*Communication*

# Dynamometer for rat plantar flexor muscles *in vivo*

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**Abstract:**—*A dynamometer is designed and fabricated to measure the force output during static and dynamic muscle actions of the plantar flexor muscles of anaesthetised rats in vivo. The design is based on a computer-controlled DC servomotor capable of angular velocities in excess of 17.5 rad $s^{-1}$. The system controls the range of motion, angular velocity and electrical stimulation of the muscles, while monitoring the force output at the plantar surface of the foot. The force output is measured by a piezo-electric load cell that is rated at 5 kg capacity. Angular velocity and position are measured by a DC tachometer and potentiometer, respectively. All measurement devices are linear ($r^2 = 0.9998$). The design minimises inertial loading during high-speed angular motions, with a variation in force output of less than 0.2%. The dynamometer proves to be an accurate and reliable system for quantifying static and dynamic forces of rat plantar flexor muscles in vivo.*

**Keywords**—*Dynamometer, Plantar flexor muscles, In vivo; Servomotor, Load cell, Force output, Rats*

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## 1 Introduction

UNTIL RECENTLY, the study of skeletal muscle mechanics and contraction-induced muscle injury in animals has involved invasive procedures utilising *in vitro* (BAHLER *et al.*, 1968; WARREN *et al*, 1993) and in situ (FAULKNER and JONES, 1989; LIEBER and FRIDEN, 1988; NIKOLAOU *et al.*, 1987) preparations. Although these studies have yielded much information about the contractile properties of isolated muscle and muscle–tendon preparations, they have not revealed the contractile properties of whole muscle groups working as functional units *in vivo*.

Although tendon buckle transducers (LEWIS *et al.*, 1982; WALMESLEY *et al.*, 1978) have been used to study forces during volitional movement *in vivo*, they are not appropriate for the study of muscle contractile properties and require surgery. A dynamometer, similar to that used for studying humans (FARELL and RICHARDS, 1986), was needed. Such a dynamometer was designed by ASHTON-MILLER *et al.* (1992) to measure the *in vivo* biomechanical behaviour of mouse dorsi and plantar flexor muscles. Taking the biomechanics into account, the behaviour of the dorsi and plantar flexor muscle groups *in vivo* was found to be in close agreement with *in situ* results (FAULKNER and JONES, 1989). Thus *in vivo* dynamometry can be used for the study of skeletal muscle response.

The mouse dynamometer design (ASHTON-MILLER *et al.*, 1992) used a torque cell to measure the torque generated about the ankle joint and operated in an isokinetic mode. The dynamometer presented here was designed to measure the force of the rat plantar flexor muscles at the plantar surface of the foot and to examine the skeletal muscle mechanics under static, isokinetic, and controlled non-isokinetic conditions that involve acceleration and jerk.

## 2 Rat dynamometer

### 2.1 *General description*

The dynamometer was specifically designed to quantify the static and dynamic muscle response of anaesthetised rats *in vivo* by automation of the testing and data-acquisition procedures. The dynamometer can operate in isometric, isovelocity, or controlled non-isokinetic, modes, in which range of motion, angular dynamics of the ankle joint and electrical stimulation of the rat muscles are each independently controlled. Computer programs were developed in QUICKBASIC to interface with the operator, communicate with a motor controller unit for control of the DC servomotor, collect data, activate the electrical stimulator and display procedural data on the screen in real time. The platform of the dynamometer structure is an aluminium table that holds all the testing components, such as the Aerotech DC servomotor and gearbox, an animal-positioning platform, the load cell fixture and a potentiometer.

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Fig. 1. *Position of rat's foot in load cell fixture and knee in support device*

## 2.2 *Data acquisition (force, angle and velocity)*

To measure the muscle forces at the plantar surface of the foot, an aluminium fixture was fabricated to hold both a piezo-electric load cell (Z-11/5 kg)* and the animal's foot (Fig. 1). The Z-11 load cell is designed for the measurement of dynamic signals with a natural frequency of 550 Hz and response from zero load to full scale (5 kg) rated at approximately 24 ms.

To translate the force into a vertical movement relative to the load cell transducer, a 20 g rectangular aluminium plate was mounted on three linear bearings†. The force values are converted into a 24-bit number by an external transducer and sent to the host computer by an RS-232 port at a maximum rate of 264.5 Hz. In addition, the load cell fixture acts as a couple between the servomotor shaft (Fig. 1) and a drive shaft connecting a precision potentiometer‡. The potentiometer, which is used for angular measurement of the load cell fixture, has a range of 0–10 K Ω and requires a 5 V excitation voltage. The potentiometer uses stainless-steel ball bearings around the output shaft for durability, low running torque and consistency of performance. Voltage from the potentiometer is converted to angular position (deg.).

The DC tachometer, which is used to record angular velocity of the load cell fixture, is connected directly to the servomotor. It produces a linear voltage of 3V per 1000 revolutions per minute, with a ripple of 1.5% RMS, a ripple frequency of 16 cycles per revolution and an error of 0.2%. The output of the DC tachometer is connected to a 1 kHz low-pass filter in series with an analogue channel of the CIO-AD08 board. A low-pass filter with a corner frequency of 1 kHz was selected to eliminate any high-frequency harmonics generated by the tachometer windings.

## 2.3 *Muscle stimulation*

Electrical stimulation of the plantar flexor group is achieved by a stimulator** and platinum needle electrodes or implanted nerve-cuff electrodes. Stimulation of the plantar flexor group is controlled by the computer via a single digital line and can be turned on and off as a function of either time or position of the load cell fixture. These parameters are configured by the operator.

## 2.4 *Motion control*

Movement of the shaft, load cell fixture and the rat's foot is controlled by an Aerotech DC servomotor††, with a 500-line quadrature output encoder, a 10 : 1 ratio gearbox and two motor controller units. The signal from the internal encoder is used by both motion controllers to control the position of the motor shaft. Isovelocity motions use an Unidex 1 motion controller†† and complex motions involving acceleration and jerk are controlled by an Unidex 100 motion controller. After the computer communicates the desired motion of the motor, the operation of the motor controllers becomes independent of the host computer. Thus an entire series of tests can be sent to the motor controllers, including motion, delays and repetition number.

The DC servomotor (model 1410 DC) and gearbox produce a peak torque more than 100-fold greater than the maximum torque that a rat can produce. A rat of approximately 200–320 g should be able to exert a maximum force of 30 N (ASHTON-MILLER *et al.*, 1992) or a torque of approximately 0.75 N m to the load cell. With the motor rated at 14.1 N m driving the 10 : 1 ratio gearbox, the peak torque of the motor and gearbox exceeds 100 N m. As the torque generated by the animal is negligible compared with the torque capability of the servomotor, performance testing and optimisation of the motor can be conducted without an animal.

## 2.5 *Software*

An IBM-compatible 80486 microcomputer was fitted with a 20 kHz CIO-AD08 board‡‡ to convert the analogue signals to 12-bit digital values. The A/D board is designed for eight single-ended analogue inputs and digital I/O capability. The custom software sampled the transducers at 264.5 Hz. Numeric values of force, velocity and position were displayed on the screen in graphic form in real velocity and saved to a RAM drive in a data-file format. The software, stored in an executable format, allowed the user to specify the file name for data storage and to download the appropriate motion control file to the controller. Additional software was used to generate the motion control files, which could be changed in seconds to change test protocols. The software was menu driven and 'user friendly'.

# 3 Quantification of force, angle, and velocity

Knowledge of the inertial loads generated during motion reversal of the oscillatory movements was important in determining actual muscle forces. Inertial effects were quantified using oscillatory movements (0.52–15.7 rad $s^{-1}$) driven by a square-wave velocity command signal. As the piezo-electric transducer was mounted in the load cell fixture, inertial loads were generated by the 20 g load plate. A piece of PE tubing was compressed between the foot clamp and the load to provide a constant compressive force to the load cell. When the force was 7.2 N, an oscillatory movement was initiated (ranging from 0.52 to 15.7 rad $s^{-1}$) to quantify force variations due to inertia produced by the load plate. The force was monitored during ten successive movements at each velocity. The force varied from 0.059 N at 0.52 rad $s^{-1}$ to 0.195 N at 15.7 rad $s^{-1}$; a small force variation.

The output of the load cell was linear over the range of static loads applied outside the dynamometer ($r^2 = 0.9999$, standard error $< 0.002$ N) and in the load cell fixture of the dynamometer (load plate trials, $r^2 = 0.9998$, standard error $< 0.0025$ N). The mean and standard deviation were calculated for each applied weight to determine the accuracy of the load cell (Table 1). The 20 gram load plate was then subtracted from the A/D value thus zeroing the load plate.

The DC tachometer output was linear over the range of velocities tested (0–94.24 rad $s^{-1}$, $r^2 = 0.9998$, standard error

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† THK CO, Ltd., Tokyo, Japan

‡ 112-P19, Maurey Instrument Corp., Chicago, IL, USA

** Grass SD-9, Grass Medical Instruments, Quincy, MA, USA

†† Aerotech Inc., Pittsburgh, PA, USA

‡‡ Computer Boards Inc., Mansfield, MA, USA

*Table 1 Calibration of force on load plate*

| Applied load, g | Recorded force, N |
|---|---|
| 20 | $0.39 \pm 0.01$ |
| 50 | $0.68 \pm 0.02$ |
| 100 | $1.15 \pm 0.03$ |
| 200 | $2.08 \pm 0.18$ |
| 500 | $5.01 \pm 0.11$ |
| 1000 | $9.89 \pm 0.14$ |

Data are presented as mean $\pm$ SD for three measurements
Applied load was added to the 20 g load plate.

$< 0.004$ rad $s^{-1}$). When the output of the tachometer was measured over time, the coefficient of variance was less than 0.002% in the range of velocities tested. The higher velocities resulted in a lower standard deviation as a percentage of the mean value, owing to the higher DC signal and resulting signal-to-noise ratio.

Output of the potentiometer was also linear over the range tested (0–3.14 rad, $r^2 = 0.9998$). When the potentiometer was fixed in a static position corresponding to 2.094 rad, the output, recorded for 20 s, was $2.095 \pm 0.002$ rad.

### 3.1 *Quantifying performance of servomotor for isovelocity profiles*

The velocity of the load cell in response to selected oscillatory motions (30, 150, 300, 500 deg $s^{-1}$) is presented

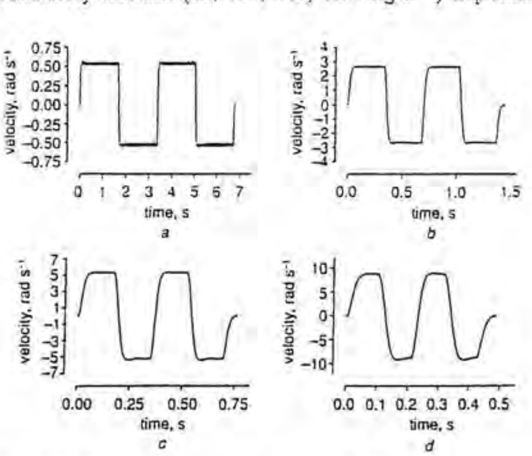


**Fig. 2.** *Velocity as function of time for Unidex 1 controller: isovelocity profiles: (a) 30 deg. $s^{-1}$; (b) 150 deg. $s^{-1}$; (c) 300 deg. $s^{-1}$; (d) 500 deg. $s^{-1}$*

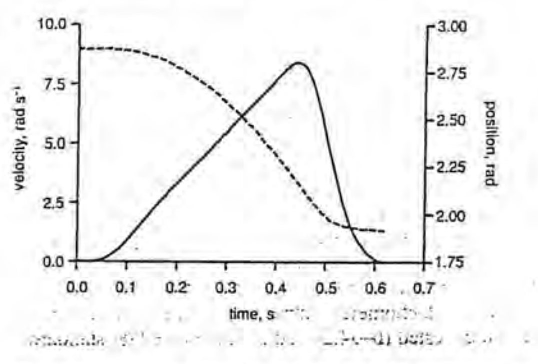


**Fig. 3.** *Velocity against time for the Unidex 100 controller: isoacceleration profiles*

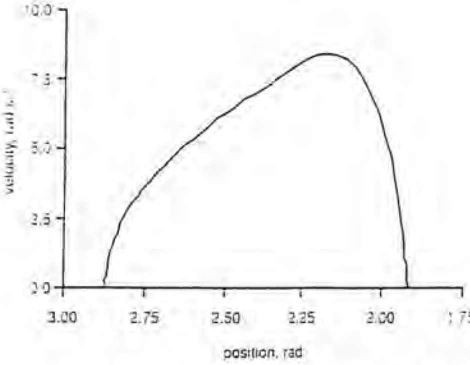


Fig. 4. *Velocity against load cell position for data in Fig. 3*

in Fig. 2. For the 300 deg $s^{-1}$ motion, the time to steady state ($-5.24$–$5.24$ rad $s^{-1}$) at the motion reversal points (where steady state is defined as a velocity variance of less than 2.0%) was 60 ms, with a maximum tracking error of 2% for the positive-velocity movement. The negative-velocity movement had an 83 ms time to steady state, with a 2.6% velocity overshoot. The ability of the servomotor to reach a steady-state velocity within 83 ms demonstrates the accuracy of programmed isokinetic motions.

### 3.2 *Quantifying performance of servomotor for isoacceleration profiles*

The velocity of the load cell to a programmed, non-isokinetic motion is presented in Fig. 3. The counter-clockwise movement was programmed for a magnitude of 0.958 rad, an acceleration ramp of 19.1 rad $s^{-2}$ and deceleration ramp of $-48.1$ rad $s^{-2}$. The velocity increased from 0 rad $s^{-1}$ to 8.42 rad $s^{-1}$ in 0.698 rad and then decreased to 0 rad $s^{-1}$ in 0.26 rad, with no velocity or position overshoot (Fig. 4).

### 3.3 *Animal retention*

The rat is positioned on its back, and a leg holder fits over the leg. The animal is held down with this device while the knee is supported. The foot is placed on the load cell plate, and a compressive force is applied to the dorsum of the foot (Fig. 1). The X–Y table is positioned so that the knee and ankle are at 90 deg. (full extension represents 180 deg.).

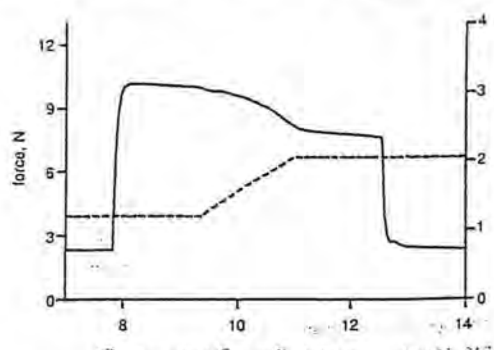


**Fig. 5.** *Force against time during slow muscle shortening (30 deg. $s^{-1}$)*

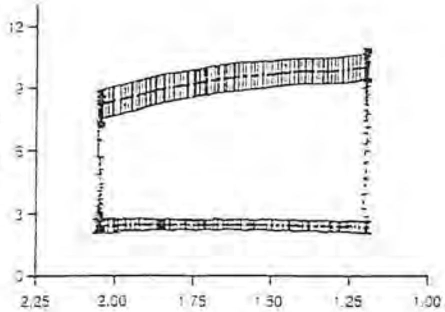

Fig. 6. *Force against load cell position for data in Fig. 5. Data are presented as mean ± SD of three trials*

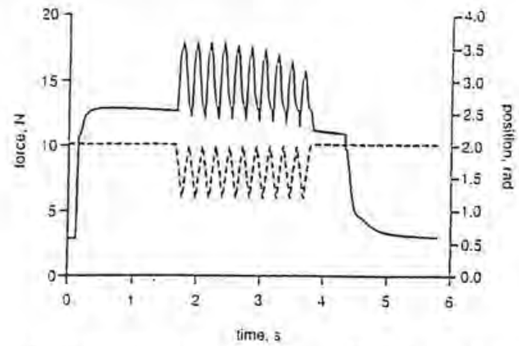


Fig. 7. *Force against time during repeated lengthening–shortening cycles (500 deg. $s^{-1}$)*

## 4 Experimental results

Two examples of dynamic testing of the rat plantar flexor muscles are presented. In the first test (Fig. 5), the muscles were stimulated to produce an isometric muscle contraction and then allowed to move at 0.52 rad $s^{-1}$ over a 0.87 rad (50 deg.) range of load cell movement. The force–position relationship for that muscle shortening test is seen in Fig. 6. In the second test, the muscles were stimulated to produce an isometric muscle contraction, and then the foot was oscillated at 8.73 rad $s^{-1}$ (500 deg $s^{-1}$) for 10 cycles over a 0.87 rad range of load cell movement (Fig. 7). The result is a repeated lengthening–shortening action of the muscles. The force–position relationship for the oscillatory part of that test is seen in Fig. 8.

## 5 Conclusions

A dynamometer was designed and fabricated to quantify muscle responses of the rat *in vivo* without invasive procedures. The dynamometer meets the scientific requirements necessary for performance testing of the plantar flexor muscle group under a wide variety of testing conditions, including static, shortening and lengthening actions of the muscles. Ease of operation and reliability of measurements allow acute and chronic testing. The Z–11 load cell was linear throughout the advertised range and performed flawlessly during repeated testing over the past four years. The signal to noise ratio and fast transient response were well suited for both static and dynamic muscle testing.

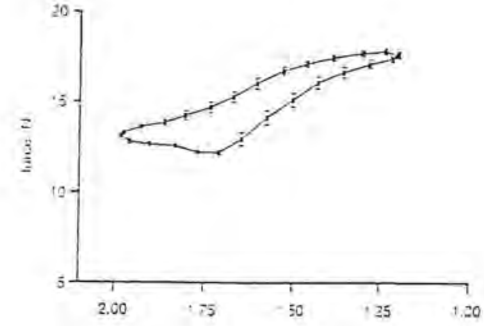

Fig. 8. *Force against load cell position for data in Fig. 7. Data are presented as mean ± SD of three trials*

The advantage of using the Unidex controllers was the ability to download commands and allow the motor to run in the background. This design allowed the data acquisition software to be responsible only for the acquisition of transducer data and not for DC servomotor performance. The servomotor's ability accurately to follow programmed motions allowed investigation of muscle responses under a variety of dynamic conditions *in vivo*.


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