Force Field Apparatus for Investigating Movement Control in Small Animals

Joseph T. Francis* and John K. Chapin

Abstract—**As part of our overall effort to build a closed loop brain-machine interface (BMI), we have developed a simple, low weight, and low inertial torque manipulandum that is ideal for use in motor system investigations with small animals such as rats. It is inexpensive and small but emulates features of large and very expensive systems currently used in monkey and human research. Our device consists of a small programmable torque-motor system that is attached to a manipulandum. Rats are trained to grasp this manipulandum and move it to one or more targets against programmed force field perturbations. Here we report several paradigms that may be used with this device and results from rat's making reaching movements in a variety of force fields. These and other available experimental manipulations allow one to experimentally separate several key variables that are critical for understanding and ultimately emulating the feedforward and feedback mechanisms of motor control.**

Index Terms—**Electrophysiology, force field, manipulandum, motor learning, rat.**

I. INTRODUCTION

Recent investigations into the use of neuro-robotic interfaces for restoration of motor function have demonstrated the importance of doing parallel studies using similar interfaces in animal models. Such investigations will continue to lead the way in helping us to determine how the nervous system encodes variables of movement that can be used by brain-machine interfaces. In the past, motor neurophysiologists and psychophysicists have used such programmable manipulandum devices in reaching paradigms utilizing monkey and human subjects. These devices have allowed a host of variables to be studied, including kinematics [1], electromyograms (EMG) [2], electroencephalograms (EEG) [3] as well as other correlates of neural signals in humans [4], [5] and action potentials from single neurons in monkeys [6], [7]. In this report we present a torque manipulandum for use with small animals. This system when coupled with multi-neuron population recordings should help elucidate the neural correlates of motor variables that can be used in a fully integrated neural prosthetic system.

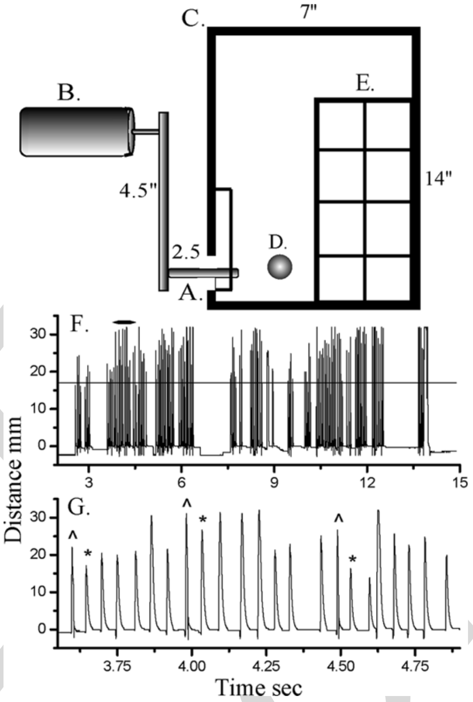

Fig. 1. Behavioral Chamber: Rats learned to grasp the handle of a manipulandum (A) that enters the workspace through a slot in the box. It is attached to a torque motor/encoder (B) that is attached to an adjustable mount (not shown). Water reward was provided through a waterspout (D) that is fed via a water reservoir and valve (Coulbourn Instruments) controlled by a digital IO board (National Instruments PCI-6036E). E is a moveable block that limits the workspace (see text). Experiments were controlled by a PC with a National Instruments PCI-7344 motion control card. Traces of 115 self paced manipulandum movements made by ratMT_09 against the velocity dependant resistive force field during a 15-min session are plotted in F. Reward was given when the manipulandum passed the target depicted by the horizontal line. G. Blow up of the traces in (F) demarcated by double arrow. Catch trials (trials with the force field turned off, CT) are marked with (^) and the trials just following the CT's with (*). Velocities of CT's were significantly greater than "fielded trials," and displacements of post-CT's were smaller than normal.

II. METHODS

A. Behavioral Workspace

The behavioral box (Fig. 1) is 7 in wide, 18 in long and 14 in high. It contains a manipulandum handle and a waterspout for administering rewards. A small block is emplaced to limit the workspace to 3" [Fig. 1(E)] ensuring that the rat maintains in a constant body position during experiments. This workspace is sufficient to allow the rat to move a recently designed 2-Degree of freedom manipulandum as well.

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B. Torque Manipulandum for Small Animals

Our manipulandum has very low inertia and is able to produce a sufficient range of torque to challenge the animal physically. Inertia minimization was necessary to achieve complete artificial control of our forces fields. We chouse a DC motor (Maxon RE-25 part # 118 746) with a negligible inertia (10 gcm^2). This motor is capable of producing a stall torque of 136 mNm, which is enough torque to challenge a rat.

We used a National Instruments PCI-7344 motion controller that is capable of a PID update rate of 62 μs. This controller sets a command voltage from -10 to 10 V on a linear servo-amplifier (4-Q-DC LSC 30/2 Maxon Motors) that was operating in current control mode and supplied the motor current. A digital encoder (HEDS 55__ Maxon Motors part #110 512) was mounted to the motor and had a resolution of 500 counts per revolution. Thus, after quadrature there were 2000 counts per revolution.

The NI PCI-7344 includes a DLL with simple C functions for polling the control card from the PC to obtain information on encoder position and velocity as well as to set the output control voltage. This system allows one to use on board PID position control or to use simple C functions to form a servo loop in software. This flexibility allowed us to quickly shift between different behavioral paradigms involving position or force targets ([8], [9]).

Our manipulandum consists of a lever ($\sim$ 8 g, 4.5” long) that carries a handle protruding 2.5” from the lever. The handle can be easily positioned within the workspace, maximizing the ease by which the rat can reach and grasp the handle that is shaped and positioned to ensure the animal grasps it with one paw in a highly specific and reproducible fashion. As the lever is hanging from its pivot point (see Fig. 1) the apparent mass of the manipulandum felt by the animal is much less than 8 g. All Data presented were sampled at 100 Hz.

III. RESULTS

A. Behavioral Tasks

We implemented four behavioral paradigms. In each paradigm, subjects (rats) grasped a 1-Degree of freedom torque manipulandum and moved it to a specific target position or force to receive a water reward. Movements were self-paced. Once the target was reached the rat was rewarded. Rats were water deprived for approximately 15 hr before an experiment, and were provided with food ad libitum. All experiments adhered to the SUNY Downstate Med center animal welfare protocols.

Paradigm 1: Resistive Viscous Force Field: The viscous force field resists movement linearly with respect to velocity. Subjects pulled the manipulandum handle past a target position in order to receive reward. Randomly ($\mathrm{p} \sim 0.1$) a “catch trial” (CT) was administered in which the subject was deliberately surprised by the sudden removal of the force field. Previous work has shown that CT can be very useful in determining the control strategy used by human subjects [10], [11]. The use of such a force field will be useful in paradigms paired with neural recordings allowing one to determine neural correlates of motor error and subsequent adaptation on a trial-to-trial basis.

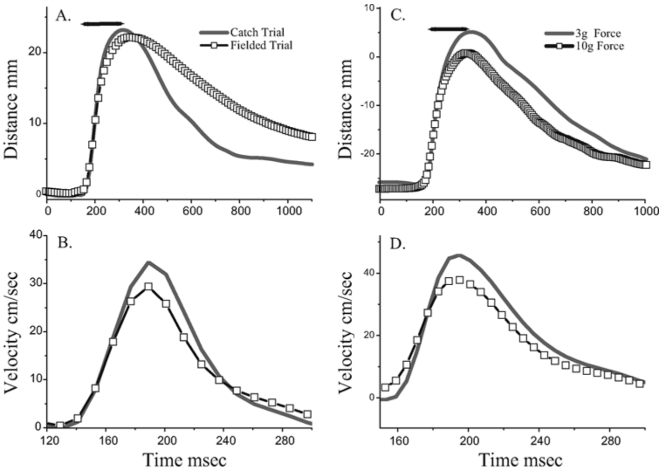

Fig. 2. (A) Average displacements of fielded trials (o) versus CT in which the viscous force field was suddenly turned off. (B) Average velocities of the fielded (o) and CT, as measured during the rising phase of the movement (A. double arrow). In 15/19 experiments the average CT had greater displacements than fielded trials, and all 19 yielded greater velocities. Average displacements (C) and velocities (D) of movements made against a 3-g versus 10-g (*) constant force field measured over 16 experiments. Average displacements and velocities were greater with the 3-g force in all experiments, even though the smaller movements were still above threshold for receiving the water reward. The right sides of these curves are skewed by the fact that on some trials the rat holds the handle back while drinking.

Paradigm 2: Constant Torque Force Field: Rats pulled the manipulandum past a target position while the manipulandum produced a constant force of either 3 g or 10 g in blocks of random length (ranges 2–16, 9–23). Overall, 63% of trials involved the 3 g force and 37% the 10 g force.

Paradigm 3: Spring Force Field: In this paradigm the manipulandum emulates a handle attached to a spring. This paradigm explicitly ties position and force together. With our system it is easy to instantaneously change the apparent spring constant and, thus, probe the animal’s motor adaptation.

Paradigm 4: Isometric Force Target: This paradigm uses force as the target criterion for reward instead of position allowing the dissociation between these parameters. It can, therefore, be used in conjunction with Paradigm 3 that conjoins these parameters.

IV. EXPERIMENTAL IMPLEMENTATION

We obtained approximately 150 reach-grasp-pull movements (range 20 – 857) within approximately 10–20 min from each rat ($\mathrm{N} = 7$) pulling against a viscous force field (VFF). We have plotted the position data from 115 movements made during one experiment using the VFF (rat MT_09). The horizontal line in Fig. 1(F) represents the target position. As subjects were rewarded for surpassing the position target they often made movements larger than necessary. Nonetheless, it can be seen in Fig. 1(G) that the catch trials (CT ^) were larger than the fielded movements that occurred immediately after the CT trials (*), an indication of adaptation. In all VFF experiments the force field sequence consisted of 13.4% CT trials and 86.6% Fielded trials with a range of 1–16 Fielded trials in a row and a range of 1–4 CT trials in a row.

In Fig. 2(A) the average fielded movement (o) and the average CT movement from 19 experiments conducted on 7 rats over 4 days are plotted. In 15/19 experiments the rats pulled the handle farther during the catch trials than the Fielded trials ($p = .002$ using a binomial statistics on the peaks of the average experimental results). This trend is reflected in the average difference seen in Fig. 2(A), and is even more obvious (19/19 experiments; $p = 0$) when velocities are compared between the two movements with the mean CT movement always having a greater velocity than the mean Fielded movement Fig. 2(B).

In our implementation of Paradigm 2 (constant force) 6 rats pulled the manipulandum against loads of 3 g and 10 g in a block paradigm.

Fig. 2(D) demonstrates that the average velocities were higher for movements against the 3 g force than the 10 g force. This result was the same in all 16 experiments ($p = 0$). The peak acceleration against the 10 g force was only 70% of that measured during movements against the 3 g force implying that the rats used a higher force output against the 10 g force, since the acceleration against the 10 g force would only be 30% of that for the 3 g force if the rats' force output was the same suggesting that the rats were attempting to conserve the velocity or duration of the movement. If so, the fact that they did not completely conserve the velocity is surprising and significant, as both of these forces are well below the maximum that rats can produce [9].

V. DISCUSSION

To this day, little is known about how forces and torques are sensed and processed in the brain. This is partly because of still unsolved questions about how force is represented by somatosensory afferents versus the degree to which it is dependent on the forward motor program. Further understanding of these issues will require development of advanced experimental paradigms involving computer generated force fields. These paradigms are uniquely capable of dissociating the many variables that are involved in coordination of movement against loads. Many such experimental paradigms are being developed in human psychophysics laboratories, but have not been adequately implemented in neurophysiology laboratories. Part of the problem is the extreme time and effort required to implement these difficult and elaborate experiments in monkeys. An increased level of efficiency would be achieved if similar but simpler experiments could be implemented in smaller animals such as rodents [12].

We have shown here that it is not only possible to implement particular force field paradigms with rats, but that the same rat can learn several such paradigms. Thus, we are now beginning to use these tools to investigate the activity of neuronal populations in the motor cortex and thalamus of rats carrying out the paradigms.

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