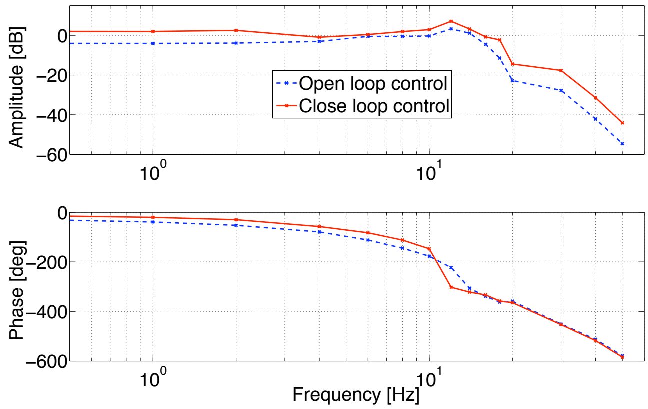

Fig. 5. Bode plot of the system in open and closed loop force control over a frequency range of 0.05 to 50 *Hz*. The closed loop force control bandwidth is about 18 *Hz*.

D. Representative Task

In order to illustrate the dynamic behavior of the *ReGrasp* during a typical sensorimotor experiment, a simple task has been implemented, in which the user has to pinch a virtual rigid object of 3 *cm* width simulated by an impedance controller. Fingertip positions are measured by the encoders placed on the finger modules while finger pinching forces are inferred from the motor currents. Figure 6 illustrates the position and force profiles for the two fingers while performing the described task.

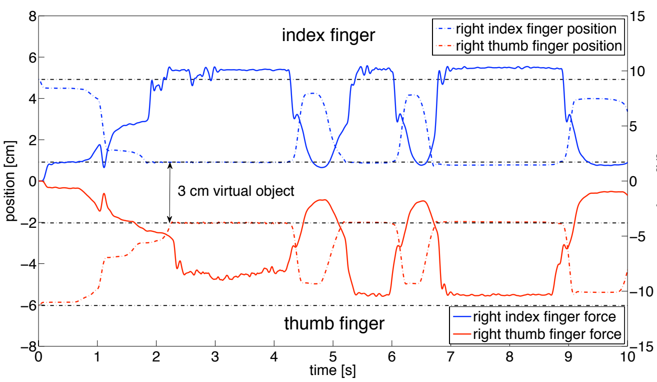

Fig. 6. Position (dashed) and force (plain) profiles for the index and thumb fingers during a pinch movement against a virtual object of 3 *cm* width simulated by the *ReGrasp*.

E. MRI Compatibility

The MRI compatibility of the *ReGrasp* can be decomposed into that of the transmission and finger modules (slave device) and that of the actuation system. Thanks to the low friction and inertia of the stiff cable transmission, interaction forces at the fingertips can be inferred from motor currents within the shielded actuation system, and the finger position from the motor encoders. The compatibility of the transmission and finger modules therefore entirely depends on the used materials, which were selected according to their compatibility. The remote sensing and actuation module is based on the approach proposed in [25] where a combination of magnetic and electric shield with incorporated power and control hardware is used. In the current design, batteries were integrated into the actuation box to realize an embedded system, which is linked to a control PC located in the control room over a fiberoptic link (Fig. 7). Data from encoders and servoamplifiers are sampled by a USB data acquisition card (USB-6212, National Instruments) and sent through the fiberoptical USB 1.1 extension cable (Opticis®, Korea), which achieves a maximum sampling rate of 200 *Hz*. This sampling frequency is sufficient compared to the mechanical bandwidth of the system and that of human movement, which is around 7 *Hz* (2 *Hz* for natural movements).

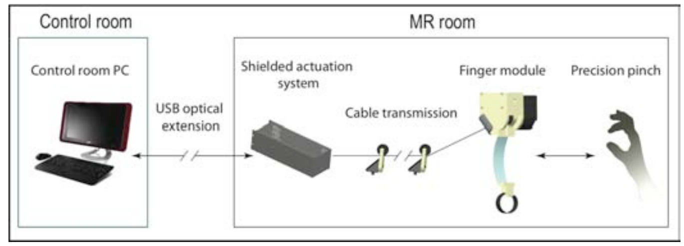

Fig. 7. Diagram representing the different components of *ReGrasp* combined with a shielded sensing and actuation box, from PC in the control room to the finger modules at the entry of the scanner bore, as it will be used in fMRI studies.

Detailed compatibility tests of the actuation system were performed, but are beyond the scope of this paper and are summarized in the following. We investigated static changes in the magnetic field due to the presence of the actuation system by acquiring field maps, RF interference by a gradient echo sequence without excitation pulses and dynamic changes of the magnetic field using a phase navigator with a sampling frequency of 17 *Hz* all of which showed none or negligible changes.

V. Conclusions and Outlook

This paper presents a proof of concept for a novel, high-fidelity haptic interface to investigate the neural correlates of fine motor control and track therapy-induced neuroplasticity in combination with functional MRI. To take advantage of the good dynamic performance of direct drive torque motors, a cable transmission was designed and characterized in open loop control. The resulting force bandwidth of 16 *Hz* as well as the minimal lag and offset in position measurements between the motor encoder and the one located on the output module, allow moving all electronic and electromagnetic components into a shielded sensing and actuation box located about 2 *m* away from the edge of the scanner bore. The system can thus infer the force applied at the subject's fingertip from the motor current, and render various force effects to interact with the user. The structure of the *ReGrasp* can be adjusted in order to provide a comfortable position for each subject and accommodate for left or right hand use. As the transmission and output module of the *ReGrasp* are purely mechanical, the MRI compatibility is determined solely by the selected materials. The supporting frame was realized from aluminum profiles while the pulleys, finger modules, spring blades and transmission cable, i.e. the moving parts, are made from polymers. The shielded actuation box is based on a previously evaluated concept [25], which was extended to achieve an embedded system including batteries, servoamplifiers, DC torque motors, position encoders as well as a USB data acquisition card for control. This module is linked to a PC located in the control room over a fiberoptical USB connection. Current work focuses on further reducing the size of the output structure and optimizing it for a specific precision grip task. Compatibility tests with the complete system will then be performed, and a pilot fMRI study to investigate the neural correlates of unstable grasping will be implemented. Given the good dynamic performance, ease of installation and ease of use, *ReGrasp* promises to become a powerful neuroscience tool to investigate the neural correlates of fine sensorimotor control and to track neuroplastic processes following brain damage.

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