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Design and implementation of a rodent voluntary wheel-running exercise facility incorporating dynamically controllable torque load

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Design and Implementation of a Rodent Voluntary Wheel-Running Exercise Facility Incorporating Dynamically Controllable Torque Load

Bernard Guillemin, *Member, IEEE*, and Heather Smith

***Abstract*—The design and implementation of a rodent voluntary wheel-running exercise facility for use in the study of changes in muscle structure and composition arising from different exercise regimes are discussed. The novel feature of this personal-computer-based system is its capability of dynamically adjusting torque load on the wheel independently of rotational speed and with zero impact on the rodent's environment in terms of noise, heat, or vibration. Emphasis in this paper is given to the unique set of requirements of this application that lead to the choice of an electromagnetic braking device, specifically the hysteresis brake, and its incorporation into a complete system for use in the research arena.**

***Index Terms*—Animals, braking, design methodology, electric machines, hysteresis, muscles, torque control.**

I. Introduction

THE MECHANISM by which skeletal muscle, used in voluntary movement of the skeleton, adapts at a cellular level to changes in use has received considerable attention in recent years [1], [2]. This has implications for both humans and animals. With respect to humans, it has relevance in the study of the physiological and biomechanical influences on human performance in sport, work, and exercise, including the molecular and cellular processes that contribute to changes in muscle structure and composition during exercise of high intensity or prolonged duration.

Such studies into the physiological adaptation of skeletal muscle to a variety of exercise regimes are typically performed on rats and mice because they are biologically similar to humans and other animals. More importantly, their environments can be easily controlled, making them ideal experimental subjects.

Current studies undertaken at the Department of Sport and Exercise Science at the University of Auckland use traditional voluntary running wheels to study the effects of different physical activities, with each experiment typically lasting between 4 and 12 weeks. Given that such systems introduce a very low fixed resistance (i.e., torque load arising from friction in the wheel axle) on the running wheels, their application is limited to the simulation of endurance-type exercise. The aim of the research facility described in this paper is to significantly extend this work to the study of the physiological adaptation of skeletal muscle to controlled and dynamically adjustable high-intensity exercise regimes.

Based around traditional voluntary running wheels, the personal-computer (PC)-based facility discussed here has the capability to dynamically introduce controlled measurable changes in torque load on the wheel in each of six parallel load-controlled wheel-running stations, thereby altering the loading on the limb muscles and thus mimicking higher intensity training (sprint or strength training) stimuli. Multiple stations (one rat per station) operating in parallel in an identical manner are needed to test for the statistical significance of hypothesized changes in most physiological variables of interest. The activity of each animal on a wheel is continuously monitored, and this information is recorded along with applied torque profiles. All of this capability makes it possible to not only significantly extend such studies in the manner described but also to include experiments into the responsiveness and running behavior patterns of the animals to exercise involving different loads and loading patterns.

Whereas the overall features and implementation aspects of this facility are likely to be of general interest to researchers in this field, a specific goal of this paper is to discuss the issues surrounding the implementation of continuously variable and controlled amounts of torque load under computer control in a manner that has zero impact upon the environment of the rat in terms of noise, heat, or vibration.

Section II of this paper discusses the unique set of requirements of a torque load capability used in this application, followed in Section III by the various implementation strategies considered. A brief overview of the system hardware is presented in Section IV, followed by a discussion of the functional requirements of the system in Section V. Section VI presents a brief overview of the LabVIEW environment that has been developed, followed by some preliminary experimental results in Section VII.

II. Requirements of the Torque Load Capability

The primary initial requirement of this experimental facility was the capability of applying accurate and repeatable, dynamically adjustable, torque load independent of speed and under computer control. The braking motion applied had to be smooth to allow the animal to run comfortably, and there had to be minimal impact upon the animal's environment in terms

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of noise, heat, vibration, etc. (minimizing negative stimuli to wheel running is essential to encourage the animals to run). A free-running state, which typically is the starting point for most exercise regimes, was required, as well as bidirectional capability to allow running in either direction. The system had to be long wearing, durable, and require zero ongoing calibration. Finally, there had to be little ongoing technical support required, given that the intended users of the system are animal researchers with little or no engineering knowledge.

Before discussing strategies for satisfying these requirements, some estimate needs to be made of the maximum torque load requirement of the system. The following calculation is based on a mass $m = 350$-g rat (an expected maximum figure based on previous experience) and a standard rat wheel of diameter $d = 280$ mm, resulting in a predicted maximum torque of

$$T_{\max} = F(d/2) = (0.35 \times 9.8) \times 0.14 = 0.48\ \mathrm{N \cdot m}. \quad (1)$$

(Note: This calculation is approximate only and is based on the mass of a rat positioned at a point on the circumference of a wheel at a height equivalent to the center of the wheel.)

III. Strategies for Implementation

This demanding set of requirements discussed above narrowed significantly the implementation options available. At the outset, for reasons of cost, need for compactness, and low-noise operation, solutions incorporating gearboxes were eliminated, the aim being to find a solution that could be direct coupled to the shaft of the running wheel.

Mechanical or electromagnetic friction brakes, although simple in concept and able to provide torque load independent of speed, are not an option because they wear over time, making the requirement for precise and repeatable torque load difficult to achieve without ongoing calibration. Guaranteeing a smooth braking motion would be problematic, and there would doubtless be noise, heat, and vibration produced.

Eddy current brakes are ideal from the standpoint of having low inertia and producing torque load without the use of friction [3], [4]. Based on the principle of opposing magnetic fields, these devices at their simplest consist of a rotating disk and a magnetic field source. When the magnetic field is established and passes through the disk, eddy currents form within the rotating disk, in turn, generating their own opposing magnetic field. However, unfortunately for this application, this produces a torque load that is a function of rotational speed.

Another option that does not suffer from this drawback is a magnetic particle brake. These devices have within their casing a fine, dry, free-flowing stainless steel powder together with a rotating disk attached to an outer shaft. When a direct current (dc) is applied to the brake, a magnetic field is set up within the casing, causing the particles in the powder to form chains along the resulting magnetic field lines linking the disk to the housing. An opposing torque, proportional to the strength of the applied magnetic field, is produced, which is independent of rotational speed, with full torque being available even at

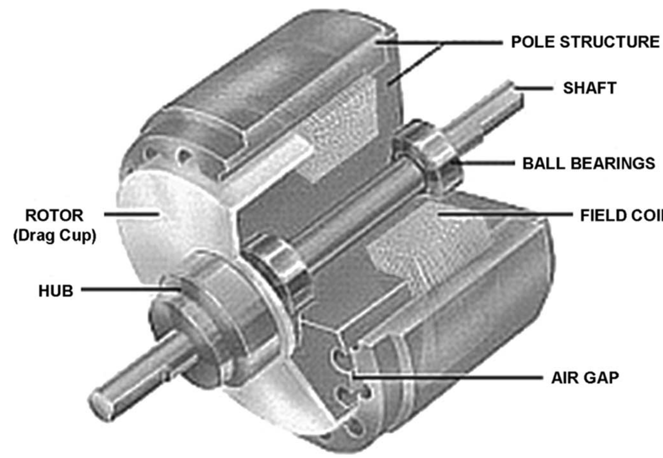

Fig. 1. Internal structure of a hysteresis brake (reproduced from Magtrol Inc. [5]).

0 r/min. However, because of the manner in which friction is produced between the magnetic particles, smooth operation is not achievable and precision and repeatability cannot be guaranteed, making these devices also unsuitable for this application.

The device that was finally chosen is a hysteresis brake. This differs from a magnetic particle brake in that, apart from bearings, it contains no physically contacting members. Torque is produced electromagnetically, which means the operation of the device is relatively smooth and has a long life expectancy. Torque is also independent of rotational speed, with full torque being available even at 0 r/min.

As shown in Fig. 1, these devices consist of inner and outer pole structures and a field coil (all fixed) and a rotor (drag cup) connected to a shaft, which rotates in the air gap between these inner and outer pole structures. A dc applied to the field coil produces a magnetic field proportional to current in the air gap. The rotor is thereby magnetically restrained, providing a braking action between the pole structure and the rotor. Because torque is produced magnetically in the air gap without the use of friction or sheer forces, these brakes operate quietly, providing absolutely smooth, infinitely controllable torque loads, independent of speed. They are also available in models with torque loads as small as $T_{\max}$ calculated previously. Further, with the exception of shaft bearings, no wear components exist [5].

There are two problems associated with the use of hysteresis brakes in this application that need to be overcome, strategies for which will be discussed in Section V. The first is a condition called "cogging," which is caused by the rotor retaining a magnetic memory and results in a pulsating torque load. The second is hysteresis in the device's torque versus current characteristic, as shown in Fig. 2.

The specific hysteresis brake chosen for this application was a Magtrol HB-140-3, which produces a maximum torque load of $1\ \mathrm{N \cdot m}$ for an applied voltage to the field coil of ± 12 V and a driving current of ± 504 mA [5]. An overview of the hardware of the system, which has been developed comprising six parallel voluntary rat-wheel exercise stations incorporating these hysteresis brakes, will be discussed next.

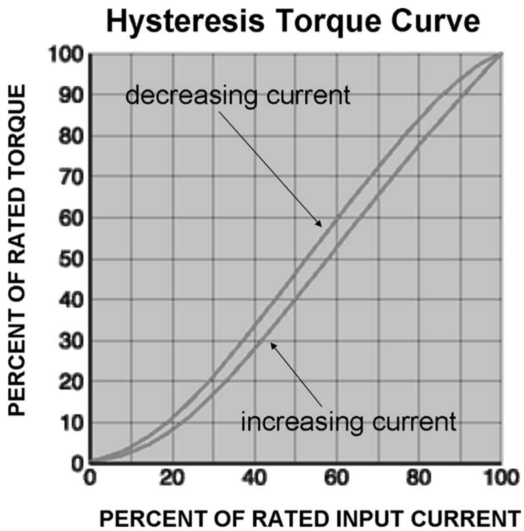

Fig. 2. Typical hysteresis characteristic (reproduced from Placid Industries, Inc. [6]).

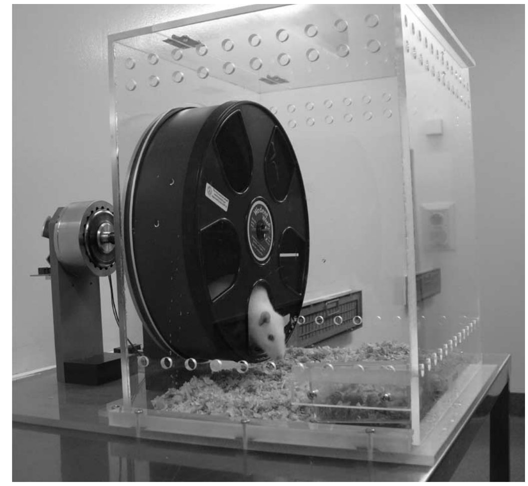

Fig. 4. Front view of a rat exercise station showing a rat using the wheel.

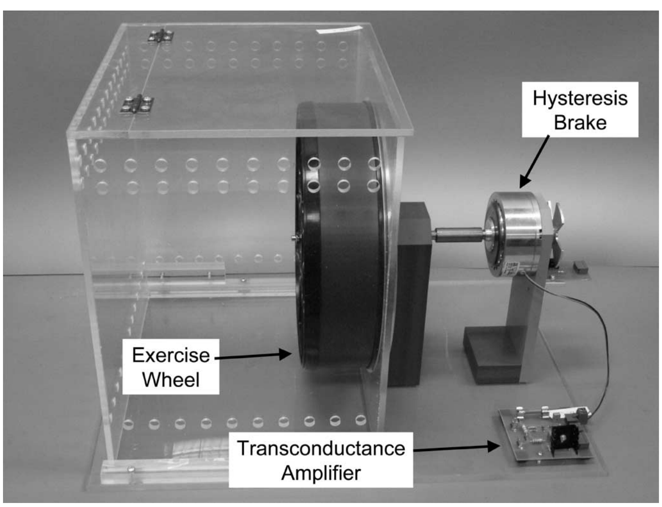

Fig. 3. Side view of a rat exercise station.

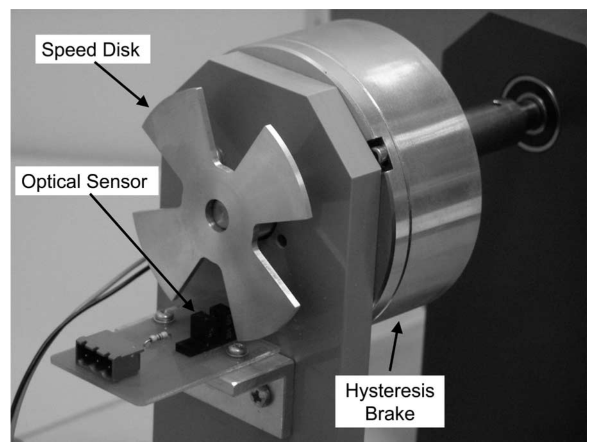

Fig. 5. Optical sensor used for movement and speed measurement.

IV. System Hardware

Figs. 3 and 4 show a single rat-wheel exercise station comprising a Perspex cage of dimensions 330 mm long × 280 mm wide × 360 mm high and a 280-mm wheel.

To keep the animals separated from all wiring, electronics, etc. (experience has shown that bored rodents will chew on almost anything!), the hysteresis brake and associated electronics are located outside the cage (to the right of the cage in Fig. 3), the brake being connected to the wheel via a rotating shaft mounted on low-friction bearings. Attached to this shaft, and again external to the cage, is a simple movement and speed-measuring device shown in Fig. 5, comprising an aluminum disk with slits and associated infrared optical sensor. The only other electronics required for each station is a transconductance amplifier (see Fig. 3), providing the necessary drive current to the field coil of the brake.

The entire system comprises six identical exercise stations interfaced to a central PC via the Peripheral Component Interconnect (PCI) bus to a Data Acquisition Board (DAB; Eagle PCI-766-8) having eight 16-bit digital/analog (D/A) channels (six of these are used for controlling each of the hysteresis brakes, the remaining two being available for later expansion) and six digital input channels (used for monitoring the rotation of the wheels via the signals produced by the infrared optical sensors attached to each shaft). For ease of programming for the intended users, the central PC is programmed using LabVIEW.

A schematic of the interface electronics between the DAB and one of the exercise stations is shown in Fig. 6.

The signal to drive the hysteresis brake is sent to the appropriate D/A channel on the DAB (AOCH 0), which, in turn, is connected to a power operational amplifier (LM675T) configured as a transconductance amplifier delivering 0–333 mA. The 200-Ω 10-turn pot included in the circuit is adjusted to ensure that 0 V on the AOCH 0 output results in 0 mA of drive current to the hysteresis brake. The infrared optical sensor (Honeywell HOA2001-1) used to monitor wheel rotation (see Fig. 5) is connected directly to the appropriate transistor–transistor logic (TTL) digital input line (DI 0) on the DAB.

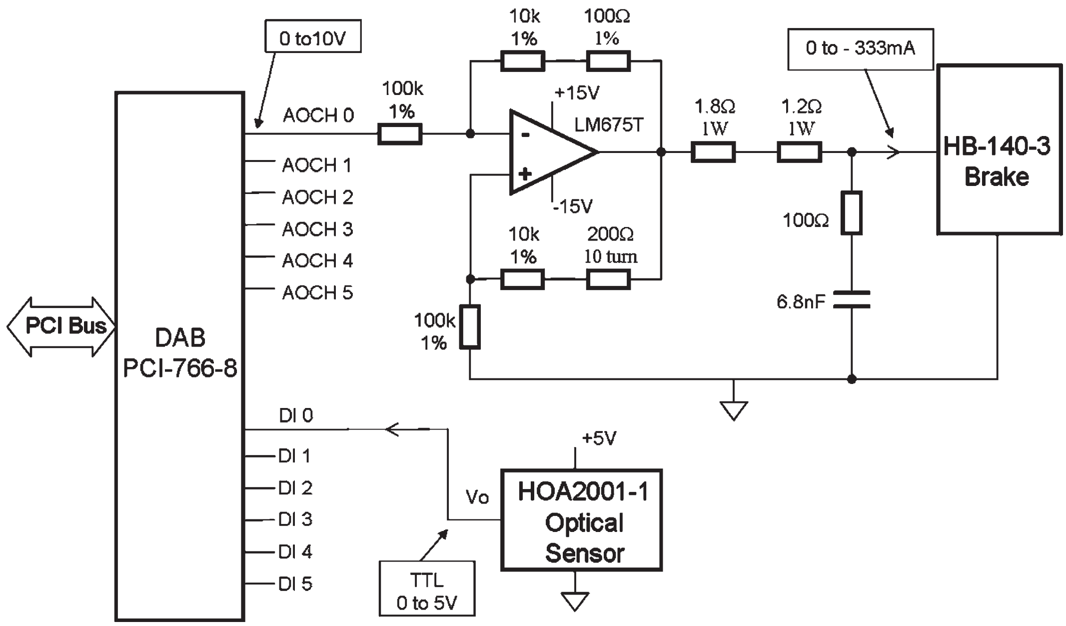

Fig. 6. Interface electronics between the DAB and one of the exercise stations.

V. Software Requirements of the Facility

Before giving an overview of the software features that have been implemented in the system, the requirements of the system from a functional standpoint will be discussed.

A. Primary Functional Requirements

The primary functional requirements of the system that dictated the development of the LabVIEW environment used for programming and control are as follows:

1) Each station needs to be separately monitored in terms of wheel activity and separately controllable in terms of exercise profile. (Note: Although an initial aim was to have the same exercise profile running on each of the six parallel stations, the flexibility to be able to change this in the future to having different profiles operating on each station was seen has highly desirable.)
2) Data collection in respect to wheel activity needs to include the following parameters recorded against date and time: speed of running, running duration, distance traveled, and torque loading. Although these data are only required during periods of wheel activity, it needs to be collected for the duration of an experiment, which could last days or weeks.
3) To minimize disincentives to wheel running (encouraging some rats to use the wheel can be difficult), specific exercise profiles must be gradually introduced each time the rat gets on the wheel by including a "warm-up" period, which starts with the wheel in the free-running state.
4) Simplified online statistical summaries of wheel activity (such as distance run, average running speed, number of running bouts, and average speed of each bout) should be available to the experimenter to permit rapid verification of equipment functionality as well as easy experiment monitoring.

There are a number of additional features that needed to be incorporated into the system to overcome the two main disadvantages associated with the use of hysteresis brakes in this application, namely, cogging and hysteresis.

B. Overcoming Cogging

Cogging is associated with the creation of salient poles in the hysteresis brake. These arise whenever the brake current is reduced to zero, whereas its rotor is either stationary or moving quite slowly. When this occurs, the rotor, being comprised of a permanent magnetic material, retains a magnetic orientation, thus forming these salient poles beneath each of the tooth combinations located in the pole structure. This magnetic memory results in a residual pulsating torque load, rather than a free-running state, being present at the commencement of the next running bout.

The system has been programmed to try and ensure that under normal operation this eventuality is avoided, although absolutely guaranteeing that cogging does not occur is not likely to be possible. Whenever a substantial reduction in wheel speed is detected (which could be a cue to one of three possibilities occurring: 1) termination of the current bout of activity, 2) running in the opposite direction, or 3) continued running in the same direction but at a slower speed), the load torque is quickly, but smoothly, reduced to zero. This, in turn, requires careful monitoring of the observed speed profile during a running bout to detect this situation in sufficient time to take the appropriate corrective action before the wheel stops rotating.

This necessity to avoid cogging does restrict the range of torque load profiles that can be implemented, which is a downside of using a hysteresis brake in this application. For example, profiles characterized by constant load torque irrespective of wheel speed could not be implemented. However, this is not seen as a major disadvantage for two reasons. First, if the rat has decided to terminate the current bout of activity anyway, for reasons unrelated to the current load torque profile being applied, what happens to torque load after that decision becomes inconsequential. Second, if the torque load being applied is acting as a deterrent to further running and is thus the cause of a significant reduction in wheel speed, the best strategy, in line with the underlying philosophy of wanting to encourage wheel running, is to immediately reduce the torque load, which is exactly what the anticogging process will do. Admittedly, the anticogging process will reduce the torque to zero, whereas it might be argued that reducing it to some lower level might be more appropriate. However, if wheel running continues subsequent to anticogging having been implemented, the load torque can again be rapidly, but smoothly, increased to whatever value seems appropriate.

Thus, although cogging does impose restrictions from an experimental standpoint, it should be possible to work around these in a manner that does not compromise the fundamental aim of the equipment, namely, to study the impact of high-intensity exercise regimes on skeletal muscle growth.

Given that complete avoidance of cogging during normal operation cannot be guaranteed, facility for manual decogging is also required. With this process, the software sets the torque load to its maximum value. The operator is then instructed to rotate the shaft at about 100 r/min, whereas the software smoothly reduces the torque load to zero. Although not an ideal scheme, this is workable given the experimental nature of the facility, the need for fairly regular monitoring of the rodents during the course of an experiment, and the corresponding requirement for some degree of operator interaction and expertise.

C. Compensating for Hysteresis

A primary requirement of this facility is the ability to apply accurate and repeatable amounts of torque load to the exercise wheel. With hysteresis brakes, torque load is repeatable over time to within 1%; thus, achieving this aspect is not a problem. The difficulty arises in respect to accuracy because these devices exhibit hysteresis in their torque load characteristic, as shown in Fig. 2. The best approach to solving this is to determine the hysteresis torque curve for a particular brake and use this to take account of whether field current to the brake is increasing or decreasing. The manufacturers of these devices can provide sets of matched brakes (matched to within $\pm 1\%$ of a specified torque point), together with precise calibration curves for individual breaks. This overcomes the twin problems of ensuring identical operation over all six exercise stations as well as determining their hysteresis torque curve. Obtaining matched brakes, together with precise calibration curves, must be specified at time of order and does incur a small additional charge. With our system, both matched brakes together with associated calibration curves were obtained. Because the brakes are matched, only one of these calibration curves was incorporated into the source code by way of a lookup table and used to drive all six brakes.

These individual calibration curves supplied by the manufacturer represent the torque-to-current ratio of a particular brake when measured while taking the brake from 0 to approximately 120% of its rated current value and then returning it to 0. They are typically produced at operating speeds of approximately 100–200 r/min and can, therefore, according to the manufacturer, be considered as static calibrated values that are accurate to within 2% at low speeds (up to 300–400 r/min) [7]. In our experience, rats rotate the wheels at rates well below these values; thus, the calibration curves supplied match our application well in this respect.

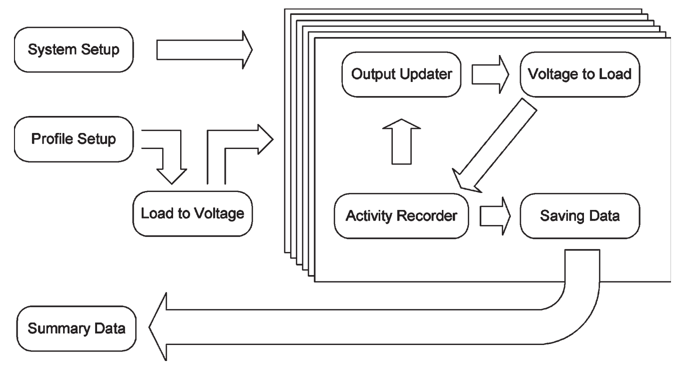

Fig. 7. Major blocks of the software environment.

A difficulty arises, however, in respect to how these curves should be used when the current supplied to the brake is taken to some value below 120% of its rated maximum, before being returned to zero, which is likely to be the typical mode of operation. Although the manufacturer acknowledges that the brake will then follow a different torque-to-current ratio curve, they have not been able to provide any information on the extent of this discrepancy from the calibration curves supplied [7]. We expect this deviation to be greatest in the region of the calibration curve close to the actual maximum current supplied, with the resulting modified hysteresis curve then asymptotically approaching the manufacturer's supplied calibration curve as the current reduces below this value. We are currently investigating this issue further, together with strategies for overcoming these discrepancies.

Due to component tolerance, the input/output (I/O) characteristics for the transconductance amplifiers used to drive the hysteresis brakes (see Fig. 6) are unlikely to be the same. To achieve as high accuracy as possible in respect to applied torque load, both for an individual exercise station and across all six stations, these characteristics also need to be determined and compensated for. We produced calibration curves for each transconductance amplifier and loaded this into the software, again by way of a lookup table.

VI. Software Environment

An overview of the software environment showing the upper-level functional blocks that have been developed is shown in Fig. 7. The first of these is the "system setup" block having two primary functions. It provides limited capability to check the operation of the system hardware, specifically the movement detection sensors (the operator is required to rotate each of the wheels in turn during this process). It also provides for manual decogging.

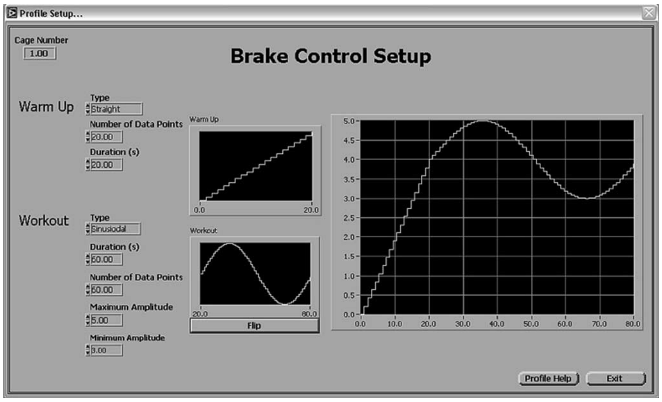

Fig. 8. GUI used to setup load torque profiles.

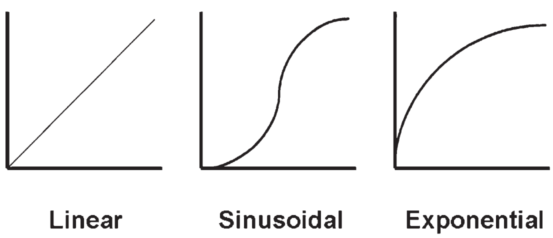

Fig. 9. Warm-up phases.

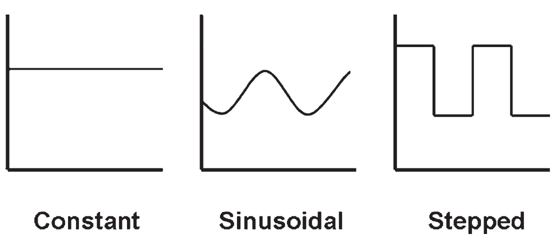

Fig. 10. Workout phases.

Next is the "profile setup" block that presents to the user a graphical user interface (GUI; shown in Fig. 8) in which the user defines individual load torque profiles for each wheel. These profiles comprise both a warm-up phase and a workout phase.

Currently, three fully configurable warm-up phases have been implemented, namely 1) linear, 2) sinusoidal, and 3) exponential, as shown in Fig. 9, as well as three workout phases, namely 1) constant, 2) sinusoidal and 3) stepped, as shown in Fig. 10. This very limited repertoire of torque profiles will be extended once experimentation is fully underway and preliminary results analyzed.

The "load to voltage" block shown in Fig. 7 allows the user to incorporate corrections for hysteresis and nonlinearities in the transconductance amplifiers. Each of the six cages has four functional blocks associated with them. The "activity recorder" block both continuously monitors and records wheel activity as well as torque profiles being applied (via the "voltage to load" block). One of the tasks of the activity recorder is to distinguish between movement of the wheel caused by movement of the rat in the cage and movement caused by actual wheel running. Dynamic alterations to torque load profiles as a result of wheel activity are handled by the "output updater" block, and the

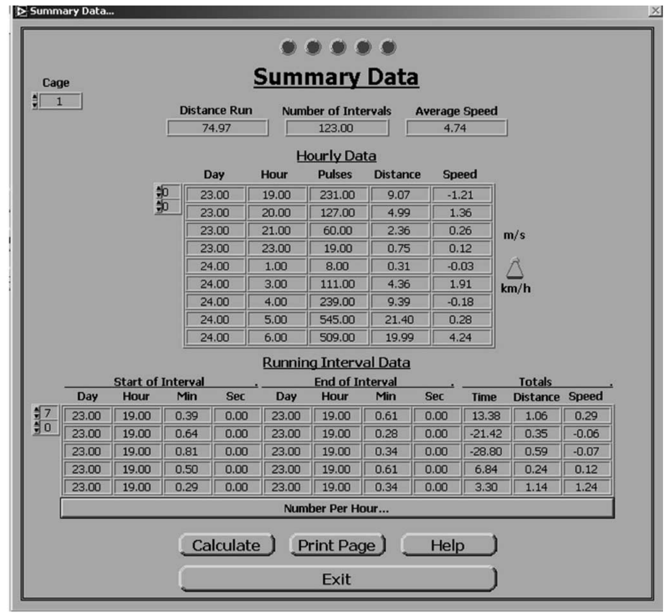

Fig. 11. Example of the summary data page available during an experiment.

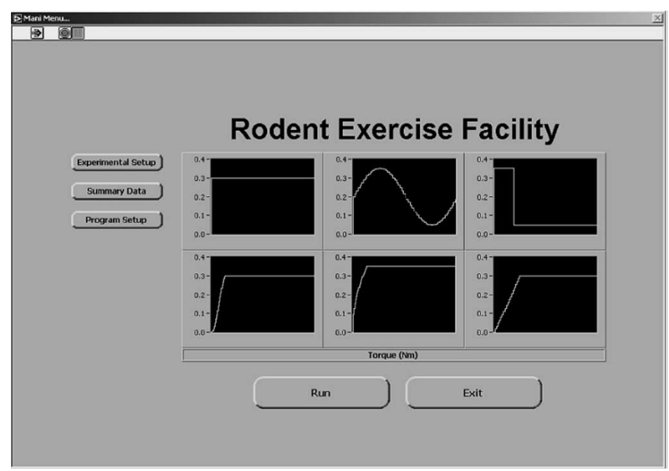

Fig. 12. Main screen visible during an experiment.

"saving data" block stores all of the above data to the PC's hard disk for later analysis.

The "summary data" block provides some ongoing statistical analysis of the data being collected for each cage as an experiment is being run. This includes ongoing as well as summary data of distance run, number of intervals (i.e., running bouts), and average speed, as shown in Fig. 11. While an experiment is running, the user can observe, via the main screen shown in Fig. 12, the individual torque load profiles being applied to each cage.

The individual displays in Fig. 12 show examples of torque profiles that can be implemented. The top three graphs do not have a warm-up period. The workout profiles, from left to right, correspond to constant, sinusoidal, and stepped (20% duty cycle) functions. The bottom three graphs include warm-up profiles corresponding to, from left to right, sinusoidal, exponential, and linear. The workout profiles in each of these latter cases is constant.

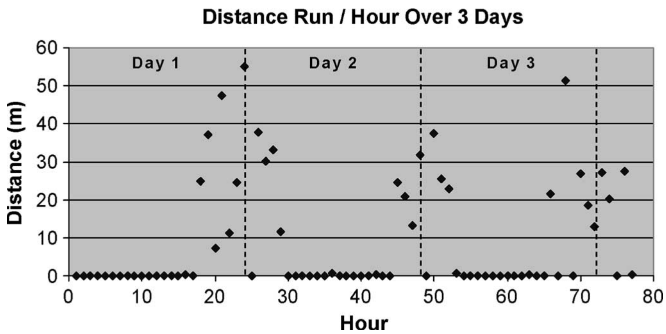

Fig. 13. Example of distance data collected over 3 days.

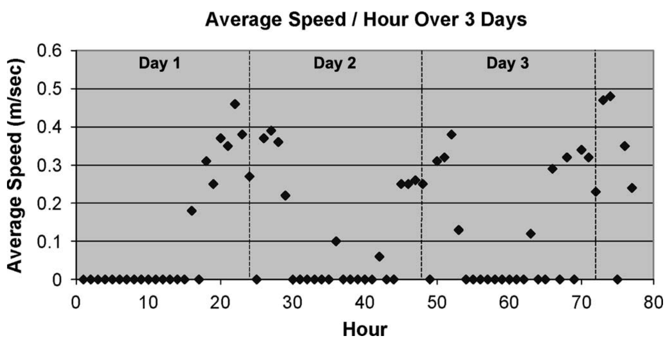

Fig. 14. Example of speed data collected over 3 days.

VII. Preliminary Experimental Results

Figs. 13 and 14 show examples of summarized distance and speed data for a single rat exercise station collected over a 3-day period, starting from midnight on Day 1 and ending at 5 A.M. on Day 4. The torque profile applied during each running bout comprised a linear warm-up phase lasting 10 s, after which a low constant torque of 0.03 $N \cdot m$ was applied. The total distance run by the rat over this period was 703 m, which was achieved over 432 separate running bouts. Over these bouts, the average speed of running was 0.31 m/s.

As expected from previous experiments undertaken with simple running wheels, running was concentrated between the hours of 9 P.M. and 4 A.M. and generally peaked around 1–2 A.M. The overall distance traveled during this period was low by comparison with previous experience (distances of several kilometers per night are not uncommon). However, experience has shown that a high variability in running behavior between rats is to be expected. Although the load torque applied during these 3 days was low, the experiment did confirm that wheel running will take place even if a nonzero value of load torque is applied.

VIII. Conclusion

The design and development of a PC-based rodent voluntary wheel-running exercise facility incorporating dynamically controllable torque load have been presented. This highly adaptable experimental facility, which makes possible the implementation of a wide variety of exercise profiles, is to be used in the study of the molecular and cellular processes that contribute to changes in muscle structure and composition during exercise of high intensity or prolonged duration. A unique feature of the system is the manner in which load torque in the range 0.0–0.5 $N \cdot m$ has been implemented using a device called a hysteresis brake, which has the characteristics of high precision and repeatability, torque independent of speed, smooth operation, as well as minimal noise, heat, and vibration artifacts. Approaches to overcoming the only two negative characteristics of these devices for this application, namely, cogging and hysteresis, have been discussed. An overview of the LabVIEW software environment for the facility has been given, along with some preliminary experimental results recorded over a 3-day period.

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He is currently a Senior Lecturer in the Department of Electrical and Computer Engineering, University of Auckland. His interests include speech analysis, synthesis and recognition, as well as speaker recognition and verification. The latter has become his significant area of research in recent years and has been applied to the problem of forensic speaker identification.

Heather Smith received the B.P.H.E. degree from the University of Toronto, Toronto, ON, Canada, in 1984, the M.A. degree in exercise physiology from McGill University, Montreal, QC, Canada, in 1987, and the Ph.D. degree from the University of Toronto in 1997. Her Ph.D. dissertation on the cellular adaptation of skeletal muscle necessitated the implementation of animal exercise models that she has since continued using.

She worked in human health and athletic performance physiology at the University of Toronto and with various sporting organizations until 1996. She is currently a Senior Lecturer in exercise physiology at the University of Auckland, Auckland, New Zealand. Her research now encompasses the cellular and molecular adaptation of skeletal muscle to physical exercise or inactivity using both human and animal models of experimentation.