A Small-Scale Robotic Manipulandum for Motor Training in Stroke Rats

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Abstract—The investigation and characterization of sensorimotor learning and execution represents a key objective for the design of optimal rehabilitation therapies following stroke. By supplying new tools to investigate the learning process and objectively assess recovery, robot-assisted techniques have opened new lines of research in neurorehabilitation aiming to complement current clinical strategies. Human studies, however, are limited by the complex logistics, heterogeneous patient populations and large dropout rates. Rat models may provide a substitute to explore the mechanisms underlying these processes in humans with larger and more homogeneous populations. This paper describes the development and evaluation of a three-degrees-of-freedom robotic manipulandum to train and assess precision forelimb movement in rats before and after stroke. The mechanical design is presented based on the requirements defined by the interaction with rat kinematics and kinetics. The characterization of the robot exhibits a compact, stiff and low-friction device suitable for motor training studies with rodents. The manipulandum was integrated with an existing training environment for rodent experiments and a first study is currently underway.

I. INTRODUCTION

Motor rehabilitation following stroke requires neural adaptations that also occur during skill learning. These adaptations comprise motor refinement, skill acquisition and decision making [16]. During motor learning, the central nervous system (CNS) builds a representation of the external dynamics with which we interact, commonly referred to as internal models [8], [19]. Gaining a detailed understanding of how these mechanisms operate and how they are impaired after damage to the CNS is important to optimally support the recovery of sensorimotor function following brain injury, as well as to design novel therapies to accelerate and further promote rehabilitation.

In recent years, robotic interfaces have provided novel insights into motor learning, offering scientific evidence for the existence of internal models. A typical experimental paradigm widely used to study motor learning involves having subjects hold the output handle of a planar robotic manipulandum and perform reaching movements while the robotic interface renders virtual dynamics that perturb the movement [15]. Robot-assisted rehabilitation represents a promising approach to complement current clinical strategies for rehabilitation after injury to the CNS, and supplies new tools to investigate and objectively assess sensorimotor recovery [7]. Patient-tailored haptic training to restore reaching skills in patients with poststroke hemiparesis demonstrated a great potential for rehabilitation tools that augment error to facilitate functional recovery [12]. Nevertheless, the mechanisms underlying robot-driven neural adaptations are not yet fully understood and there is a lack of evidence regarding the most efficient usage of robotic systems for sensorimotor recovery. Moreover, performing clinical investigations with stroke patients using robotic devices, such as the study reported by Lo et al. [9], is an enormous challenge due to large dropouts and highly heterogeneous patient populations.

Rat models may provide a substitute to explore the mechanisms underlying sensorimotor control and recovery after stroke in humans. The similarity of fundamental brain regions to those of the human model, the possibility to study large, homogeneous populations, and the fact that sensorimotor learning and performance can already be assessed before the stroke, make rats the ideal model to investigate these mechanisms. The ability to induce stroke in the rodent model could give many novel insights into stroke recovery and neural plasticity. Further, investigating the behavioral deficits and therapeutic treatments in animal models of stroke is essential for potential translational applications [13].
Mechanisms of motor learning and re-learning (after stroke) can be investigated by training precision movements in rats, such as accurate reaching for food pellets. Schubring-Giese and coworkers used this method to investigate the influence of prior knowledge on re-learning of a precision reaching skill after a cortical lesion in a rat [14]. However, the assessment of motor performance was limited because of the variability of the outcome measure, i.e. the number of successful reaches. Current experimental methodologies suffer from limited task complexity and a lack of objective performance metrics of the rat forelimb, such as kinematics and kinetics, thus restraining insights into the motor learning process [18].

Using a robotic manipulandum that the rat is trained to actively manipulate in a specific way in order to obtain a food reward would not only increase the intricacy of the assignment, but also give more control over how this task is performed. Similar to robotic devices used in human motor learning studies, force fields could be implemented to perturb motion of the rat forearm in a well-controlled and repeatable manner, while providing a quantitative assessment of motor performance and adaptation. Further, this system could be integrated with current rat training environments, including response buttons, pellet dispensers, automated doors, etc., allowing to automate the training procedure. The robot can be used to study skill learning as well as transient motor adaptations.

Several robotic systems have been developed for lower and upper limb movement tasks with rodents. Nessler et al. designed a robotic device (the “rat stepper”) to train and assess locomotor function of spinal cord injured rodents [10]. The device consists of a pair of lightweight, robotic arms that attach to the rodent hindlimbs, a body weight support and a motorized treadmill. Devices that can be manipulated by the rat forearm have also been reported. Francis et al. proposed a one degree-of-freedom (DOF) manipulandum that could be actively grasped and pulled or pushed to a specific target position by a water deprived rat against programmed force field perturbations, in an attempt to understand the feedforward and feedback mechanisms of motor control [6]. This device is limited to the learning of skills of restrained complexity.

This paper presents the design and development of an actuated 3-DOF small-scale planar robotic manipulandum to train and measure precision forelimb movements in rats before and after brain injury. The system has two translational DOF and one rotational DOF, hence allowing in-plane movement and pronation/supination of the rat forelimb. The latter DOF is particularly important for the acquisition of motor skills, in which movement sequences and movement complexity are required, and is also of high functional relevance in grasping and manipulation of objects. The design and characteristic data of the device are reported, and the potential of this novel technology is discussed.

II. DESIGN AND IMPLEMENTATION

A. Requirements for the Robotic Manipulandum

To allow interaction of the robotic device with the forepaw of a rat, the workspace of the device and the forepaw should overlap as much as possible. No studies investigating the range of motion of rat forepaws were found, but a few studies analyzed the inverse dynamics of rat locomotion, which report joint angles, joint moment and joint power [1], [4], [17]. Using these, the range of motion of a rat forepaw can be estimated from the averaged joint angle ranges, and thus approximations can be made for the required workspace and the resulting dimensions of the robotic manipulandum.

Besides the range of motion, the maximum force which the rat is able to exert at the end-effector of the manipulandum needs to be estimated in order to select the appropriate actuators. By combining the maximum joint moments with the segment lengths, a maximum possible force at the paw of 2.33 N for a 300 g rat was estimated, a value that is well above the one reported by Fowler et al. (0.65 N) using a pressure sensor [5].

No scientific literature was found describing the maximum pronation or supination moment of the rat forelimb. These values were estimated by downscaling the torques reported in a study involving 24 healthy human male subjects [11] using the law of similitude based on the proportionality between weight and moment. A mean maximum value of 61 mNm and 49 mNm for forepaw supination and pronation torques in the rat can be estimated, respectively.

The requirements for the robotic device are summarized in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>RAT MANIPULANDUM REQUIREMENTS</th>
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<tbody>
<tr>
<td>force at the end-effector</td>
<td>&gt; 2.4 N [5]</td>
</tr>
<tr>
<td>torque for pronation/supination</td>
<td>&gt; 61 mNm [11]</td>
</tr>
<tr>
<td>force resolution</td>
<td>&lt; 3.2 mN [5]</td>
</tr>
<tr>
<td>position error</td>
<td>&lt; 1.1 mm [10]</td>
</tr>
<tr>
<td>inertia at the end-effector</td>
<td>&lt; 8 g [6]</td>
</tr>
<tr>
<td>controller update rate</td>
<td>&gt; 100 Hz [6]</td>
</tr>
<tr>
<td>workspace</td>
<td>&gt; 20x40 mm [1], [4], [17]</td>
</tr>
</tbody>
</table>

B. Mechanical Design

Both serial and parallel mechanisms were investigated for the design of the robotic manipulandum. Despite the simpler forward kinematics and large workspace with respect to their volume, serial robots present several drawbacks such as low stiffness, relatively low effective load, error summation from link to link and reduced dynamics [3]. Considering the rapid movements of the rat forearm and the need for a transparent device, a parallel mechanism was selected since it can achieve high dynamics with good precision while assuring a transparent interaction.

The design of the robotic manipulandum is based on the Pantograph, a 2-DOF, five-bar-linkage planar mechanism developed at McGill University, Canada [2]. The structure was redesigned so that it would meet the requirements for
training and measuring of planar movements of rats. Several mechanical changes had to be performed in order to adapt the workspace and downscale the output forces based to the rat kinematics. In addition, to incorporate training of pronation and supination movements, an extra DOF was added. Fig. 2 presents a detailed CAD drawing of the rat manipulandum design.

The base of the robot is composed of four aluminum plates (lower base, upper base, and motor plate, which are connected to a back plate), holding the system together. The movable parts of the robot consist of four aluminum rigid arm-linkages (two proximal and two distal) connected together at the end-effector, defining the planar workspace of the device. The end-effector, represented by a titanium sphere of diameter 6 mm, is attached to a telescopic brass shaft that transmits rotation for the pronation/supination DOF. The respective actuator is mounted on the back plate and connected to the telescopic shaft through a universal joint. The two actuators driving the four rigid links are mounted on the motor plate and connected to the manipulandum arms through couplings.

The lower base plate is mounted on an aluminum mechanical support adjustable in the x and y directions, that serves the purpose of both precisely positioning the manipulandum in front of the rat cage and ensuring its physical stability during experiments.

C. Robot Kinematics

The kinematic structure of the manipulandum is shown in Fig. 3. The interaction with the rat takes place at the output P₆, which represents the position of the spherical end-effector, which can move in a horizontal plane and additionally rotate around the P₆P₇ segment. The two actuated joints for planar movement are located at points P₁ and P₅ respectively.

1) Forward Kinematics: the position of the end-effector sphere P₆(x₆, y₆) can be determined using the sensed angular positions θ₁ and θ₂. The nominal lengths of the links aᵢ in mm are:

\[ \mathbf{a}_{\text{nom}} = [50, 45, 45, 50, 26, 15] \text{T} \]  (1)

According to geometrical inspection, it follows that:

\[ \mathbf{P}_2 = \begin{pmatrix} x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} a_1 \cos \theta_1 \\ a_1 \sin \theta_1 \end{pmatrix} \]  (2)

\[ \mathbf{P}_4 = \begin{pmatrix} x_4 \\ y_4 \end{pmatrix} = \begin{pmatrix} a_4 \cos \theta_1 \cos \theta_2 - a_5 \\ a_4 \cos \theta_1 \sin \theta_2 \end{pmatrix} \]  (3)

By performing a coordinate system transformation, the coordinates of point P₃ can be computed:

\[ \mathbf{P}_3 = \begin{pmatrix} x_3 \\ y_3 \end{pmatrix} = \begin{pmatrix} a_1 \cos \theta_1 + a_2 \cos(\theta_1 + \gamma) \\ a_1 \sin \theta_1 + a_2 \sin(\theta_1 + \gamma) \end{pmatrix} \]  (4)

where \( \gamma = 180^\circ - (\alpha + \beta) \) and \( \alpha \) and \( \beta \) can be determined from the triangles P₁P₂P₄ and P₂P₃P₄ respectively using the law of cosines:

\[ \alpha = \cos^{-1} \left( \frac{a_1^2 + D_1^2 - D_2^2}{2a_1 D_1} \right) \]  (5)

\[ \beta = \cos^{-1} \left( \frac{a_2^2 + D_1^2 - a_3^2}{2a_2 D_1} \right) \]  (6)

The position P₆(x₆, y₆) can be translated to the position of the sphere end-effector P₆(x₆, y₆) using the following equation:

\[ \mathbf{P}_6 = \begin{pmatrix} x_6 \\ y_6 \end{pmatrix} = \begin{pmatrix} (L + a_6) \sin \phi \\ (L + a_6) \cos \phi \end{pmatrix} \]  (7)

where:

\[ L = \sqrt{\left( \frac{x_3 + \frac{a_5}{2} }{2} \right)^2 + y_3^2} \]  (8)
The angular velocity of the output varies with the rotational position of the universal joint and the angle between the input and output links. The relationship between the output ($\omega_o$) and input ($\omega_i$) angular velocities is given by:

$$\omega_o = \frac{\alpha \omega_i}{1 - \sin^2\beta \cos^2 \gamma}$$  \hspace{1cm} (17)

4) **Singularities and Kinematic Constraints**: information about the singular configurations of the rat manipulandum is given by the velocity Jacobian, which maps the joint velocities $\omega$ onto the sphere end-effector velocities $v$:

$$v = [x_6, y_6]^T = J\omega = J[\dot{\theta}_1, \dot{\theta}_2]^T$$  \hspace{1cm} (18)

The Jacobian is calculated by taking the partial derivatives of the forward kinematics map with respect to the actuated joint angles $\theta_1$ and $\theta_2$. The singularities of the system correspond to the zeros of the determinant of the Jacobian:

$$\det[J] = a_1a_2\sin \gamma$$  \hspace{1cm} (19)

This yields two singularities when $\alpha = \beta = 0^\circ$ and $\alpha + \beta = 180^\circ$ respectively. If the former case is not reachable due to robot design, the latter must be prevented by implementing software limitations. Another kinematic restriction that has to be taken into account is represented by the configuration when points $P_2$ and $P_4$ overlap, determining the “crossing” of the left and right arms. In order to avoid this, an additional constraint $x_4 < x_2$ is imposed at all times.

**D. Actuation, Sensors, Control and Safety**

The three DOF of the manipulandum are actuated using three motors as follows:

- two brushed DC motors (Maxon Motor, Switzerland; RE25, graphite brushes, 20 W) coupled with two high resolution rotary optical encoders (Gurley Precision Instruments, USA; R119B, 65k counts/rev) control and monitor the movement of the end-effector in the x-y plane. They are capable of producing a force of at least 2 N in any direction throughout the usable workspace.
- one brushed DC motor (Maxon Motor, Switzerland; RE-max 24, graphite brushes, 11 W) coupled with a high resolution rotary optical encoder (Gurley Precision Instruments, USA; R112, 32k counts/rev) provides the required pronation and supination torque. The maximum continuous torque it can deliver is 66 mNm, which is above the requirement defined previously.

Control of the motors is performed by means of three servo drive amplifiers (Maxon Motor, Switzerland; 4-Q-DC Servo Control LSC 30/2). Data acquisition is carried out via two
data acquisition cards (National Instruments Corp., USA; PCI-6221, 68-pin). For safety, ease of debugging and transportation reasons, all the electronic components are comprised in an electronic box.

The control program, implemented in LabVIEW 9.0 (National Instruments Corp., USA), runs on a personal computer (Dell, Optiplex 960, Intel Core(TM)2 Quad CPU 2.83 GHz, 3.25 GB RAM, Windows 7 Enterprise) at a frequency of 1 kHz. A Graphical User Interface (GUI) enables the user to visualize in real time the preferred trajectories, choose between various modes of operation and select which data to record for subsequent offline analysis.

Safety measures have been implemented in the form of both hardware and software emergency units. Mechanical stops serve the purpose of limiting the movement range of the proximal arms. The user can select a velocity limit for the end-effector, as well as a current limit for the actuators, thus limiting the maximum force that can be produced. Moreover, an emergency push button is available to the operator, cutting the power to the entire system if pressed. A custom made acrylic protection cover is placed over the robot to protect it during transportation and experiments.

III. RESULTS

A. General Characteristics

The rat manipulandum has a compact structure, with external dimensions of 212 × 160 × 150 mm³. Using the kinematics dimensions and equations, the workspace of the manipulandum was calculated and overlapped with the rat forearm kinematics to determine an usable area of approximately 40 × 20 mm².

The manipulability ellipsoid has been determined by investigating the eigenvectors and eigenvalues of \( J J^T \). The largest forces can be applied in the direction where maximum velocity is the smallest. The results, depicted in Fig. 4, indicate that throughout the usable workspace a force of at least 2 N can be applied at the sphere end-effector, except close to the edge of the workspace. The values are in good accordance with the forces exerted by rats.

Due to friction and lubrication between various moving components (e.g. motors, arms, couplings and ball-bearings), the device exhibits a static friction torque of 7.2 mNm, which has to be compensated for in the control program.

The control program capable of running at frequencies up to 1 kHz allows the user to drive the robot in different modes of operation, selected from a GUI (e.g. haptic tunnel, error-enganced guidance, etc).

B. Position Bandwidth

In order to identify the dynamic behavior of the system, a position bandwidth test was conducted. A sinusoidal oscillation with an amplitude of 2 mm was commanded, with frequencies ranging from 0.01 Hz to 30 Hz in steps of 0.5 Hz, for a time period of 5 sec for each frequency. Fig. 5 shows the frequency response of the system when controlled using a PID controller (the gains were tuned to \( P = 0.11, I = 0.01 \) and \( D = 0.00017 \) according to the Ziegler-Nichols method). The resonance frequency of the system is around 11 Hz, while the position bandwidth is around 15 Hz.

C. System Integration for Experimental Trials

Fig. 6 depicts the experimental setup and how the different components are interconnected. The manipulandum interacts
directly with the rat using a conventional impedance-type haptic architecture, measuring the position imposed by the rat forelimb, based on which it displays the corresponding forces. In case of a successful trial, the rat is rewarded a pellet supplied by a commercial pellet dispenser (Lafayette Instrument Comp., USA, Model 80208) integrated into the control scheme. At the same time, a particular sound is played. If the trial has failed, no reward is given and a different sound is presented. After each trial, whether successful or failed, the arms of the manipulandum retract to a predefined initial position. In order to reposition the end-effector in the start position for the next trial, the rat has to touch an infrared (IR) sensor (response button) located at the back of the cage. Should unexpected events occur, an emergency button is available on the operator console to stop the system. This console further incorporates two push buttons, allowing to override the automated performance rating and to manually rate a task as being successful or failed.

IV. CONCLUSION AND FUTURE WORK

This paper presented the mechanical design and development of a three-degree-of-freedom robotic manipulandum to interact with the rat forelimb in motor learning experiments. The device can render virtual dynamics in a well-controlled and repeatable manner, offering the possibility of implementing various force fields to assist or perturb the movement in order to investigate motor learning, adaptation and recovery after stroke in animal models. The three degrees of freedom (in-plane movement and pronosupination) will for the first time give the possibility to study skill learning of various complexities versus movement adaptation (e.g. force field adaptation) in rodents. Furthermore, the robotic device provides objective assessments of motor performance, and allows to automate the time-consuming training period.

Preliminary training has shown that rats can be trained to grasp, pull and rotate the end-effector of the robotic system. Extensive studies are now planned with both healthy and stroke rats for a complete validation of the usefulness of the device. Several training stages are under development, through which the rats will be guided to accomplish various motor tasks of increasing complexities. We will investigate mechanisms responsible for acquisition of new motor skills and recovery after stroke, in an attempt to gain a better understanding of the mechanisms underlying sensorimotor control and recovery after brain injury.

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