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Design and Characterization of the *ReHapticKnob*, a Robot for Assessment and Therapy of Hand Function

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***Abstract*— Robot-assisted rehabilitation can complement conventional rehabilitation after stroke, by increasing the duration and intensity of therapy and providing precise and objective measurements of interaction dynamics and performance. Such information can be used to drive assist-as-needed control strategies or to complement clinical assessments by reconstructing the scores from robot data. This paper presents the *ReHapticKnob*, a new end-effector-based hand rehabilitation robot with unique sensing and actuation capabilities for therapy of grasping and forearm rotation tasks. A compact design with high stiffness and high-fidelity instrumentation is presented, allowing for precise assessment and dynamic interaction. The device has two degrees of freedom (DOF), allowing independent control of hand opening/closing and forearm rotation. Each degree of freedom is equipped with a brake to allow independent training of either DOF or to assess isometric force through the two six-axis force/torque sensors located beneath the exchangeable finger fixations. The design, safety features and performance evaluation of the device are discussed and preliminary results from a study on grasping performed with healthy subjects are presented.**

I. INTRODUCTION

Stroke is one of the leading causes of long-term disability in the world. Hand impairment resulting from a stroke limits patients in their activities of daily living (ADL) such as eating, writing or object manipulation, severely decreasing their physical independence and social integration.

Studies have shown that rehabilitation therapies consisting of intense and repetitive movements can improve functional recovery of impaired upper limbs [1], [2]. Additionally, it has been suggested that promoting active participation of a patient during rehabilitation, as well as proposing performance-based therapy taking into account inputs from the patient to optimally challenge him/her are parameters to consider for the optimization of rehabilitation therapies [3]–[6].

In recent years, robotic tools have been developed as a promising solution to complement the limited resources that clinics have for rehabilitation [7], [8]. Robots can increase the intensity of a therapy, its repeatability and can accurately and objectively assess and monitor a patient's performance through integrated sensing. Such data could be used to reconstruct clinical scores or even to select the sensorimotor task and difficulty level based on the level of impairment [9], [10]. Robots can also provide motivating visual feedback, which has been shown to be positively perceived by stroke patients [11], [12].

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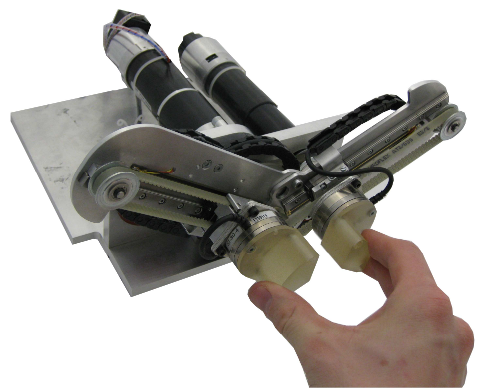

Fig. 1. The *ReHapticKnob*, a robot for assessment and therapy of grasping and forearm pronation/supination tasks.

Existing robotic devices for upper limb rehabilitation can essentially be categorized into *exoskeleton* systems or *end-effector-based* systems [13]. With exoskeleton robots, the movement of each joint can be precisely guided and controlled. However, this approach quickly leads to complex designs when including the hand, with high inherent friction and inertia. This affects system transparency, i.e. the apparent dynamics felt by the user during operation, and can thus impede training of patients with muscle weakness or limit the implementation of assist-as-needed strategies. In the case of exoskeletons for hand rehabilitation, the high number of required degrees of freedom, adaptability to the size of the user's hand and limited output force/torque are additional concerns [14]. In end-effector based robots, the interaction between the robot and the user is only at one point, e.g. at the level of the hand or individual fingers, thus simplifying design constraints. While such an approach does not give control over the posture of the upper limb, nor provide support to the proximal arm joints, it may better correspond to functional tasks encountered in daily life, e.g. manipulating objects. Further, due to the reduced complexity and grounded actuators, higher transparency and dynamic fidelity can be achieved, and more precise functional assessments can be performed. An end-effector based approach thus seems well suited for the design of hand rehabilitation devices where the goal is to simulate dynamic interactions with objects and assess the precise control necessary for such tasks.

We previously presented the *HapticKnob*, a 2 degrees-of-freedom (DOF) end-effector robot, designed for rehabilitation of grasping and forearm pronation/supination [15]. Results of a 6-week pilot study with this robot performed with chronic stroke subjects showed improvement in arm and

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hand function as a result of training with the robotic device [16] and the possibility of reconstructing clinical scores from assessments made with the robot [10]. Despite promising clinical results, the *HapticKnob* robot suffered from several hardware limitations such as large inherent friction and low structural stiffness limiting the transparency of the device and the quality of the interaction with the patient. The low output force limited the training of patients with spasticity. Further, indirect force sensing with low range and precision along only two degrees of freedom limited the assessment capabilities of the device. These limitations motivated the design and development of an improved version of the *HapticKnob*, with a special focus on the ability to precisely assess sensorimotor functions during therapy.

This paper presents the design and performance evaluation of a novel rehabilitation robot, the *ReHapticKnob*, building on a similar end-effector based approach as the *HapticKnob* and aiming at training similar hand functions, but proposing a simpler and more compact design with improved assessment abilities (Fig. 1). The objective of this novel design is to provide a more complete rehabilitation platform adaptable to patients with a wider range of impairments thanks to improved mechanical structure, actuation and sensing systems.

The paper is structured as follows. Section II lists the requirements and presents the device design. Section III describes the evaluation of the realized device and presents data from a preliminary study with healthy subjects, and Section IV discusses the results and potential of this novel device.

II. DESIGN AND IMPLEMENTATION

A. Requirements

After a stroke, patients typically suffer from weakness, abnormal muscle tone, or lack of coordination limiting their ability to grasp, hold and manipulate objects [17]. Forearm pronation/supination and its coordination with grasping are among the tasks commonly performed during ADL such as opening a door knob, or pouring water out of a bottle, and are among the tasks stroke survivors most desire to recover [15]. With the aim of training these two functions in conditions similar to interaction with real objects, an end-effector based approach has been selected for the design of the *ReHapticKnob*. Such a robotic device to train grasping and forearm pronation/supination requires at least two independently actuated DOF: (i) one moving the fingers in flexion/extension and (ii) one to actuate the forearm rotation.

The requirements in terms of workspace for these two DOF are defined by biomechanical considerations of the human hand. The maximum hand aperture between thumb and middle finger is about 180 *mm* and the maximum rotation of the forearm is about 180° [18]. Based on previous studies with the *HapticKnob* and measurements on stroke patients, forces at the fingertip of over 200 *N* can be required to passively open the hand of a stroke patient suffering from hypertonus. On the other hand, typical object manipulation, e.g. holding a fork or manipulating a key involves forces up to 20 *N*, and torques below 1 *Nm* [18]. These observations

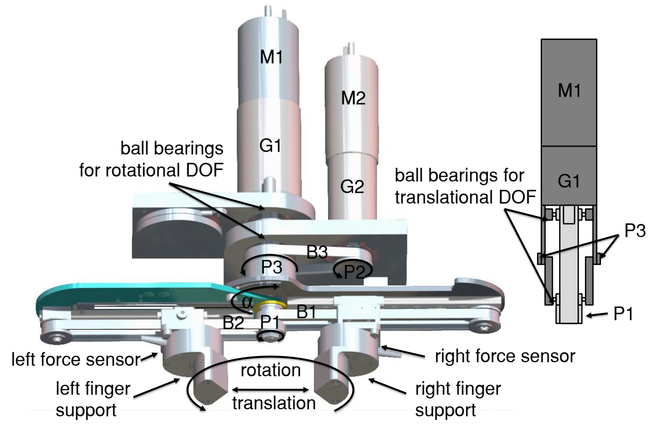

Fig. 2. *Left:* CAD model of the *ReHapticKnob*: The geared motor M2-G2 rotates via a belt transmission B3 the ball bearing supported structure consisting of the geared motor M1-G1 and the two front arms on which the finger supports are placed. *Right:* Principle sketch: the translational DOF is actuated by motor M1 which is connected to gear G1 and rotates a pulley P1 which is connected through a shaft extension (bright grey) and gets supported by two internal ball bearings. Pulley P1 is connected with two other belt transmissions B1 and B2 which are fixed to the left and right finger supports, respectively. Pulley P1 transforms the rotation of motor M1 into a translation of the finger supports mounted on linear guides. 6DOF force transducers are placed directly under each finger support. It is possible to adjust the angle α between the two finger supports for different exercises by shifting the right (light blue) aluminum plate by $\pm 60°$ starting from the horizontal initial position.

define the requirements in terms of actuation and sensing at the level of the end-effector where the fingers interact with the robotic device. To quantify and assess the forces applied by stroke patients and make comparisons to healthy subjects a high sensing reliability and precision is needed. The robot should also allow monitoring of undesired forces/torques (e.g. push, pull, lift etc.) that could be indicative of a compensatory strategy involving the proximal limb or trunk to perform the task.

Further, to render different haptic effects under a stable closed-loop behavior, the inherent friction of the device should be minimized, while the structural stiffness should be maximized to better transmit forces to the subject. Finally, to keep the advantages of an end-effector based robot, the size of the structure should be minimized to facilitate the set up and integration of the robot into a clinical environment and its acceptance by patients and therapists.

B. Design Concept

Several concepts for a 2 DOF robotic device training grasping and forearm pronation/supination have been presented and evaluated in previous work [15]. However, to maximize structural stiffness, provide a large range of motion and forces while maintaining the design simple, a novel design has been chosen for the *ReHapticKnob* (Fig. 2). A first linear DOF, moving on the one side the thumb and on the other side the opposing fingers, is actuated by a first motor M1. The rotation of this motor is transformed into a translation of two finger supports via transmission belts (Synchroflex AT3) connected to custom made aluminum carriages mounted on linear guides (THK miniature guides RSR-WN).

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The two finger supports thus move together in opposite directions resulting in opening and closing movements. This design ensures a more direct transmission of forces from the motor to the fingers and limits friction in the transmission compared to the parallelogram structure of the *HapticKnob* [18]. The second DOF, for forearm pronation/supination, is actuated over a third transmission belt connecting motor M2 to the main axis of the robot defined by motor M1. When actuating motor M2, the whole motor structure M1 and the connected aluminum plates on which the finger supports are mounted rotate. As the rotation axis is aligned with motor M1 and the mass of the moving parts is small, the inertia of the system remains low. To allow training of different types of grip and simulate various objects, the angle α between the two aluminum plates supporting the linear guides (see Fig. 2) can be shifted between $\pm 60°$. Furthermore, the knobs supporting the fingers can easily be exchanged, and can be rapidly manufactured on a 3D printer to the needs of different exercises focusing on different types of grip.

C. Kinematics

Positions of the two finger supports are measured in joint space with encoders attached to the motor shafts θ_1 (for motor M1) and θ_2 (for motor M2). The position of the finger supports are described in polar coordinates q_1 and q_2 in the fixed $\{x,y,z\}$-frame of the task space (Fig. 3).

The transformation from joint space to task space is described by two linear equations. The derivatives of these equations can be written in matrix form and result in the following forward and inverse kinematics:

$$\begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{r_{40}} & 0 \\ 0 & \frac{1}{r_{35}} \end{bmatrix} \cdot \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} = \begin{bmatrix} r_{40} & 0 \\ 0 & r_{35} \end{bmatrix} \cdot \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} \tag{2}$$

with

$$r_{40} = -i_{G1} \cdot \frac{2/\pi}{c_{P1}}, \quad r_{35} = -i_{G2} \cdot \frac{d_{P3}}{d_{P2}}$$

where i_{G1} and i_{G2} are the gear ratios of the gears G1 and G2, d_{P2} and d_{P3} are the diameters of the pulleys P2 and P3 and c_{P1} is the circumference of pulley P1. Since the determinant of the Jacobian matrix is not equal to zero for any given state the system has no singularities. The only mechanical limitations of the device are thus defined by the range limits of the two DOF.

D. Hardware and Setup

The *ReHapticKnob* forms a closed-loop setup with the human user as represented in Figure 4. A desktop computer (Intel Core 2 Quad 2.83GHz, 2.0GB RAM) running LabVIEW Real-Time 9.0 (National Instruments) commands the ReHapticKnob via two data acquisition cards (NI PCIe 6321 and NI PCI 6254). This real-time target computer is connected via Gigabyte Ethernet LAN to an all-in-one touchscreen host computer (Shuttle X50V2, 1.66GHz Dual core, 4GB RAM) used to operate the robotic device and provide interactive visual feedback to the user.

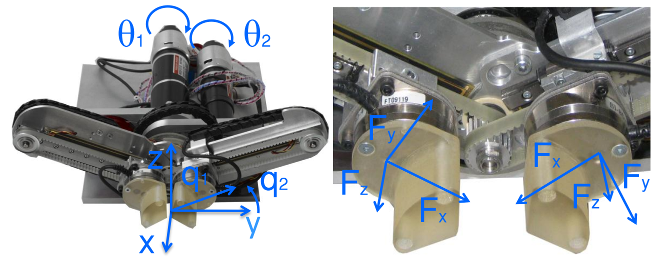

Fig. 3. *Left:* Variables describing the end-effector position in joint space (θ_1 and θ_2) and task space (q_1 and q_2). *Right:* Reference frame of the left and right force/torque sensors.

1) Actuation: The dimensioning of the actuators was driven by the need to provide sufficient forces/torques to interact with patients with hypertonia, and offer the possibility to implement various force effects on both DOF. Motor M1 is a brushed DC motor with a gear reduction of 12:1 (RE 40, 150W, GP 42 C, Maxon Motor). Motor M2 is a brushed DC motor with a gear reduction of 14:1 (RE 35, 90 Watt, GP 32 HP, Maxon Motor). Both motors are controlled by 4-Q-DC servoamplifiers (ADS 50/10, current control mode, Maxon Motor). For safety purposes, each motor is equipped with a brake (AB 28, Maxon Motor) blocking motor shafts when the motors are unpowered. Further, brakes can be independently controlled enabling stable decoupling of the two DOF, and offers the possibility to block the device for isometric force/torque measurements in different positions within the workspace of the device.

2) Sensors: Motors are equipped with optical encoders (HEDL 5540, 2000 counts per turn, Avago). For redundant measurement of the end-effector position, two linear potentiometers (WL1000, travel 100 *mm*, resolution 0.05 *mm*, Contelec) are placed on the side of the linear guides on which the finger supports are mounted. For position sensing of the rotational DOF, a potentiometer (SCAIME MTA, travel 127 *mm*, resolution 1.4°) is mounted on the base plate of the *ReHapticKnob* and connected to motor M1. Two 6DOF force/torque transducers (mini40, ATI Industrial Automation) are mounted directly beneath the finger supports (Fig. 3) to enable precise monitoring of forces/torques applied by the thumb on the one side and the opposing fingers on the other side during grasping or pronation/supination movements.

E. Safety

To fulfill safety norms required for electronic equipment designed to interact with human subjects, the following safety features were implemented on the *ReHapticKnob*:

- To fulfill the European Standard safety requirement for medical electrical equipment (Norm EN 60601), an isolation transformer (ERT 230/230/10G, Thalheimer) is used to isolate all the electronic components from the power network of the building (Fig. 4). Therefore

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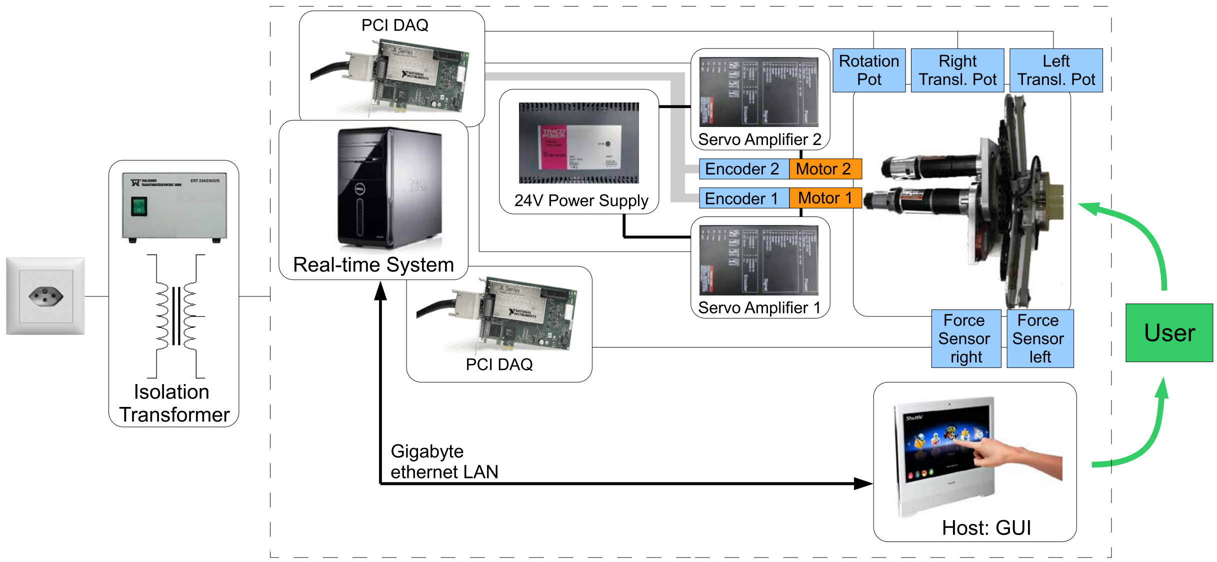

Fig. 4. Closed-loop system architecture of the *ReHapticKnob*. The safety features (not shown in the picture) including a safety relay, power contactors, watchdog and emergency buttons are described in section II-E.

the whole electronic setup is "floating" and users are protected from leakage currents.

- In case of emergency during interaction with the robot, the user and the operator can press one of two emergency buttons located on the side of the robot. Emergency buttons activate a safety relay (PNOZ s4, Pilz) which operates two power contactors connected in series to redundantly cut the power supply to the servoamplifiers. A cross circuit recognition is provided by connecting the emergency buttons in the entry circuit of the safety relay with 2 channels. This setup fulfills the highest safety level as stipulated by the European Norm EN ISO 13849-1 on safety of machinery.
- A WatchDog circuit is placed at the entry circuit of the safety relay to cut the power supply in case the real-time system crashes.
- Software safety limitations have been implemented on position, velocity and acceleration. Further, if a mismatch is detected between the redundant position sensing, the power supply to the electronic system is cut.
- Mechanical stops are implemented on both DOF to limit the workspace of the robot and prevent any movements that could harm the user.

III. ROBOT EVALUATION

A. Performance

Performance of the *ReHapticKnob* in terms of workspace, dynamics and sensing has been evaluated. Table I summarizes key values and compares them with the original *HapticKnob* robot to underline advantages provided by the novel design.

The workspace of the *ReHapticKnob* is similar to the one of the *HapticKnob* and corresponds well to the biomechanical requirements. The maximal opening between the two finger supports is 200 *mm* while with the current finger supports, the minimal opening is 30 *mm*. However, this can easily be adapted by using different finger supports. The device can generate peak forces to open or close the hand of up to 1180 *N*, and peak pronation/supination torques of up to 12 *Nm*, which should offer the possibility of training various

TABLE I

PERFORMANCE MEASURES OF THE *ReHapticKnob*, AND COMPARISON WITH THE *HapticKnob*

Performance measure	*HapticKnob*		*ReHapticKnob*	
DOF	translation	rotation	translation	rotation
Range of motion	30-150 *mm*	$\pm 180°$	30-200 *mm*	$\pm 159°$
Position resolution (encoder)	0.23 $mm/count$	$0.021°/count$	0.0024 $mm/count$	$0.009°/count$
Velocity resolution (encoder) @ 1kHz	230 mm/s	$21°/count$	2.45 mm/s	$9°/count$
Maximum velocity	-	-	520 mm/s	4.8 $rotations/s$
Maximum acceleration	-	-	13.25 m/s^2	124 $rotations/s^2$
Static friction	9 *N*	0.02 *Nm*	6 *N*	<0.4 *Nm*
Maximum actuation force at end-effector (continuous)	50 *N*	1.5 *Nm*	1181 *N* (88 *N*)	12.18 *Nm* (0.98 *Nm*)
Force/Torque meas. in x,y direction (Resolution)	30 *N* (0.2 *N*)	-	80 *N* (0.02 *N*)	4 *Nm* (0.0005 *Nm*)
Force/Torque meas. in z direction (Resolution)	30 *N* (0.2 *N*)	-	240 *N* (0.04 *N*)	4 *Nm* (0.0005 *Nm*)
Closed-loop (PID) position bandwidth	-	-	6.6 *Hz*	7.6 *Hz*
Control frequency	100Hz		1kHz	

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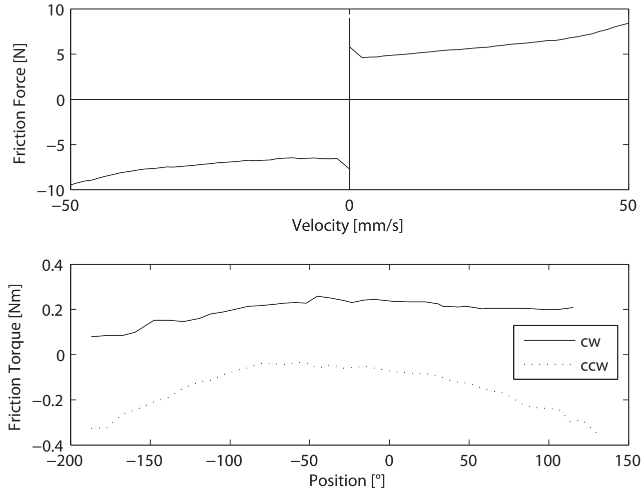

Fig. 5. *Top:* Static and dynamic friction forces measured for the translational DOF. *Bottom:* Static friction of the rotational DOF as a function of the position angle and the two different rotation directions.

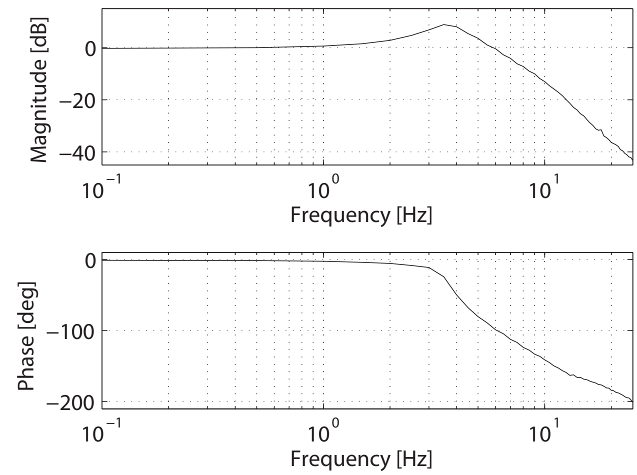

Fig. 6. Bode plot of the translational DOF to determine the PID controlled position bandwidth of 6.6 *Hz*.

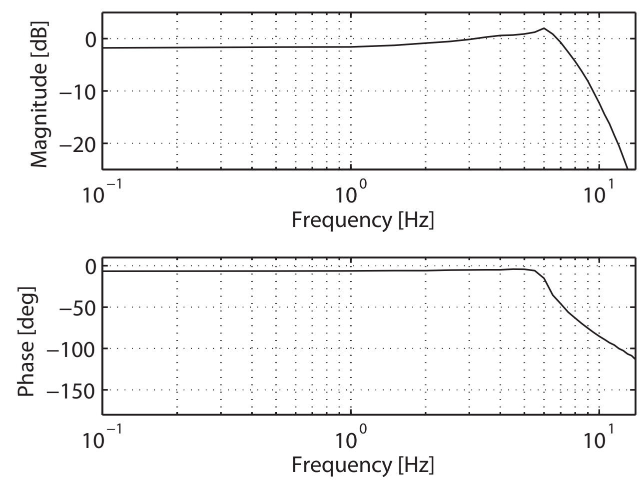

Fig. 7. Bode plot of the rotational DOF to determine the PID controlled position bandwidth of 7.6 *Hz*.

types of grips, e.g. power grasp, cylindrical grasp, precision grip, and provide a rehabilitation robot suited for patients suffering from various levels of impairment, e.g. with high muscle tone.

The velocity resolution was calculated by dividing the smallest detectable movement at the end-effector by the sampling interval of 0.001s (sampling at 1kHz). The peak velocity and peak acceleration were estimated using offline filtered position measurements of the potentiometers when giving a maximum current step (for velocity estimation) respectively a maximum current impulse (10ms long, for acceleration estimate) to the motors.

Static friction forces in both DOF are presented in Figure 5. Static friction has been measured by increasing motor current by small steps until movement of the end-effector was detected. From the bottom plot of Figure 5 it can be observed that the static friction in the rotational DOF is not constant over the workspace, as it is influenced by gravity forces acting on the finger supports. The dependency on the rotation direction can also be seen in the asymmetric friction curves, i.e. the static friction at any given position is not the same for both rotation directions. The dynamic friction in the linear DOF was determined by moving the end-effector at constant speeds and recording the required current (torque). Static friction of 6 N on the linear DOF is reduced compared to the *HapticKnob* robot, and can further be compensated in the control algorithm by providing feedforward compensation based on measured grasping force.

Closed-loop position bandwidth has been identified by following with the end-effector a PID controlled sinusoidal position input trajectory, with an amplitude of 2.5 mm for the linear DOF and 5° for the rotational DOF. The Bode plots for the two DOF are presented separately in Figures 6 and 7. For the translational DOF a resonant peak at 3.5 Hz and a bandwidth of 6.6 Hz have been observed. The rotational DOF shows a resonant peak at 6 Hz and a bandwidth of 7.6 Hz. Both DOF have a typical phase shift which differs from that of a second order system mainly at high frequencies. The large phase shift at high frequencies stems from the dynamics of the mechanical parts (reduction gears and belt transmissions) and non-linearities in the system (play in the gears, static friction and quantized position measures form the encoders).

B. Preliminary Measures with the ReHapticKnob

Motivated by our previous studies [16], a first task focusing on opening/closing hand movements has been implemented and tested with healthy subjects to evaluate interaction with the *ReHapticKnob*. The task consisted of two phases: (i) the hand was opened with a PID position controller following a position ramp to reach a 30 mm opening of the robot, and (ii) after a short waiting period, the subject was asked to close the hand by following a desired trajectory. A resistive force field was applied against the closing movement to increase the difficulty of the task. The desired trajectory was implemented as a minimum

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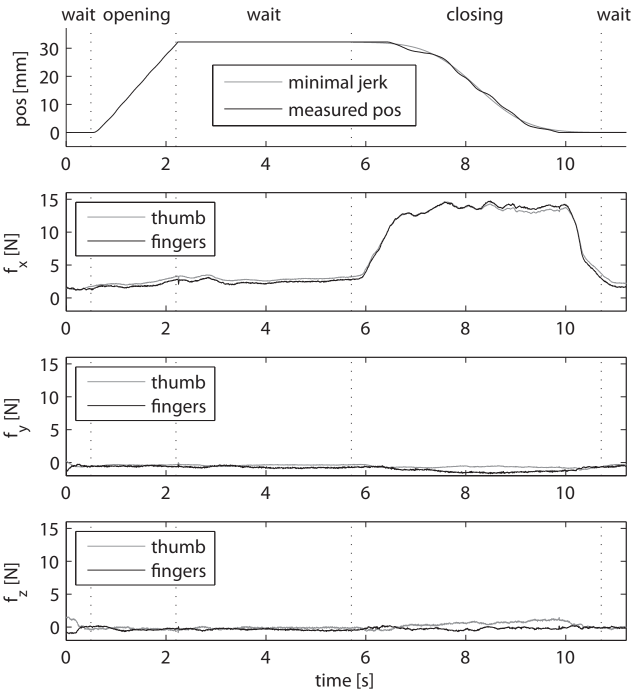

Fig. 8. Example of a representative opening/closing movement of the hand: measured position and force profiles during the passive hand opening (position control following a ramp profile) and the active hand closing against a resistive force, following a minimum jerk profile. The two force trajectories in each force plot show the forces applied by the thumb and the fingers against the two finger supports.

jerk profile and displayed with a moving indicator on the screen. During the whole task, the position of the actual hand opening was also displayed on the monitor using a second indicator, and the rotational DOF remained blocked. The resistive force used in this preliminary experiment was composed of a constant force F_{const} of 20 N and a damping component: $F_{res} = F_{const} + 0.5\dot{q}_1$.

Figure 8 presents hand opening position and grasping force signals during one representative opening and closing movement of the described exercise. In the position plot it can be seen that the healthy subject was able to close the hand against the applied resistance while following the minimum jerk profile. The force trajectories show that almost no force is applied in y- and z-direction for both the thumb and the opposing fingers, indicating that grasping force was applied perpendicularly to the finger supports. Further, the subject applied nearly symmetrical forces (10 N) with the thumb and fingers to close the hand.

IV. DISCUSSION

This paper presented the design, implementation and performance evaluation of the *ReHapticKnob*, a novel end-effector based robot for the assessment and therapy of grasping and pronation/supination tasks. The *ReHapticKnob* builds on a previously developed system, the *HapticKnob*, with the aim of improving mechanical properties and dynamics, and incorporating unique sensing functionalities to evaluate and monitor hand impairment level in stroke patients, thereby offering the possibility of using these measures to better adapt rehabilitation therapy.

In terms of performance, the static friction in the translational DOF was reduced compared to the *HapticKnob* through a simpler design. Although the friction in the rotational DOF increased due to the used gearbox, this allowed an increase in the maximum output force at the end-effector, thus offering the possibility to train patients with high spasticity. The friction provides stability and can be compensated over the force sensors when rendering low impedance. These improved characteristics allow more dynamic interaction with the patient. Also the increased control frequency by the use of a real-time system leads to a higher range of achievable impedances (broader Z-Width). The closed-loop position bandwidth on both DOF is around 7 Hz and is thus well suited for interaction with the human hand which operates in the range of 4-8 Hz while performing tasks like handwriting, typing, tapping, playing musical instruments [19]. The observed phase shifts on both DOF have no implications on the planned exercises. The integrated brakes provide a simple means of training with one of the two DOF independently, or completely locking the device in any position to perform an isometric assessment with the 6DOF force/torque sensors located directly beneath the exchangeable finger supports.

By providing precise measures of position and forces applied at the end-effector by the patient's hand, it is possible to quantitatively assess parameters such as grip strength, force control, thumb-fingers coordination or finger spasticity (e.g. during passive hand opening). This will further allow the implementation of performance-based exercises adapted to specific hand impairment, and should offer the unique possibility of combining assessment and therapy on a single robotic device and using online assessments to adapt the therapy.

V. ACKNOWLEDGMENT

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