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Design of a Rodent Dynamometer

Angel M. Dorsch

Thesis Submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of

Master of Science
in
Mechanical Engineering

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2004

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Abstract

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Angel M. Dorsch

In the past, computer controlled dynamometers have been used to perform isometric and isovelocitv testing to study the effects of velocity, acceleration, and position on muscle injury. However, the effect of constant force on muscle injury in animals has not yet been studied.

A computer controlled dynamometer was designed which could perform isometric, isovelocitv, and isotonic (constant force) testing on both male and female rats. A mechanical device was designed to precisely position the rats for testing as well as provide a platform for the motor and other system components. All of the system components were connected electrically through a National Instruments UMI-7764 breakout box which allowed for convenient integration of all the components.

Individual programs were written in LabVIEW to perform concentric and eccentric isometric, isovelocitv, and isotonic testing. The programs allowed for many variations to the standard programming such as isometric holds, repetitive cycles, and rest times. All of the data gathered from the testing was automatically sent to a user-specified program at the end of testing. In addition the programs were able to control all of the testing parameters for an extended period of time allowing the user to simply begin testing and then work on other projects.

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List of Symbols and Abbreviations

Symbol	Description
α	Acceleration
“	Inches
σ	Position
°	Degrees
CDC	Center for Disease Control
D	Distance, Diameter
DAC	Data Acquisition Channel
DC	Direct Current
EMG	Electromyogram
F	Force
G	Grams
Kg	Kilograms
I_z	Moment of Inertia
I_{zCG}	Moment of Inertia about the Center of Gravity
LVDT	Linear Variable Differential Transformer
M	Meters, Mass
M	Moment
MAX	Measurement and Automation Explorer
MI	Milli-Liters
Mm	Millimeter
Ms	Milli-Seconds
N	Newtons
NIOSH	National Institute for Occupational Safety and Health
PCI	Peripheral Component Interconnect
PID	Proportional, Integral, Derivative
Rad	Radians
Rpm	Revolutions per Minute
S	Seconds
T	Time
T	Torque
UMI	Universal Motion Interface
V	Volts
VI's	Virtual Instruments
ω	Velocity

Chapter 1 - Introduction

1.1 Introduction and Motivation

Muscle injury occurs in different forms. The injury can be small, causing muscle soreness that is of little consequence or it can be severe enough to keep people from going about their daily lives. According to the United States Department of Labor, 43.6 percent of work related injuries in 2001 were caused by sprains and strains leading to an average loss of 6 workdays (14). For other injury-related disorders such as carpal tunnel syndrome, the loss of workdays increased to 25. As a result, research into the prevention of muscle injuries is a major priority of NIOSH/CDC.

Several different non-invasive methods have been developed to study muscle response. These include weights on the wings of chickens (12), treadmills (9,11), and dynamometers (1,5,6,7). Dynamometer configuration varies based on the muscle group under study. However, all dynamometers employ a shaft that is rotated by the test subject. Figure 1 is an example of a dynamometer used to study fatigue in human quadriceps femoris muscles (2).

Figure 1 – Dynamometer Setup for Human Testing (2)

Dynamometers perform three basic tests to study muscle function. They are the isometric test, the isotonic test, and the isovelocitity test. For each of these tests the dynamometer must incorporate sophisticated controls and a powerful motor to impose force on a stimulated muscle. In an isometric test the motor holds the muscle length in a fixed position during stimulation to prevent the muscle from shortening. Since the muscle cannot shorten, tension occurs at a constant muscle length. By varying the stimulation frequency at which the muscle is activated, a force-frequency relationship can be determined (2,10,16).

In an isovelocitity test, the motor moves the joint at a constant angular velocity determined by the control system. The movements can either be concentric (shortening of the muscle) (3,17), eccentric (lengthening of the muscle) (8,15), or a combination of both (13). By changing the velocity of movement, a velocity-force relationship (4) can be determined.

For the isotonic tests the motor must regulate the motion to force the muscle to exert a constant torque. In order for this to occur, the control system must monitor the varying force produced by the stimulated muscle, and either increase or decrease the velocity of the motor to achieve the desired constant force. If the force produced by the stimulated muscle is below the desired force, then the velocity of the motor is linearly decreased, whereas if the force produced by the stimulated muscle is above the constant force, then the speed of the motor is linearly increased. This is due to the fact that the relationship between force and velocity has been found to be linear (13).

Isometric tests, isovelocity tests, and isotonic tests have all been performed on humans to study muscle response (7,8,13). However, the testing of muscle response on humans has several drawbacks. It requires large equipment and is expensive due to the size of equipment and use of human subjects. Repeated muscle injuries cannot be produced and the injured muscles cannot be removed after testing to study the muscle tissue morphology and biochemistry.

To continue testing without the drawbacks involved in human testing scientists use animals. Ashton-Miller developed the first device to study muscle response in intact animals' (1). The dynamometer was able to indirectly study how stimulation and velocity altered the force of muscles in mice. A device to measure the response of rat plantar flexor muscles to stimulation and velocity was constructed by Cutlip (5). However, neither of these machines could perform isotonic testing. Isotonic testing has been studied in humans but not in animals (13). A device with the ability to perform isotonic testing would allow researchers to study how an applied constant force alters

muscle response in animals. Therefore, a new device must be designed that can perform isotonic testing as well as isovelocitv and isometric testing.

1.2 Objectives

The objective of this research is to design a computer-controlled dynamometer to study muscle response in male and female rats. The dynamometer has to meet the following requirements:

- Wide range of velocities (i.e. isovelocitv testing), $15^{\circ}/s$ to $2000^{\circ}/s$
- Fast accelerations, $1600\text{rad}/s^2$
- Quick ramp time to maximum velocity, 0.0225s
- 110° range of movement
- Accurate positioning to 1°
- 0-120N force range
- 10.75"x7.25"x1/4" bed for male and female rats
- Hard and soft stops and limits
- User friendly interface

Along with these requirements the dynamometer must be able to perform isotonic testing as well as isometric and isovelocitv tests. It must also be able to run modified versions of these tests to allow more flexibility in testing. Finally the dynamometer must employ a form of software that will not be obsolete in the near future so that future researchers and engineers can continue to use and modify it.

Chapter 2 - Literature Review

2.1 Force Generation in Muscles

Muscles can exist in either a passive or active state. In the passive state no stimulation acts on the muscle. When stimulation is applied to the muscle, either from a mechanical device in the lab or motor neuron axons in the body, an electrical pulse is transmitted to the muscle fibers causing them to contract and become active. The degree of muscle contraction depends on the frequency and magnitude of stimulation.

As the magnitude, or voltage, of stimulation increases, the number of muscle fibers activated increases causing contractions to occur with greater force. A voltage that produces the first observable muscle twitch is the threshold stimulus. In some experiments, threshold stimulus is used to determine accurate positioning of electrodes (18). The voltage that activates all the muscle fibers is called the maximal stimulus. Once the maximal stimulus is reached any further increase in voltage will not produce an increase in contraction force since all the muscle fibers are already activated. The maximal stimulus is used in experimentation to study the force-frequency relationship in muscles (16).

While the magnitude, or voltage, of stimulation controls the number of muscle fibers activated, the frequency of stimulation controls how often the fibers are activated. Low frequencies create a muscle twitch. As the frequency is increased the twitches occur closer together and a wave summation occurs due to the fact that new contractions are induced before the muscle has had time to relax from preceding contractions. If the stimulus is delivered with a great enough frequency, the muscle experiences no relaxation

and a smooth sustained contraction termed tetanus occurs. The following figure demonstrates wave summation due to increasing frequency of stimulation.

Figure 2 – Wave Summation Due to Increased Frequency of Stimulation (19)

Most experiments use constant frequency trains that are pulses of single frequency stimulation separated by regular intervals of time (16, 21, 22). However, the actual production of stimulation in the body does not occur at regular intervals. Rather the motor neuron varies its firing of electrical impulses to include brief, high frequency bursts (2). Therefore “catch-like” trains with initial high frequency stimulation preceding subsequent constant frequency stimulation have been used in experimentation to more accurately model stimulation production in the muscle. The experimentation done with catch-like trains show that they produce greater peak forces in muscles than constant frequency trains (2, 20).

2.2 Mechanical Properties of Muscles

Once a muscle has been stimulated its subsequent production of force causes a vector moment, or torque about the joint to which it is attached. The moment is the cross product of the vector force produced by the muscle and the distance between the joint and the point where the force is applied.

The actual movement of the muscle depends not only on the force it is generating but also on any resistance force applied to it. Depending on the magnitude of the resistance force the movement is either isotonic or isometric. In an isometric contraction the force resisting the muscle movement is equal to the force supplied by the muscle, therefore the muscles length remains constant and tension is developed. In an isotonic contraction the tension in the muscle remains constant while the muscle length changes. If the force supplied by the muscle is greater than the resistance force, then the muscle shortens and contracts concentrically. However if the force supplied by the muscle is less than the resistance force then the muscle lengthens and contracts eccentrically (19). Numerous experiments have been done to show that eccentric contractions produce greater muscle damage than concentric or isometric contractions (10, 15, 22). Tests done in-situ on mice found that eccentric contractions, but not isometric or concentric contractions resulted in injury to skeletal muscle fibers (10). In-vitro tests on rats found that the degree of muscle injury resulting from eccentric contractions is a result of the peak force produced by the muscle during the contraction (15).

2.3 Experimental Models

Experiments to study muscle injury can be performed in three different ways: in vitro, in situ, or in vivo. In vitro tests are performed in an artificial environment instead of in the living organism. To study muscle injury in vitro, the muscle is completely removed from the body and placed in a physiologic bath where it is tested. In situ tests are performed in their natural environment. For muscle injury tests this means the muscle remains in the body where it is tested. However, an incision is made into the living organism to expose the nerve and tendon. In vivo tests are performed completely within a living organism. The muscle, tendon, and nerve all remain inside the living organism making in vivo testing a non-invasive technique. In vitro, in situ, and in vivo testing has been performed on animals while humans are tested in vivo due to its non-invasive nature. An in depth review of the three different testing techniques along with their advantages and disadvantages is presented in order to gain an understanding of what has been learned about muscle injury and what still needs to be studied.

2.3.1 In vitro Studies

For in vitro studies the muscle being studied is completely removed from the animal and placed in a buffering solution that simulates the natural environment of the muscle and provides it with nutrients. Figure 3 shows a thermopile muscle chamber device developed by Fenn to determine the heat liberated by frog sartorius muscle (23).

Figure 3 – Fenn thermopile and muscle chamber (23)

The muscle chamber consisted of a test tube, rubber stopper, and glass tubing. A thermopile was run through the muscle chamber and connected to a galvanometer to record the deflection produced when the muscle was stimulated and allowed to contract. Fenn found that the heat produced when a muscle is stimulated depends not only on the number of fibres stimulated but also on the amount the muscle shortens and the tension developed in the muscle during shortening (23). Furthermore, when the muscle was attached to the lever device shown in figure 4 it was determined that shortening or lengthening the muscle during contraction varied the amount of heat liberated by the muscle (24).

Figure 4 – Fenn Muscle Lever (24)

When the muscle was shortened during contraction it released more heat than was released during an isometric contract. However, when the muscle was lengthened during contraction it released less heat than during an isometric contraction. In terms of work done this means that the excess energy from a shortening contraction is equal to positive work done while the surplus energy during a lengthening contraction is equal to negative work done.

Many experiments have been done in vitro to determine the mechanical factors that cause muscle injury. Warren studied the effects of peak eccentric contraction force, initial muscle length, muscle length change, and lengthening velocity on rat soleus muscle during eccentric contraction-induced injury (15). To perform the studies the

soleus muscle from an untrained female Sprague-Dawley rat was placed in a 7ml-glass chamber containing buffering solution. One end of the muscle was attached with a silk suture to a stainless steel support while the other end was attached with a silk suture to the lever arm of a position feedback servomotor. The muscle was stimulated by a Grass S48 stimulator and an SIU5 isolation unit and the length and force outputs from the muscle were sampled by a Metrabyte DAS-16 interface board and computer. Warren found that increased peak force caused the greatest amount of injury during eccentric contractions. Furthermore he determined that peak force alone was the cause of the initiation of eccentric contraction muscle injury (15). This seems to demonstrate that a few high force eccentric contractions can cause initial muscle injury.

Edman studied how the magnitude of the force produced by a muscle depended on the velocity at which the muscle was stretched (25). The tests were conducted on single-fibres from the semitendinosus muscle of the common frog. The fibres were placed in a buffering solution with one end attached to a RCA 5734 machine-electric tension transducer and the other end attached to a lever arm connected to an electromagnetic puller as shown in figure 5.

Figure 5 – Edman Apparatus (25)

The fibre was stimulated and stretched during which time the tension and length change in the fibre were displayed on a Tetronix 5103N storage oscilloscope. The results showed that the faster the fibre was stretched the greater was its recorded force output. Edman concluded that the magnitude of force during stretch depends on the velocity at which the stress takes place (25).

A study done by Lynch, however, found that at a constant strain, the velocity of the stretch has no impact on the force generated during stretch (26). The EDL muscles of adult male Fischer 344 rats were divided into their individual fibres, which were placed in a bath containing an activation solution. One end of the fibre was tied to a fixed post attached to a force transducer while the other end was tied to the lever arm of a

servomotor. The displacement of the lever arm and force produced in the muscle were controlled and recorded by a computer utilizing ASYST software. The fibre was subjected to isometric and isovelocity stretches at 5, 10, and 20 percent length of the muscle strain. It was found that varying the velocity of the stretch had no effect on the force deficit, peak force, or work input. Therefore Lynch concluded that force, strain, and the work done to stretch the muscle fibre were the mechanical factors that initiated injury in muscles while the velocity of the stretch has no effect (26).

As previously found by both Warren (15) and Lynch (26) one of the main factors in initiating muscle injury is the peak force produced in a muscle during eccentric contractions. Warren went on to determine whether muscle injury was the result of a single high force contraction or the result of a repetition of eccentric contractions (27). The soleus muscle of female Fischer rats was placed in a 7.5mL chamber containing buffering solution. One end of the muscle was attached to a stainless steel support while the other end was attached to the lever arm of a position feedback servomotor. Length and force were measured using a computer and Laboratory Technologies Notebook. The muscle was then stimulated by a Grass S48 Stimulator to perform isometric and eccentric contractions. It was found that after 8 eccentric contractions a 40 percent force deficit began to occur while before 8 eccentric contractions the force remained fairly constant. This leads to the conclusion that muscle injury is the result of a repetition of eccentric contractions. However, it must be noted that this experiment was done within the anatomical stretch limits of the muscle. Warren also discovered that after injuring the muscle there was no recovery of peak force after 60 minutes. This indicates that repeated

eccentric contractions cause structural damage that cannot be repaired in the short-term (27).

Hubbard also studied the loss of force after repeated contractions (28). The tendons from the hind legs of canines were submerged in a bath and gripped between flat gripping surfaces covered with waterproof silicon carbide abrasive paper. An Instron testing machine was then used to stretch the tendons. The deformation was measured with an LVDT while the load transmitted through the tendon was measured with an Interface 100lb load cell. The data was collected and processed by an 11/23 microcomputer. A peak strain of 2 percent was applied to the tendon for 1800s followed by a rest period of 1800s. This cycle was repeated twice for three repetitions of strain followed by rest. The experiment was performed again at 3, 4, and 6 percent strain. It was found that after each rest period a very small amount of recovery took place that was immediately lost in the next strain period. Like Warren (27), Hubbard concluded that the restorative effects of the wait periods were transient compared to the damaging effects of repeated stretches (28).

While many of the previous studies were performed on whole muscles (15, 23, 24, 27, 28) others were performed on single muscle fibres (25, 26). While the results from both single fibres and whole muscles support the theory that force is the major mechanical cause of initial muscle injury (15, 26) a study done by Claflin indicates that tests done on single fibres and whole muscles do not always have the same results (4). The tests were performed on whole soleus muscles of female rats. One end of the muscle was tied to a force transducer while the other end was tied to the lever arm of a feed-back servomotor. The shortening load at zero velocity ($V_{\max}$) was determined by performing

isotonic releases at thirteen different loads and then extrapolating to zero load. A second velocity (V_0) was determined by performing a slack test. The slack test was carried out by applying a series of step releases of varying amplitudes to a fully activated muscle. The time it takes the muscle to shorten and take up the slack is then measured. From the relationship between the time it takes the muscle to shorten and the amplitude of the release, V_0 can be calculated (4). Edman (29) found that in single muscle fibres V_0 and $V_{\max}$ are the same. However Claflin found that in whole muscles V_0 is greater than $V_{\max}$ (4). The reason for the discrepancy between V_0 and $V_{\max}$ was found to be due to the diversity in the shortening velocities of the individual fibres in a muscle. Very few of the motor units had very fast contraction times of 15ms while the majority of the fibres had contraction times of 18-20ms. The majority of the fibres slowed down the response of the whole muscle making $V_{\max}$ less than V_0 (3).

Macpherson performed isovelocities and isometric stretches on single fibres of rat soleus muscle to study sarcomere length. A linearly polarized diode laser was used to transilluminate the muscle fibre under study as shown in figure 6.

Figure 6 – Macpherson Laser Device

The fibre was fixed between a capacitance-force transducer and the lever arm of a servomotor. As the fibre was stretched the laser beam was deflected off prisms and through the fibre beyond which it was detected by a 2038 element photodiode array, collected by a photodiode array controller, and analyzed using a microcomputer running CSMA software. From the diffraction pattern produced by the laser the length of the sarcomeres was determined. It was seen that when long sarcomeres were in series with short sarcomeres the long sarcomeres were excessively stretched causing a loss in force production.

From the previous studies it can be seen that in vitro testing has been used to study the mechanical properties of both whole muscles and single muscle fibres. The

main advantage in vitro testing has over in situ or in vivo testing is its ability to study the physical changes taking place in a muscle while they occur. However, it also has several disadvantages. The removal of the muscle from the animal must be done carefully as to not damage it. Also once the muscle is removed, it is cut off from its normal environment and nutrient supply. Therefore it must be properly maintained at a certain temperature and provided with the necessary nutrients to keep it functional. This limits the amount of time in which the test can be conducted. Finally since in vitro testing is performed outside the body it does not take into account the physiological factors that the body may contribute to the muscle.

2.3.2 In-Situ Studies

In-situ testing is able to take these factors into effect since the muscle under study remains connected to its neural and vascular supply. For in-situ testing an incision is made to expose the muscle under study. One end of the muscle is then disconnected from the body and attached to a measuring device while the other end of the muscle remains intact. An example of the setup is shown in figure 7.

Figure 7 – In-Situ Setup (31)

The previous setup was used in an experiment to study the properties of stretching in the extensor digitorum longus muscle-tendon units of New Zealand white rabbits (31). An Instron testing machine was used to stretch the muscle to predetermined lengths and strains while an Instron Servo hydraulic Materials Testing System was used to stretch the muscle at predetermined velocities. The study determined that stretching muscles cause them to elongate. Further it found that the greatest change in length occurs in the first four stretches during which there is a 16 percent force deficit. The study also concluded that increased rates of velocity were likely to produce greater muscle injury.

Like in vitro studies done by Warren (15) and Faulkner (22) a study by McCully found that eccentric or lengthening contractions cause more significant amounts of injury to muscles than isometric or concentric contractions (10). One day after eccentric testing many fibres in the muscle under study showed abnormalities while the fibres in the muscles subjected to isometric and concentric contractions showed no abnormalities. Lieber made similar conclusions and also found that the abnormal fibres had larger cross sections and more disorganization in their sarcomeric band pattern (32). Benz studied the

force change that occurs during an eccentric contraction (33). The soleus muscle of an adult male New Zealand White rabbit was attached to the motor arm of a servomotor to perform eccentric and isometric contractions. The peak isometric force, stiffness, and peak eccentric force produced in the muscle were measured using Mathematica Software Package. The studies found that the peak force produced during an eccentric contraction was twice the peak force produced during an isometric contraction. However the eccentric contraction caused a force deficit 30% greater than the isometric force deficit supporting the theory that eccentric contractions cause greater damage than isometric contractions (33).

While it is well supported that isometric, concentric, and eccentric contractions can produce muscle injury; the mechanical factors that affect the degree of injury are unclear. Herzog studied the effects of length of shortening and speed of shortening during concentric contractions (34). He found that as the length the muscle had to shorten increased, the force produced by the muscle decreased and as the speed at which the muscle shortened decreased, the force it was able to produce increased indicating that both muscle length and velocity affect the force output of muscles. When studying eccentric contractions McCully found that duration of muscle stimulation also affects the force output of muscle (35). As the length of time during which the muscle was stimulated to contract increased, the loss of force also increased. There was a 50 percent loss in peak force during the first 5 minutes of the contraction. After 5 minutes there was no further loss of force indicating that fatigue prevented any further injury.

Another mechanical factor affecting force loss is strain, which is defined as the relative muscle length change (33). A test done by Nikolaou subjected the tibialis

anterior muscle of a New Zealand White rabbit to a predetermined strain (36). After the muscle was strained it was returned to its original length and stimulated to contract. It was found that the strain caused an immediate force reduction of 29.5 percent that increased to 48.9 percent after 24 hours. Brooks determined that for passive stretches a strain of 50 percent or greater was required to produce a loss in force while active stretches only required a strain of 30 percent to produce a loss in force indicating that greater injury occurs during active stretching (37). However, when the peak force produced by the muscle during the stretch was studied it was seen that for passive stretches, the force of the muscle was less than the maximum isometric force while the peak stretch force output of active muscles was 2 to 3 times greater than the maximum isometric force. Thus, when injury occurs in passive muscles, it is at large strains and low forces while in active muscles the injury occurs at small strains and high forces. Therefore the combination of high loads and large strains produce the greatest injury. This observation is significant as these conditions often occur during accidental falls or sudden moves.

Hunter also studied the effects of strain and force along with initial length on muscle injury (39). Isometric and lengthening contractions were performed on the extensor digitorum longus muscle of adult male mice. The amount the muscles were stretched and the force output during the contraction were measured. By integrating the area under the force curve measured, the average force was calculated. The average force was then multiplied by the amount of stretch to calculate the work input during the stretch. The results of the experiment found that work input combined with initial muscle length determine the amount of muscle injury.

While Brooks and Hunter found that both strain and force affected muscle injury (37), Lieber theorized that it was strain alone that affected the degree of muscle injury (38). Using the tibialis anterior muscle of a New Zealand White rabbit attached to a dual mode servomotor a series of eccentric contractions was performed to study the effects of force and strain on muscle injury. The results showed that varying the force did not change the degree of injury, however, varying the strain did.

While in-situ studies have an advantage over in-vitro studies in that they provide the muscle being studied with a normal neural and vascular supply from the body, they also have disadvantages. While the muscle is still connected to the body it is removed from the body and must be provided with a fluid to keep it moist. Several different methods have been used to do this. McCully (10) used a 0.9% NaCl solution to periodically moisten the muscle under study while Brooks (37) and Hunter (39) periodically bathed them in isotonic saline solution. However this does not completely imitate the natural environment of the muscle.

A second major disadvantage to in-situ models is the fact that one end of the muscle must be dissected. It is possible that during dissecting and handling of the muscle damage occurs to render the results inaccurate.

2.3.3 In-Vivo Animal Studies

In vivo studies are performed with the muscle completely attached to the body in its normal environment. Therefore the muscle incurs no damage prior to testing due to dissection. Also since the muscle remains intact in the body, no external nutrients need to be provided to it. This allows the muscle to be studied in its natural environment where

it can interact with the other physiological functions of the body. One other major advantage of in vivo testing is that the animal and muscle under study can be used for multiple tests over an extended period of time to study the chronic effects of muscle injury.

2.3.3.1 Treadmills

Several different forms of in vivo testing have been performed. Many in vivo tests to study the properties of muscles have been performed on treadmills. Walmsley studied the forces produced by the medial gastrocnemius and soleus muscles in cats' (40). Force transducers and EMG electrodes were implanted onto the tendons of the medial gastrocnemius and soleus muscles in the hind legs of the cats. The force transducers operated by using a DC Wheatstone bridge arrangement to measure the strain developed in the stainless steel substrate attached to the tendon. The cats were trained to walk and run on a treadmill as well as jump. As the cats performed these tasks the force from the transducer as well as the EMG data was recorded. From the data it was seen that the force production in different muscle groups varies based on the action they are performing. The force produced by the soleus muscles remained fairly constant during walking and running and was also constant during standing. However the medial gastrocnemius muscles produced a varying force during running and walking, a small force during standing, and a large force during jumping (40).

Gruner also studied the properties of muscles using a treadmill and EMG implants (9). However his study focused on studying the difference in locomotor patterns of normal and irradiated rats and developing a description of their stepping patterns. The EMG implants were placed in the muscles under study and connected to a Grass 7P511

EMP preamplifier that recorded the differential EMG's on paper. Both the normal and irradiated rats were trained to walk on a treadmill during which time their movements were recorded by a camera and synchronized with the EMG's on paper. Gruner found that the irradiated rats tended to walk with their backs arched, body close to the ground, and hindlimbs spread wide. The irradiated rats also tended to lose their balance during walking, standing, and rearing. However if they were forced to walk between two walls supporting them on either side they were able to maintain their balance and walk normally. They were also able to swim and scratch normally. Gruner also found that normal and irradiated rats had a stepping posture that was more crouched and lower to the ground than cats or dogs and their spines would bow side-to-side during stepping (9).

Gregor studied the mechanical output of cat soleus muscles in vivo on treadmills and compared it to in situ results (43). The results indicated that it took less time in vivo to reach the peak force and that the peak force generated in vivo was greater than that generated in situ.

Treadmills have also been used to study how walking on an incline affects the forces and injury produced in muscles. Armstrong studied the effects of rats running on a treadmill at 0° , 16° , and -16° incline (41). The 0° incline imitated normal walking with concentric and eccentric contractions. The concentric contractions are performed to accelerate the animal's center of mass to its highest point in the step while eccentric contractions are performed to decelerate the animal's center of mass as the animal reaches its lowest point in the step. A 16° incline imitated uphill walking involving mainly concentric contractions, while the -16° incline imitated downhill walking involving mainly eccentric contractions. Armstrong found that after downhill and uphill

running there was an appearance of inflammatory cells indicating muscle injury while muscles subjected to level running showed no signs of injury. Furthermore the level of injury in the uphill runners was the same as in the downhill runners indicating that concentric contractions during running cause the same amount of damage as eccentric contractions (41). Komulainen also studied the effects of inclines on muscle injury and found that uphill running injured the soleus muscle, while downhill running injured the red parts of the quadriceps femoris muscle and the white parts of the vastus lateralis muscle (42).

Roberts also used a treadmill and incline to study the mechanics of muscles in turkeys' (11). Sonomicrometer crystals and strain gages were implanted in the lateral gastocnemius muscles of turkeys to measure the force produced and the length change in the muscles. The turkeys were then trained to run on a 0° and 12° incline at 3m/s. Most of the force was produced when the animal had to both support its weight and lift its body off the ground to step. When the turkeys ran on the incline the force required to support the turkeys weight did not change, however the work required to step increased proportionally to the incline (11).

The previous studies showed that treadmills could be used to study the effects of inclines on the mechanics of muscles and the forces they produce. However treadmills have several disadvantages. While the treadmill can be operated at a certain speed it is difficult to study the effects of constant velocity since the animal will run at its own pace. Also the effects of individual parameters such as stimulation, velocity, force, and muscle length can not be directly studied. Therefore dynamometers are also used in vivo to study muscle response and injury.

2.3.3.2 Dynamometers

Ashton-Miller developed one of the first dynamometers to study the mechanical properties of dorsiflexor and plantiflexor muscles in the ankles of mice (1). For their device a mouse was placed on its side and its foot was placed in a “shoe” that was attached to a strain gage torque transducer shown in figure 8.

Figure 8 – Ashton-Miller Device and “Shoe” (1)

The torque cell consisted of two pairs of strain gages that were mounted opposite each other on the cylindrical torque transducer to measure the moment produced by the mouse’s ankle during testing. The cylindrical torque transducer was then attached to a

shaft that led to an Aerotech servomotor. The servomotor had a peak torque of 1.84N-m and a continuous torque of 0.25N-m. It was able to accelerate at $48,000 \text{ rad/s}^2$ to a maximum velocity of 4,800rpm. The muscles under study were stimulated using platinum electrodes connected to a Grass Instruments stimulator. Software was written in C++ to control both the stimulator and the motor. The device was able to perform isometric and isovelocit y shortening and lengthening tests through a range of 105° . To determine the viability of their machine in vivo, in situ tests were performed and their results were compared. For isometric tests the force produced in vivo by the dorsiflexor muscles was within 8% of the force produced in situ. The force produced by the plantarflexor muscles was within 11% of the force produced in situ. For lengthening contractions of the dorsiflexor and plantiflexor muscles at constant velocity the in vivo values were within 10% of the in situ values. During isovelocit y shortening the results for the dorsi and plantar flexor muscles in vivo were also similar to the in situ values. This led Ashton-Miller to conclude that their device was reasonable for measuring the mechanical properties of dorsi and plantar flexor muscles in vivo.

While the Ashton-Miller device is suitable for studying muscle properties in vivo it does not measure the force produced by the muscles under study directly. Rather it measures the moment produced by the ankle and divides it by the appropriate muscle lever arm. Cutlip developed a device to directly measure the force produced by the muscles. The dynamometer was designed to control angular velocity, range of motion, electrical stimulation, and number of repetitions while recording the resultant force output of the muscles under study (5). A 3-D view of Cutlip's dynamometer is shown in figure 9.

Figure 9 – Cutlip's Dynamometer (5)

The dynamometer employed an Aerotech DC servomotor with a peak torque of 14.1N-m and a continuous torque of 2.89N-m. The maximum acceleration was $11,000\text{rad/s}^2$ and the maximum velocity was 2750rpm. The motor had an internal DC tachometer to measure angular velocity. A Maurey precision potentiometer was attached to the drive shaft to measure the angular position of the shaft during testing and a piezoelectric load cell was used to measure the force output of the muscles. The load cell was placed underneath the heel of the rat in a foot holder shown in figure 10.

Figure 10 – Cutlip's Footholder (5)

The rat's foot was placed in the foot holder on top of a 20g rectangular plate. When the rat's foot pushed on the plate it in turn transferred the resultant force vertically to the load cell to be recorded. Software was written in Quick Basic to perform isometric, isovelocity, and controlled non-isokinetic moves involving jerk. Along with performing the desired moves the software also allowed the tester to record the force, velocity, and position during testing. The software was also able to control stimulation by using a signal digital line to turn on or off a Grass Stimulator.

Cutlip's dynamometer was used to perform several tests determining what factors affect injury in the plantarflexor muscles of rats. Experiments were performed on the plantarflexor muscles of female Sprague-Dawley rats to determine what the effect of velocity of ankle rotation was on force output (45). The stretches were performed at a slow speed of 0.87 rad/s and a fast speed of 10.47 rad/s. The results showed that while the force output increased with each contraction number the increase was not velocity sensitive. However the relative relaxation following the stretches was velocity sensitive. The faster stretches had a greater relative relaxation than the slower stretches.

Willems also studied the relationship between force and ankle position during isometric and pre-loaded slow concentric contractions (17). The results showed that during isometric contractions the ankle position had little effect on the force output. However during slow concentric contractions the ankle position did affect the force output. The force decreased linearly as the ankle position decreased. There was also a 23% force loss during the slow concentric contractions while the force loss during the isometric contractions was much lower.

The effects of age (46) and gender (16) on force loss were also studied. While gender was determined to play no role in force loss (16), age was a factor. Rats that were 20 months older than young rats had a 18% decrease in isometric force following a lengthening stretch of 50° at a velocity of $50^\circ/\text{s}$ (46).

Finally the effect of stretching was studied. When tetanus toxin is injected into muscles, it causes the alpha motor neurons to fire continuously. If the muscles are held in a fixed shortened position while this occurs they will become anatomically shorter over time. For this experiment the muscles were held in both a shortened and lengthened position for 1-week (47). The muscles were then subjected to a preloaded isovelocity move. The results showed that muscles held in the lengthened position had less force loss than muscles held in the shortened position and that muscle held in the shortened position were more subject to acute strain injury. This finding is significant since it indicates that repeated stretches could help prevent acute strain injury.

Like tests done in vitro (15) and in situ (10, 33) tests have been performed in vivo to study the effect of eccentric injury in relation to isometric and concentric injury. A

study by Faulkner found that, after concentric contractions of the extensor digitorum longus muscles and anterior tibial muscles of mice, there was a 25 percent decrease in peak isometric force that recovered after 3 days (22). However following eccentric contractions, there was a peak isometric force loss of 48-60% that took 30 days to recover. Lieber performed similar tests on the ankle flexor muscles of rabbits and found that after isometric and eccentric contractions there was a torque loss (18). However at the end of 2 days the torque loss was recovered for the isometric subjects while the eccentric subjects had further torque loss. Willems studied the effects of repeated isometric and eccentric contractions and found that while both repeated isometric and eccentric contractions resulted in force loss the force loss following eccentric contractions is much greater than that following isometric contractions (48).

While dynamometers have been used to study many properties including the effects of velocity (1, 45), position (17), and stimulation (16, 22) on muscle mechanics in animals, they have not to date been able to study the effect of a constant force applied to the muscle during movement.

Another major drawback to in vivo testing done on dynamometers is the use of anesthetics. Anesthetics introduce a variable into testing that could affect the performance of the muscles under study. Therefore a study was done by Ingalls to determine the effects of four commonly used anesthetics (49). The four anesthetics used were fentanyl-droperidol and diazepam (F-d/d), ketamine and xylazine (K/x), pentobarbital sodium (Ps), and methoxyflurane (Mf). To study the effects of the four anesthetics, isometric, concentric, and eccentric contractions were performed on mice using a device similar to that designed by Ashton-Miller (1). The effects of the

anesthetic on the peak torque, work done, average power output, induction and recovery times, and ventilation rates were analyzed. It was found that fentanyl-droperidol and diazepam (F-d/d) had a slow but gradual induction rate along with a fast recovery and good contractile performance. Ketamine and xylazine (K/x) had fast induction rates, but a long recovery and depressed contractile response. Pentobarbital sodium (Ps) also had a long recovery time along with decreased contractile functions during isovelocity testing and easy overdosing. Finally methoxyflurane (Mf) had both fast induction and recovery times along with high peak torques. However since methoxyflurane is an inhalant not an injection, a flow meter and chamber must be used to deliver the anesthetic to the animal under study. Even so Ingalls determined that the best anesthetics to use were methoxyflurane and fentanyl-droperidol and diazepam (49).

2.3.4 In-Vivo Human Studies

While testing done in-vitro, in-situ, and in-vivo on animals has advanced our knowledge of the properties that cause muscle injury in animals, it is also necessary to directly study these properties in humans. The majority of the human muscle injury testing is done in-vivo due to its non-invasive nature. Like tests done in-vivo on animals the tests done in-vivo on humans are usually performed on treadmills or dynamometers.

2.3.4.1 Treadmills

Newham studied how walking uphill and downhill on a treadmill altered creatine kinase levels in the blood of humans (67). The treadmill was inclined at 13° and subjects walked either up or down it for 1 hour. The uphill walking produced mainly concentric contractions while the downhill walking produced mainly eccentric

contractions. It must be noted that while the subjects walked in the forward direction up the treadmill, they walked in a backward direction down the treadmill. This method was chosen as it produced the most muscle lengthening. Newham found that uphill walking required more effort than downhill walking but did not produce as much soreness as downhill walking. Immediately after downhill walking the subjects had difficulty standing on their toes due to tremors in their muscles. Several hours after the downhill exercise subjects developed pain and tenderness in their calf muscles. After uphill walking creatine kinase levels (an indicator of muscle injury) only rose slightly by 200IU/liter. However after downhill walking the rise in creatine kinase levels was 15,000IU/liter which was significantly larger. From this study, Newham concluded that eccentric contractions were the cause of the increase in creatine kinase levels in the blood.

A similar test was performed by Jones in which two subjects walked backwards down an inclined treadmill (68). After the test both subjects encountered tremor in their calf muscles and the inability to stand on one leg with its heel raised off the floor. They also developed pain in their calf muscles in the days following the test. Like Newham (67), Jones studied the creatine kinase levels and found them to be maximum 4 to 6 days after the test. Jones also studied the biopsies of the calf muscles and found that within the first seven days following the eccentric exercise no change was seen in the muscle. However, after seven days degenerating fibres were seen in the muscle, which regenerated after 20 days.

Jones also studied the effects of eccentric contractions in human biceps muscles (68). A cuff was placed on the wrist of the subject. The cuff was then attached to a

pulley, which forcibly extended the forearm. The subject then contracted his forearm muscles once a minute for 20 minutes. The subjects developed pain and tenderness in their forearms 24-48 hours after testing with peak creatine kinase levels 4 to 6 days after testing.

Tests done by Clarkson studied creatine kinase levels in the forearms following isometric exercises (69). The tests were designed to study the effects of rest intervals between isometric contractions. The tests consisted of forty 10 second long isometric contractions separated by variable rests. The first group of subjects performed the tests with 20-second rests while the second group of subjects performed them with 5-second rests. Clarkson found that the first group was able to maintain a greater tension than the second group during the tests. It was also found that the first group had higher levels of creatine kinase than the second group following the exercise. This high level was attributed to increased disruption of muscle cells due to the increased tension maintained in the first group.

The previous studies have shown that treadmills can be used to produce concentric or eccentric muscle injury in humans. The soreness and creatine kinase levels can then be studied to determine the effects of concentric and eccentric muscle injury. However the causes of muscle injury such as velocity, acceleration, force, and muscle length cannot be studied on treadmills. Therefore tests are performed on dynamometers.

2.3.4.2 Dynamometers

Stauber studied power and fatigue in knee extensor muscles using a Dynatrac dynamometer. Female subjects were seated in the dynamometer with their left leg

aligned securely with the lever arm of the dynamometer. Their lower leg was then strapped firmly to the lever arm pad. The subjects were then told to move as quickly as possible during the concentric power tests. These tests were performed at four different isotonic loads of 40.6, 54.2, 67.8, and 81.3N/m. The subjects performed three concentric movements at each constant load during which the velocity and torque were measured. From the data it was seen that the torque-velocity relationship was linear. For the fatigue test, both concentric and eccentric contractions were performed at a constant load of 33.9N/m. A concentric and eccentric contraction were performed in succession 15 times to constitute one bout. The subject then rested for 15 seconds and performed two more bouts. From the fatigue results, it was seen that as more bouts were performed the range of motion and speed of movement of the subject decreased.

Gransberg used two Kin-Com hydraulic dynamometers to study the effects of acceleration during high-speed isokinetic testing (8). The subjects were divided into two groups with half testing on the Kin-Com II and the other half on the Kin-Com 500H. The subjects were seated in the dynamometer with their right leg aligned securely with the lever arm of the dynamometer. Their lower leg was then strapped firmly to the lever arm pad. The subjects were instructed to move their leg as quickly as possible with the lever arm during the concentric test and as quickly as possible against the lever arm during the eccentric test. The concentric and eccentric tests were performed in succession with the concentric test first followed by a five-second break and the eccentric test. This cycle was performed three times with 60-second breaks in between each test. The range of motion for each test was held constant with the concentric test going from 90° to 20° and the eccentric test going from 20° to 90°. The velocity was also kept constant at 180°/s for

the subjects using the Kin-Com II and 240°/s for the subjects using the Kin-Com 500H. The acceleration rates tested were “medium”, “high”, “high++”, and “medium” again. Gransberg found that for the concentric tests as the acceleration rate increased the torque at which the subjects were able to move decreased. For the eccentric tests a phenomenon Gransberg termed torque overshoot occurred. As the lever arm began to move the subjects resisted the movement creating a torque against the lever arm that was termed overshoot. As the rate of acceleration increased the torque overshoot increased. Gransberg concluded that the rate of acceleration does affect the measurements taken during high speed isokinetic testing and that the optimum rate of acceleration was “medium”.

The effects of stimulation have also been studied. While most tests use constant frequency trains, a study done by Binder-MacLeod compared the effects of constant frequency trains to catchlike-trains (2). The subjects performed isometric contractions using both constant frequency and catch-like trains of stimulation. Binder-MacLeod found that catch-like trains produced greater peak forces than constant frequency trains. A study by Lee then went on to find that as the interpulse level between the catch-like trains was increased the subsequent force output also increased (20). Lee also found that less fatigue occurred at shorter muscle lengths than longer muscle lengths. The resulting advantage to catch-like trains is that they can produce a force output of equal magnitude to a constant frequency train only at a lower frequency.

Chapter 3 - Design of Dynamometer

3.1 Introduction

The objective of this research was to design a computer-controlled dynamometer to study muscle response in male and female rats. The dynamometer was required to perform isometric, isovelocitv, and isotonic testing. For each test type, the velocity, acceleration, position, and force output from the rat's foot must be measured and saved for later analysis of muscle response. The dynamometer control program also must turn on and off the electronic muscle stimulator by applying a signal voltage. The overall mechanical design of the dynamometer was required to accommodate both male and female rats and to allow accurate positioning for testing. In order to achieve these objectives the following components were selected for the design of the dynamometer:

- Personal computer for control, data storage, and analysis
- National Instruments 7344 Motion Control Card
- LabVIEW 6.0 software as the core component of the data acquisition and display functions. Custom elements were written to specialize the LabVIEW functions.
- UMI-7764 breakout box to provide an interface between the sensors and National Instruments hardware.
- Aerotech BMS60 motor as the primary actuator for position, force, and speed control.
- Sensotec load cell for the force feedback sensor
- Grass Stimulator to provide stimulus for muscle contraction

The complete dynamometer setup consisted of the personal computer, PCI-7344 motion control card, UMI-7764 breakout box, BA Sinedrive, BMS 60 servomotor, gearbox, load cell, load cell signal conditioner, stimulator, positioning device, limit switch, and main platform as shown in the following figure. A complete description of wiring is given in Appendix B 2.

Figure 11 – Overall Setup

A description of each of these components along with the reasoning for its selection will be given in the following sections. The overall mechanical setup of the dynamometer will then be discussed along with a description of the control programs written to run the isometric, isovelocit, and isotonic tests.

3.2.1 Motor

The foot holder was required to operate at velocities between 0-2000°/s and to accelerate from a position of 0° to 22.5° in 0.0225s. As shown in Appendix A 1.1, this required an acceleration of 1600rad/s². The motor was also required to have enough torque to overcome both the torque generated by a large male rat and the inertia of the dynamometer. Since large male rats could generate a force of up to 120N, the torque generated by the rat's foot about the dynamometer shaft was found to be 1.34N-m as shown in Appendix A 1.2.

Based on these calculations a BMS60 brushless motor was chosen from Aerotech (52). The BMS60 has a peak torque of 1.68N-m and a continuous torque of 0.42N-m. It also has a maximum speed of 60,000°/s, a maximum acceleration of 85,000rad/s², and an encoder resolution of 8000 lines per revolution. The BMS60 motor was chosen over a DC brush motor due to the fact that it provided faster accelerations and smoother velocity control at lower speeds, while having a decreased size and weight compared to brush type motors.

The BMS60 motor was able to meet and exceed the required values for maximum speed and acceleration. However, after the inertia of the system was taken into account the torque generated by the rat and system was close to the peak torque of the motor (Appendix A 1.3,1.4). A gearbox was added to the system to provide extra torque, and to take advantage of the motor's high-speed range.

The gearbox chosen was a servo gearbox from BERG (53). It was chosen for its mechanical compatibility with the motor and dynamometer shafts. Since the maximum velocity output of the gearbox was 30,000°/s and the required maximum velocity was

2000°/s a ratio of 12:1 was chosen to provide more than adequate speed reduction, and enough torque amplification to overcome the expected loads without taxing the motor.

The BMS60 motor was connected to a BA Sine Drive servo amplifier to allow velocity and torque control of the motor (54). The BA Sine Drive servo amplifier also provided compatibility between the BMS60 motor and the National Instruments DAQ hardware used to control the motor. With the BA Sine Drive, all gains and parameters such as encoder resolution, pole pairs, current limits, offsets, phase advance, and Hall device initialization could be saved to computer memory. The parameters were easily accessed and changed using a Windows-based software communications program that was supplied with the amplifier. The software program could be set to velocity or torque mode to allow for smooth velocity or torque control.

3.2.2 Motion Controller

The motion controller chosen was the PCI-7344 from National Instruments. The PCI-7344 has up to four axes, which can control either a stepper motor or servomotor (55, 56). The axes are able to function independently or as coordinated axes of motion. Each axis has dedicated input and output lines for limit, home, breakpoint, and trigger switches as well as a general purpose $\pm 10\text{V}$ analog output. The PCI-7344 has four 8-bit digital input and output ports with a 0-5V range and four analog inputs with a user specified range of $\pm 10\text{V}$, $\pm 5\text{V}$, 0-10V, or 0-5V. The PCI-7344 was chosen due to its compatibility with the BA Sinedrive servo amplifier, BMS 60 motor, and the LabVIEW software used for programming. Since the PCI-7344 card and LabVIEW were both manufactured by National Instruments they were fully compatible and designed to be

used together. The position and velocity feedback from the encoder as well as the force feedback from the analog inputs allowed programs to be run in closed-loop mode. In addition, the PCI-7344 had a position accuracy of ± 1 quadrature count of encoder feedback to provide accurate position control and a PID update rate of 62.5 $\mu\text{s}/\text{axis}$ to provide high speed communication between the personal computer and motor.

3.2.3 Universal Motion Interface

The UMI-7764 universal motion interface from National Instruments was chosen to connect the motor, load cell, stimulator, and any other hardware devices to the PCI-7344 motion control card. The UMI-7764 is connected to the PCI-7344 motion control card by a single cable for efficient wiring (56). The UMI-7764 is a compact breakout box with screw terminal connectors for four axes of motion, four analog inputs, and four breakpoint and trigger inputs as shown in Appendix B 2.1 (57). This box allows the user to connect any third party device to the National Instruments hardware. The UMI-7764 also monitors the host PC power so that in the event the PC loses power during testing the UMI-7764 will immediately inhibit motion control. The UMI-7764 was chosen due to its compact design and ability to connect various third party hardware devices to the National Instruments hardware to be controlled by the LabVIEW software.

3.2.4 Personal Computer and Software

A personal computer was needed to control the motor, acquire data, and analyze the data. The computer chosen was a Micron PC from Micron Electronics Inc., with Microsoft Windows 98. The software used to run the tests was LabVIEW. LabVIEW

was chosen because unlike other programming languages it is a graphical language that uses icons and flow diagrams instead of text (58). Each icon in LabVIEW represents a function or command. When the user clicks on an icon, a description of its function is given. Help can also be provided for a more detailed description of the icon function and how it is used. Since they give a virtual picture of instruments used in the real world, many of the icons in LabVIEW are referred to as virtual instruments or VI's (59). These virtual instruments can be used to create a user interface on the computer screen that mimics the displays on real world instruments. Therefore data acquired from sensors can be displayed on the computer screen in the same fashion as it is on the readout of a sensor device. The data is acquired and displayed on the front panel while the programming is displayed on the block diagram as shown in the following figure.

Figure 12 – LabVIEW Display (60)

In addition to acquiring data and displaying it on a computer screen, LabVIEW can also store data to the computer hard drive. The data can be stored in the LabVIEW

format or in Excel format. The stored data can then be analyzed in third party programs or in LabVIEW. LabVIEW has comprehensive libraries for data collection, analysis, presentation, and storage giving the user various ways to manipulate data.

3.2.5 Force Sensor

As force was one of the parameters used to quantify muscle injury in rats, a force sensor was required. The force sensor had to accurately measure the force output from the rat during testing and supply the reading to LabVIEW to be used in data analysis and motion control. The force sensor chosen was a Model 13 Subminiature Load Cell from Sensotec (61). The subminiature load cell was chosen due to its small size and ability to fit in the foot holder currently in use. It was capable of measuring loads from zero to fifty pounds, which was much greater than the maximum force output of 30 pounds from a large male rat. Finally it had a maximum non-linearity and hysteresis of $\pm 0.25\%$ of full scale to provide accurate force measurements.

The load cell was connected to a Model GM Signal Conditioner – Indicator from Sensotec. The signal conditioner had an excitation of 5 volts and accepted the 2mV/V nominal output from the load cell (62). It also had an accuracy of $\pm 0.03\%$ and a full-scale output of 5 volts.

3.2.6 Electrical Stimulator

A Grass SD9 stimulator was chosen to provide electrical stimulation to the rat's muscles during testing. The stimulator is capable of providing output voltages from 0.1 to 100 volts (63). The frequency, delay, and duration of the output stimulation can also

be varied from 0.1 to 200 pulses per second, 0.02 to 200 milliseconds, and 0.02 to 200 milliseconds respectively. In addition the type of output can be selected as monophasic, DC, or biphasic. The stimulator is a stand-alone unit that can be operated either manually or by computer control. When the stimulator is computer controlled, the input trigger on the stimulator is connected to an analog output on the UMI-7764. Therefore a zero or five volt signal can be sent from the UMI-7764 to the stimulator to turn it on or off. When stimulation is required in testing, LabVIEW sends a five-volt signal to turn on the stimulator. The stimulator remains on until LabVIEW sends a zero voltage signal to turn it off. In this manner all the tester has to do is set the appropriate frequency, delay, duration, voltage, and output signal on the stimulator before testing. Once the test program has been started the computer will control the stimulation.

3.2.7 Positioning Device

In order to accurately position the animals for testing a device was designed and built to adjust the animal's position vertically and horizontally with respect to the foot holder. The device was also required to accommodate both female rats and the larger male rats. A metric lab jack shown in the following figure was purchased from Edmund Industrial Optics to provide vertical positioning (64).

Figure 13 – Vertical Positioning Device

The jack was capable of supporting up to 22 pounds of weight and was made of black anodized aluminum to withstand corrosion. Motion was achieved through a screw mechanism with one 360° revolution equal to 1 millimeter of vertical movement for a total of 1.65 inches of vertical movement. The jack was also equipped with a locking knob to prevent vertical movement during testing.

Since only one direction of horizontal movement was required (towards and away from the foot holder) a medium linear motion ball bearing slide also from Edmund Industrial Optics was purchased (64). The linear slide had a maximum travel distance of 4 inches. A screw mechanism was designed to control the movement of the slide as shown in the following figure. The screw mechanism provided for 3 ½" of travel.

Figure 14 – Horizontal Positioning Device

A bed made of aluminum 6061 was mounted on top of the linear slide. The dimensions of the bed were 9.75 inches by 7.25 inches. A $\frac{1}{2}$ " aluminum rod was attached to the bed to serve as a mounting device for a knee holder previously designed (44). The knee holder was required to hold the rat's leg in the proper position during testing.

3.2.8 Foot Holder and Shaft

An aluminum shaft was designed to connect the gearbox to the foot holder. The ends of the shaft had to be $\frac{1}{4}$ " in order to fit into the bearing mounts and connect properly to the $\frac{1}{4}$ " shaft from the gearbox. However the foot holder to be used required a shaft connection of $\frac{1}{2}$ ". Therefore a $\frac{1}{2}$ " diameter aluminum tube was attached to a $\frac{5}{8}$ " aluminum rod that was turned down to $\frac{1}{4}$ " at both ends. An aluminum tube was chosen instead of an aluminum rod to reduce inertia in the system.

The footholder used was designed by Vincent L. Kish for a previous dynamometer (66). The purpose of the footholder was to not only hold the rat's foot in position during testing but to also provide a way to measure force output. The footholder consisted of three main pieces, which will be referred to as the foot block, the foot plate, and the load cell mount. The foot block and footplate were designed by Kish and are shown in the following figure.

Figure 15 - Foot holder (designed by Vincent L. Kish (66))

The foot block was constructed out of aluminum and acts as the support for the foot plate and load cell mount. It also connects the two ends of the aluminum shaft together. The footplate was also constructed out of aluminum and fits into four linear bearings in the foot block. These bearings restrict the movement of the footplate into a purely vertical movement to be measured by the load cell. In order to attach the load cell to the previously designed footholder a new load cell mount was constructed as shown in the following figure.

Figure 16 – Load Cell Mount

The load cell mount was attached to the footblock and the load cell was secured in the load cell mount using mounting glue. The load cell mount was designed to place the top of the load cell in direct contact with a pin on the bottom of footplate. When a force

was applied to the footplate it moved vertically against the load cell striking the pin on the top of the load cell.

3.3 Overall Setup

The main platform was custom designed and fabricated to mount the positioning device, motor, gearbox, foot holder, and shaft. The platform was made out of 6061 aluminum with an overall size of 17 inches by 19 inches and is shown in the following figure.

Figure 17 - Platform

Each of the components including the platform had a thickness of $\frac{1}{2}$ inch and the entire platform was mounted on 6061 aluminum legs that were 7 inches tall with a 1 inch diameter. The legs were designed to position the platform at a height that was

comfortable for testing. Detailed drawings of each of the platform pieces are shown in Appendix B 1.

The motor, gearbox, and position device were mounted directly to the platform. Since the output shafts of the gearbox and motor were both $\frac{1}{4}$ inch, they were coupled together with spider couplings that provided good vibration and chemical resistance as well as tolerance for up to 1° of angular misalignment and 0.015" of parallel misalignment (65). A spider coupling was also used to connect the output shaft of the gearbox to the aluminum shaft containing the foot holder.

In order to control the range of movement of the shaft a limit switch was designed with forward and backward stops. The limit switch consisted of an optical sensor and plate. The plate was mounted to the shaft and the optical sensor was mounted above it as shown in the following figure.

Figure 18 – Limit Switch

As the shaft rotated the plate passed through the optical sensor. The range of motion was limited to 270 degrees which was equal to the portion of the plate that blocked the optical sensor (Detailed drawings of the plate are shown in Appendix B). The forward limit was found by rotating the plate until the cutout portion of the plate was reached and the optical sensor was unblocked. The direction of rotation of the shaft was then reversed 270 degrees until the opposite edge of cutout portion, or backward limit, was reached. The limits were necessary to keep the shaft from making a complete revolution and damaging the rats foot or wires connected to the load cell.

The complete dynamometer platform is shown in the following figure.

Figure 19 – Complete Dynamometer Platform

The positioning device is situated so that at its highest point the bed touches the bottom of the shaft. When the bed is moved to its farthest position away from the shaft the front of the bed sits 2” back from the shaft. Likewise when the bed is at its closest point to the shaft, the front of the bed is 1” in front of the shaft. This allows for various positions depending on the length of the leg of the animal currently being tested.

This particular design is very open, and allows the tester sufficient room to work with the animals being tested. The platform was sized to fit in the work area currently used for testing. In addition the entire platform was designed so that it could be turned in two different directions and still be useful. Depending on the preference of the tester the machine can be turned with the knobs on the front of the device facing the user or on the

right of the device facing the user. This along with its small size allows the platform to fit in many different work areas.

3.4 Computer Control and Software

It was necessary to develop computer programs to control the velocity, acceleration, position, force, and stimulation applied to the rat's leg. The computer programs also had to acquire data from the motor and load cell, and display or save all required data. The motor, load cell, and stimulator were connected to the UMI-7764, which was directly connected to the computer. This allowed all of the devices to be controlled through the LabVIEW software.

Three main tests were written in LabVIEW to study muscle injury: isometric, isovelocity, and isotonic. Each of these tests shared several main features. They all required user inputs for velocity, acceleration, position, and number of repetitions. For isometric tests the user could also input hold times when the muscle was held at a constant length for a given amount of time. In addition all of the control programs provided signals to activate and deactivate stimulation. They all provide for acquisition of pertinent data and for storage of the data in a convenient format for later processing.

Chapter 4 – LabVIEW Programming

Control programs were written in LabVIEW to study muscle injury using the isometric, isovelocitv, and isotonic protocols. In addition auxiliary programs were written to initialize the machine. A detailed description of each of the LabVIEW programs and their respective setup and execution procedures is provided in the following sections.

4.1 *“Find Limits” Program*

The “find limits” program was written to incorporate hard limits into the software programs. As described in section 3.3, an optical limit switch was attached to the dynamometer above the shaft. As the shaft rotated, an aluminum piece rotated through the optical switch activating or deactivating the limits. The limits served two purposes. 1) To prohibit complete revolutions of the shaft during testing. This was necessary to keep the shaft from rotating continuously which would have damaged both the subject’s leg and the load cell wires. 2) To specify and find a “home” position from which all other positions could be referenced. This program positions the footholder with the bottom surface parallel to the base plate and defines the position as zero.

The front panel of the “find limits” program is shown in the following figure.

Figure 20 – “Find Limits” Front Panel

For this program, no user inputs are required except to confirm that the limit switches are enabled. These can be confirmed in the Measurement and Automation Explorer software. The correct values are shown in Appendix D. To run the “find limits” program, the user must click on >Window>Show Diagram in the toolbar on the front panel. This will open the block diagram shown in the following figure.

Figure 21 – “Find Limits” Block Diagram

One item must be noted on the “find limits” diagram shown in the above figure. At the far-left side is a block, which contains two light bulbs. This block stands for initialize controller. At the beginning of every test the PCI-7344 motion control card must be initialized in the Measurement and Automation Explorer software to the proper setup values in order for the programs to function properly. These values are shown in Appendix D along with the proper values for the BA Sinedrive software. By inserting this command into the programs it alleviates the need for the user to manually initialize the board before each test.

Before the “find limits” program can be run, the highlight execution button in the toolbar of the find limits window must be pressed. (This button has a picture of a light bulb on it.) Once it appears as yellow the run arrow on either the front panel or block diagram will run the program. At the end of the program the footholder should be in its parallel position and its new position should be defined as zero.

4.2   *Initial Positioning*

The initial positioning program was developed to allow the user to specify the initial position of either an eccentric or concentric test. The initial positioning program can be run after the find limits program, or after any test dependent on the user knowing where the specified zero location is. However the initial positioning program must be run immediately after the find limits program before any of the other tests can be run. This is due to the fact that the limit switch is active at the end of the find limits program. In order to deactivate the limit switch the initial positioning program is run with a desired end position of 350 degrees as shown in the following figure.

Figure 22 – Initial Positioning Front Panel (Diagram shown in Appendix D 3.0)

From this position any of the muscle injury programs can be run or the initial positioning program can be run again to move to a suitable starting point for testing. However it must always be taken into consideration that this program resets the end position to zero. Therefore if the user wishes to move the footholder to a final position of 40 degrees but only moves 20 degrees during the first run of the program then the second time the program is run the end position will be 20 degrees not 40 degrees since the program reset the position to zero after the first 20 degree move.

The footholder can be moved in either a concentric or eccentric direction to allow for proper positioning. Concentric moves are entered as positive numbers. Eccentric

moves are entered as negative numbers. This allows for great flexibility in the positioning of the test subject.

4.3 Isovelocity Program

The isoveLOCITY program was designed to perform “constant” velocity moves in either the concentric direction, eccentric direction, or to cycle back and forth. The program was designed to accelerate from zero up to the constant velocity and then decelerate back to zero. The user was able to specify the acceleration and deceleration rates as well as the constant velocity. The front panel of the isoveLOCITY test is shown in the following figure.

The screenshot displays the 'Isovelocity Tests' front panel, which is organized into several functional sections:

- Isovelocity Forward Speed Parameters:** Includes input fields for Velocity (RPM) set to 300.00, Acceleration (RPS/S) set to 100.00, and Deceleration (RPS/S) set to 100.00.
- Isovelocity Return Speed Parameters:** Includes input fields for Velocity (RPM) set to 300.00, Acceleration (RPS/S) set to 100.00, and Deceleration (RPS/S) set to 100.00.
- Isovelocity Forward Positioning Parameters:** Includes an End Position (deg) set to 350.00, with a note: '(Positive for Concentric Moves Negative for Eccentric Moves)'. Below this is a yellow 'Repetition Inputs' section with 'Number of Cycles' set to 1 and 'Number of Times to Complete Cycles' set to 1.00 (with a note: '(Must be Equal to One at Least)').
- Isovelocity Return Positioning Parameters:** Includes a Beginning Position (deg) set to 0.00, with a note: '(Equal to Zero)'.
- Isovelocity Time Inputs:** A blue section containing several rest and hold times, all set to 0.00 ms:
  - Repeated Isometric Hold (ms): '(Creates an Isometric Hold at the Beginning of Each Con, Ecc, or Con/Ecc Tests)'
  - Rest Time Before Reverse Moves (ms): '(Creates a Rest Period at the End of Each Con or Ecc Test Before it is Repeated)'
  - Rest Time Before Forward Moves (ms): '(Creates a Rest Period at the End of Each Con/Ecc Test Before it is Repeated)'
  - One Time Isometric Hold (ms): '(Creates an Isometric Hold at the Beginning of Each Repetitive Con/Ecc Test)'
  - Rest Time for Con/Ecc Tests (ms): '(Creates a Rest Period Between Each Cycle of Repetitive Con/Ecc Tests)'
- Stimulation Inputs:** A section with four rows of controls for On Voltage (Begin/End of Forward/Reverse Move) and DAC (Channel 2) settings, all set to 0.00.
- Emergency Stops:** A red section with two large 'STOP' buttons labeled 'Forward Stop' and 'Reverse Stop'.
- Other Programmed Inputs:** Includes Board ID (Set to 1), Axis (Set to Axis 1), Primary Feedback (Set to hex 51), and Primary Feedback 2 (Set to hex 51).

Figure 23 – Isovelocity Front Panel (Diagram shown in Appendix D 3.0)

Depending on the inputs entered into the front panel, a variety of tests can be performed. However each of these tests has a few common parameters that do not change. These are:

Board ID = 1

Axis = Axis 1

Primary Feedback = hex 51

DAC = DAC Channel 2

Each of the tests that can be performed along with the user inputs necessary to run such a test are described in the following sections.

4.3.1 Concentric Move

The concentric test performs a concentric move followed by a rest period and a return move to the beginning position. The concentric test can be performed with or without an isometric hold at the beginning of each concentric move. In order to insert an isometric hold into the beginning of each concentric test the first box in the isovelocity time inputs is assigned a nonzero number equal to the amount of milliseconds of the isometric hold.

Each concentric move is followed by a return move whose parameters are entered into the return parameter sections. The return positioning parameter labeled *beginning position* is always equal to 0. Before the return move is made a rest period can be inserted by entering a nonzero number equal to the rest time in the second box under the isovelocity time inputs. The concentric test can be performed for any number of repetitions by entering the number of repetitions into the *number of cycles* box. For this test the *number of times to complete cycles* box next to the *number of cycles* box must be equal to 1. The stimulation inputs for this test are set to 5, 0,0,and 0 consecutively. An example front panel is shown for an isovelocity concentric move in the following figure

with an isometric hold of 1000ms, a rest time of 100,000ms, and an end position of 110 degrees. The test runs for 30 repetitions with a constant velocity of 300rpm followed by a slower return move of 30rpm.

Figure 24 – Example of Concentric Isovelocity Test Front Panel

4.3.2 Eccentric Move

The eccentric move performs the same as the concentric move just in the opposite direction. It also has the same inputs as the concentric move except the end position for the eccentric test is a negative number.

4.3.3 Concentric/Eccentric Single Move

The concentric/eccentric single move is a concentric move followed immediately by an eccentric move. Like the concentric and eccentric moves an isometric hold can be added before each concentric/eccentric move. A rest period can also be added at the end

of each eccentric move. This time however the rest period is entered into the third box in the isovelocity time inputs. The stimulation inputs for this test are 5,0,5,and 0 to turn the stimulation on at the beginning of the concentric and eccentric moves and turn the stimulation off at the end of the moves. An example front panel for a concentric/eccentric single move is shown in the following figure with an isometric hold of 1000ms, a rest time of 10,000ms, and an end position of 110 degrees. The test runs for 30 repetitions with a constant velocity of 300rpm.

Isovelocity Tests

Isovelocity Forward Speed Parameters		Isovelocity Return Speed Parameters		Stimulation Inputs		Other Programmed Inputs	
Velocity (RPM)	Acceleration (RPS/S)	Velocity (RPM)	Acceleration (RPS/S)	On Voltage Beg of Forward Move	DAC (Channel 2)	Board ID (Set to 1)	Axis (Set to Axis 1)
300.00	100.00	300.00	100.00	5.00	DAC Channel 2	1	Axis 1
	Deceleration (RPS/S)		Deceleration (RPS/S)	Off Voltage End of Forward Move	DAC 2 (Channel 2)	Primary Feedback (Set to hex 51)	
	100.00		100.00	0.00	DAC Channel 2	51	
Isovelocity Forward Positioning Parameters		Isovelocity Return Positioning Parameters		On Voltage Beg of Reverse Move	DAC 3 (Channel 2)	Primary Feedback 2 (Set to hex 51)	
End Position (deg)	Beginning Position (deg)	5.00	DAC Channel 2	0.00	DAC Channel 2	51	
110.00 (Positive for Concentric Moves Negative for Eccentric Moves)	0.00 (Equal to Zero)	Off Voltage End of Reverse Move					
Repetition Inputs				Emergency Stops			
Number of Cycles	Number of Times to Complete Cycles			Forward Stop Reverse Stop			
30	1.00 (Must be Equal to One at Least)			STOP STOP			
Isovelocity Time Inputs							
Repeated Isometric Hold (ms)							
1000.00 (Creates an Isometric Hold at the Beginning of Each Con, Ecc, or Con/Ecc Tests)							
Rest Time Before Reverse Moves (ms)							
0.00 (Creates a Rest Period at the End of Each Con or Ecc Test Before it is Repeated)							
Rest Time Before Forward Moves (ms)							
10000.00 (Creates a Rest Period at the End of Each Con/Ecc Test Before it is Repeated)							
One Time Isometric Hold (ms)							
0.00 (Creates an Isometric Hold at the Beginning of Each Repetitive Con/Ecc Test)							
Rest Time for Con/Ecc Tests (ms)							
0.00 (Creates a Rest Period Between Each Cycle of Repetitive Con/Ecc Tests)							

Figure 25 - Example of Concentric/Eccentric Single Move Isovelocity Test Front Panel

4.3.4 Eccentric/Concentric Single Move

The eccentric/concentric single move performs the same as the concentric/eccentric single move just in the opposite direction. It also has the same inputs as the concentric/eccentric single move except the end position for the eccentric/concentric single move test is entered in a negative number.

4.3.5 Concentric/Eccentric Train Move

The concentric/eccentric train move performs a train of concentric/eccentric moves followed by a rest and then repeats the train. An isometric hold can be added at the beginning of each train by entering a number in the fourth box below the isovelocity time inputs. A rest can be added at the end of each train before the isometric hold by entering a number in the last box beneath the isovelocity time inputs. The number of trains is determined by entering a number in the *number of cycles* box. The number of times to complete each cycle (isometric hold, concentric/eccentric train, rest period) is entered into the *number of times to complete cycles* box. The stimulation inputs for this test are 5,0,5,0. An example front panel for a concentric/eccentric train move is shown in the following figure with an isometric hold of 1000ms, a rest time of 10,000ms, and an end position of 110 degrees. The test runs for 30 trains with a constant velocity of 300rpm and repeats itself 3 times.

Isovelocity Tests

Isovelocity Forward Speed Parameters	Isovelocity Return Speed Parameters	Stimulation Inputs	Other Programmed Inputs
Velocity (RPM) 300.00 Acceleration (RPS/S) 100.00 Deceleration (RPS/S) 100.00	Velocity (RPM) 300.00 Acceleration (RPS/S) 100.00 Deceleration (RPS/S) 100.00	On Voltage Beg of Forward Move 5.00 DAC (Channel 2) DAC Channel 2 Off Voltage End of Forward Move 0.00 DAC 2 (Channel 2) DAC Channel 2 On Voltage Beg of Reverse Move 5.00 DAC 3 (Channel 2) DAC Channel 2 Off Voltage End of Reverse Move 0.00 DAC 4 (Channel 2) DAC Channel 2	Board ID (Set to 1) 1 Axis (Set to Axis 1) Axis 1 Primary Feedback (Set to hex 51) x51 Primary Feedback 2 (Set to hex 51) x51
Isovelocity Forward Positioning Parameters End Position (deg) 110.00 (Positive for Concentric Moves, Negative for Eccentric Moves)	Isovelocity Return Positioning Parameters Beginning Position (deg) 0.00 (Equal to Zero)	Emergency Stops Forward Stop STOP Reverse Stop STOP	
Repetition Inputs Number of Cycles 30 Number of Times to Complete Cycles 3.00 (Must be Equal to One at Least)			
Isovelocity Time Inputs Repeated Isometric Hold (ms) 0.00 (Creates an Isometric Hold at the Beginning of Each Con, Ecc, or Con/Ecc Tests) Rest Time Before Reverse Moves (ms) 0.00 (Creates a Rest Period at the End of Each Con or Ecc Test Before it is Repeated) Rest Time Before Forward Moves (ms) 0.00 (Creates a Rest Period at the End of Each Con/Ecc Test Before it is Repeated) One Time Isometric Hold (ms) 1000.00 (Creates an Isometric Hold at the Beginning of Each Repetitive Con/Ecc Test) Rest Time for Con/Ecc Tests (ms) 10000.00 (Creates a Rest Period Between Each Cycle of Repetitive Con/Ecc Tests)			

Figure 26 - Example of Concentric/Eccentric Train Move Test Front Panel

4.3.6 Eccentric/Concentric Train Move

The eccentric/concentric repetitive move performs the same as the concentric/eccentric repetitive move just in the opposite direction. It also has the same inputs as the concentric/eccentric repetitive move except the end position for the eccentric/concentric repetitive move test is entered in a negative number.

4.4 Isometric Test

The main function of the isometric program was to study the effect of position and change in muscle length on muscle injury. The program was designed to activate stimulation of the subject's muscle and then perform a series of move and hold steps until a final position was reached. An isometric hold could also be performed before any movement. The following figure shows the front panel for the isometric tests.

Isometric Tests

Isometric movement speed parameters		Returning Parameters		Stimulation Controls	
Velocity (RPM) 300.00	Acceleration (RPS/S) 100.00	Velocity (RPM) 30.00	Acceleration (RPS/S) 100.00	On Voltage 5.00	DAC (Channel 2) DAC Channel 2
	Deceleration (RPS/S) 100.00	End Position (deg) 0.00	Deceleration (RPS/S) 100.00	Off Voltage 0.00	DAC 2 (Channel 2) DAC Channel 2
Isometric movement destination parameters		Emergency Stops			
Final Position 110.00	Increments 10.00				
(These Numbers are Positive when Concentric Test and Negative when Eccentric Test)		Forward Motion		Reverse Motion	
		STOP		STOP	
Isometric time parameters		Other Programming Controls			
Beginning Isometric Hold Time (ms) 1000.00	Rest Time Between Steps (ms) 500.00				
		Board ID (Set to 1) 1		Axis (Set to Axis 1) Axis 1	
		Primary Feedback (Set to Hex 51) x51			

Figure 27 – Isometric Control Panel

Like the isovelocidity tests the isometric test has certain inputs that never change and certain inputs that vary due to the type of test being performed. The parameters that never change are as follows:

On Voltage = 5

Off Voltage = 0

DAC = DAC Channel 2

Board ID = 1

Axis = Axis 1

Primary Feedback = hex 51

The remaining parameters can be varied by the user to perform different isometric tests. While most of the parameters are rather straightforward, some special points must be noted. The end position under the returning parameters is always equal to zero. The isometric hold time is a one-time hold that occurs before any movement is performed while the rest time between steps occurs after each incremental move. For example in the above figure when the test begins the stimulation is turned on and the subject's muscle is

held at a constant length for 1000ms (the isometric hold time). After the 1000ms is up the footholder moves 10 degrees and then stops and holds the muscle length constant for 500ms. At the end of the 500ms the footholder moves another 10 degrees followed by another 500ms wait. This cycle continues until the footholder reaches 110 degrees and the stimulation turns off.

This test can be run concentrically or eccentrically. To run the test concentrically the final position and increments are positive numbers. However when the test is run eccentrically the final position and increments must both be negative numbers to make the test function properly.

4.4 Isotonic Testing

The main function of the isotonic program is to study the effect of constant force on muscle injury. To date there have been no isotonic tests performed on animals. The isotonic program is run in the following manner. A “setpoint” force is entered by the user. The subject is then stimulated and held in a constant position until it generates a force equal to the setpoint force. At that point the motor begins to move in a concentric or eccentric direction. When the force produced by the subject is greater than the constant force selected, the velocity of the motor is increased. This is done by reading the force input from the load cell and comparing it to the constant force. If the output force is greater than the control force the motor is told to increase its speed by 10rpm. If the output force is less than the control force the motor is told to decrease its speed by 10rpm. The control program runs at a fast enough speed to check the two forces and make adjustments to the speed of the motor almost instantaneously. This allows for the motor

to adjust its speed at a fast enough rate to allow the subject to output a constant force.

The whole reasoning behind the program is that the relationship between force and velocity is linear (13).

Two different programs were developed for isotonic testing. One was for concentric isotonic movements and the other was for eccentric isotonic movements. The front panel of the concentric isotonic test is shown in the following figure.

Concentric Isotonic Tests

Isotonic Speed Inputs

Velocity (RPM) Acceleration (RPS/S)
 Deceleration (RPS/S)

Isotonic Position Inputs

End Position (deg) (Positive Number)

Isotonic Force Input

Control Load (kg) Force Error (Equal to .1)

Return Parameters

Velocity Acceleration
 End Position Deceleration
 (Equal to Zero)

Hold Times

Isometric Hold Time (ms) (Amount of Time to Hold After Isotonic Move Before Return Move)

Emergency Stops

Stop 1 (Stop During Isotonic Hold)
 Stop 2 (Stop During Isotonic Move)
 Stop 3 (Stop During Return Move)

Stimulation Controls

On Voltage (Equal to 5) DAC (Channel 2)
 Off Voltage (Equal to 0) DAC 2 (Channel 2)

Other Control Inputs

Board ID (Equal to 1) Axis (Set to Axis 1)
 Primary Feedback (Set to Hex 51)
 Primary Feedback (Set to Hex 51) 2

Isotonic Cycles

Number of Cycles (Number of Times to Repeat Isotonic Test Followed by a Rest and Return Move)

Figure 28 – Concentric Isotonic Control Panel (Diagrams shown in Appendix D 3)

The front panel and inputs for the eccentric test are nearly identical, except for the sign of the end position which was explained in the previous tests.

The ability to perform isotonic testing on animals has never been available before and offers the chance to study new forms of muscle injury in animals. While the program shown here is very basic it provides the frame work and guide for more varied and complex isotonic programs.

Chapter 5 – Calibration and Accuracy Testing

The calibration procedure involved testing of the load cell and testing of the motor. The load cell was tested for accurate force readings while the motor was tested for accurate position and velocity readings. It was necessary to test the load cell and motor to make sure that they were functioning properly and providing accurate results to the software programs.

5.1 Testing of the Load Cell

The load cell was tested using two separate methods. The first test involved checking the accuracy of the load cell and signal conditioner using known weights. The second test checked the accuracy of the load cell readings in LabVIEW using known weights. The accuracy was checked in LabVIEW while isovelocity, isometric, and isotonic tests were run.

Before any tests could be performed the load cell had to be properly zeroed and calibrated to factory specifications. The method for zeroing and calibrating the load cell was shown in Appendix C 1. Once the load cell was calibrated and the scale on the amplifier was set to the proper units the load cell could be tested for accuracy.

5.1.1 Load Cell Test 1

As described in section 3.2.8 the load cell was mounted in a block in the footholder. The top of the load cell was in direct contact with a pin located on the bottom of the footholder. Therefore the weight of the footholder had to be taken into account

during all measurements. The foot holder was weighed using a digital scale and the following measurements were taken.

Table 1 - Footplate Measurements

Measurement	Weight
1	64.28 g
2	64.29 g
3	64.27 g
Average	64.28 g

When the foot-plate was placed in the footholder the load cell amplifier read a force of 0.06kg which was equivalent to the weight measured for the footplate by the digital scale. This weight was then subtracted from all force measurements to accurately measure the force applied by the animal to the load cell. To place the larger weights on the footplate a support table designed by Mark Willems was used. The support table was fabricated from plastic and is shown in the following figure.

Figure 29 – Weight Support Table (Mark Willems)

The support table had a known weight of 90.33 g. When the support table was placed on the footplate, the load cell read a value of 0.15kg which was an accurate

display of the combined weights of the footplate (.6kg) and the support table (.9kg).

Known weights ranging from 10g to 5 kg were then placed on the footplate and support table and their equivalent weights were recorded from the load cell amplifier. The actual weight applied to the load cell, the value read on the amplifier minus the weight of the footplate and support table, was recorded. The results were shown in Appendix C, Table 3.1A. From the results, it was seen that for weights from 10g to 5kg the load cell and amplifier were able to accurately measure the known weights. To see this more clearly the known and measured weights were plotted together and are shown in the following figure.

Figure 30– Load Cell Test 1 Accuracy Measurements

Figure 30 shows that the known and measured weights were nearly identical. To determine where the slight error in readings came from two different theories were tested. One was that the weight read by the load cell depended on the location of the weight on the footplate. To test this, known weights of 10g, 20g, 50g, 100g, 200g, and 500g were each placed in three locations on the footplate (back, middle, front) and the corresponding force readings were taken. The results are shown in Appendix C, Table

3.1B. The results showed that the force readings did vary slightly based on the position of the weights on the footplate. The back position seemed to give slightly lower readings than the middle or forward position. The error was slight and varied with a standard deviation that was $\pm 0.01\text{kg}$ at low weights and increased to $\pm 0.02\text{kg}$ at higher weights.

The second possibility for error was improper zeroing of the load cell. At various points in the load cell testing it was noticed that the constant 0.06kg the load cell continuously measured from the footplate varied slightly. Then it was necessary to remove the footplate and make sure the load cell was properly zeroed. Normally it was found that the load cell was properly zeroed. However, at times there was a slight zero drift usually less than 10g.

5.1.2 Load Cell Test 2

The load cell was also tested to verify that it was providing accurate readings in the LabVIEW software programs. The load cell was tested in the same fashion as in Test 1 described above but the data were collected from the both the load cell signal conditioner display and from the three LabVIEW muscle testing programs. The results from the load cell signal conditioner display and LabVIEW programs were then compared to make sure that the programs were accurately receiving and displaying the proper force values.

Each of the programs was set up to measure the force from the load cell and send the resulting data to Excel. LabVIEW reads a 0-5V signal from the load cell signal conditioner via a 12-bit analog to digital converter in the PCI-7344 motion control card. These tests verified the accuracy of the algorithm used in the LabVIEW programs to

convert the sensor output to engineering units. The scaling equations are shown in Appendix C2.

The LabVIEW programs were set up to collect data at regular sampling intervals during the test and then send that data to Excel in a single file. The results were averaged to give one force reading per known weight.

Each of the three programs, isovelocity, isometric, and isotonic (concentric and eccentric) were run with weights ranging from 10g to 5kg on the load cell in the same manner as Load Cell Test 1. The reading on the signal conditioner as well as the reading in LabVIEW were recorded once when the test was run with no weight (except the footholder and support table) and once with the weight. The results were shown in Appendix C 3.2. The results from the LabVIEW programs were shown graphically in the following figures.

Figure 31 – Isovelocity Force Readings

Figure 32 – Isometric Force Readings

Figure 33 – Concentric Isotonic Force Readings

Figure 34 – Eccentric Isotonic Force Readings

From the above figures it was seen that for each of the tests the force readings in LabVIEW were slightly higher than the known weights. Using the results shown in Appendix C Tables 3.2B,D,F,H it was seen that for low forces the standard deviation in the force reading in LabVIEW and on the amplifier was approximately $\pm 0.035\text{kg}$. As the force applied to the load cell increased this error decreased. Each of the LabVIEW programs produced similar results and aside from the slight error in the readings the LabVIEW programs were able to accurately display the force data.

5.2 Testing of the Motor

The motor was tested for both position and speed accuracy. The Measurement and Automation Explorer software was programmed to move the motor at a constant speed a set number of encoder counts and stop. The move was timed as an approximate measure of motor speed. The range of velocities at which the footholder was required to move were $15^\circ/\text{s}$ to $2000^\circ/\text{s}$. Since the footholder was connected to the

motor through a 12:1 ratio gear box the speeds at which the motor was required to run were 180°/s to 24,000°/s (30rpm to 4000rpm).

The following equation was used to determine how many encoder counts the motor would move in a set amount of time.

$$Targ et Position(counts) = (Velocity(rpm)) \times \left(\frac{8000 counts}{1 rev} \right) \times (Time elapsed(min))$$

The motor was run from speeds of 2.5rpm to 4000rpm and the target position, time elapsed, and voltage output on the oscilloscope were recorded. The results are shown in Appendix C Table 4.0A.

The speed of the motor was also checked using a stroboscopic tachometer. The stroboscopic tachometer was used to directly check the velocity of the motor from 100rpm to 1000rpm. The results from the stroboscopic tachometer and Appendix C Table 4.0A showed that the motor was functioning properly throughout the complete range of speeds.

In addition to testing the speed with the Measurement and Automation Explorer software, the isovelocity and isometric programs were also run to verify that they were operating at the proper speeds. The results for the isovelocity tests at 15°/s and 2000°/s are shown in the following figures while the remainder of the results are shown in Appendix C4.0.

Figure 35– Isovelocity Test Results at 15°/s

Figure 36 – Isovelocity Test Results at 2000°/s

Chapter 6 –Conclusions

6.1 Mechanical Design

The mechanical design of the dynamometer included the positioning device, main platform, load cell device, and all the other components that had to be designed and machined for proper functioning of the dynamometer. These included the shaft, limit switch, optical limit sensor, gear box mount, and motor mount. Each of the pieces was designed and machined to fulfill the objectives set out at the beginning of the project.

All of the mechanical components work according to their intended purpose. In addition the design of this machine is more compact, and the controls and operator access are more convenient than that of prior models.

6.2 Systems Integration

The systems integration was the most difficult part of the project. A National Instruments UMI-7764 was used to connect the load cell, stimulator, limit switch, and motor to the computer. The UMI-7764 was very useful in that it allowed for easy access to the connections for the stimulator, load cell, and limit switch. Each of the programs was designed to output a 0V or 5V signal through the UMI-7764 to the stimulator. The programs were run and tested with a voltmeter to verify that the appropriate signals were sent to turn the stimulator at the appropriate times. All of the tests showed that the stimulator outputs functioned as desired.

The limit switch also functioned properly as evidenced by running the find limits program and also trying to run the isovelocit, isometric, and isotonic tests beyond the

range of the limits. When the limits were hit the program halted the motion of the shaft and ended. The load cell was also tested as shown in Chapter 5 and was able to accurately acquire data and display it in LabVIEW.

The integration of the motor proved very difficult due to poor documentation and conflicts between the Aerotech software and the National Instruments software. The input parameters required to operate the motor correctly are shown in Appendix D.

6.3 Computer Programs

Computer programs were written in LabVIEW to perform all of the operator interface, system control, and data storage tasks. All of the operator screens feature step-by-step instructions, radio buttons, or parameter entry fields for ease of use. The system provides several new features not available on previous dynamometers, including selectable isometric hold times, significantly higher and lower speed ranges, and a completely new test protocol (Isotonic) not available to any other researchers at this time.

Chapter 7 – Recommendations

There is much work that could still be done on this project. Currently data collected from the tests is sent to Excel to be analyzed. This allows the user to store the data and analyze it after testing is complete. However, it does not allow for the user to view the results of the test as they occur. Additions could be made to the LabVIEW programs to collect and display the data directly on the front panel of the tests. This would allow the user to view the results of the test as they occur.

A computer controlled temperature system would also be beneficial to the dynamometer. Currently the temperature on the rat's leg is measured by an external device and as the temperature drops above or below an acceptable range, the user activates a heat lamp. If the computer were able to monitor the temperature and activate the lamp it would be beneficial to the user.

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Appendix A - Calculations

1 Motor Calculations

1.1 Acceleration

The requirements for the system were a maximum velocity of 2000°/s, and an acceleration from rest at 0° to 22.5° in 0.0225s. From these requirements the acceleration was found using the following equations.

$$\sigma = \omega_0 t + \frac{1}{2} \alpha t^2$$

$$22.5^\circ = \frac{\pi}{8} = 0 \times t + \frac{1}{2} \alpha t^2$$

assuming constant acceleration

$$\frac{\pi}{8} = \frac{1}{2} \alpha t^2 = \frac{1}{2} (\alpha t) t = \frac{1}{2} \omega t$$

$$\frac{\pi}{8} = \frac{1}{2} \times (2000^\circ / s) \times t = \frac{1}{2} \left(\frac{2000^\circ}{s} \times \frac{2\pi}{360^\circ} \right) t$$

since $t = 0.0225s$, then

$$\frac{\pi}{8} = \frac{1}{2} \alpha t^2 = \frac{1}{2} \alpha (0.0225s)^2$$

$$\alpha = 1551.4 \text{ rad} / s^2$$

Thus, the motor must be able to provide adequate torque to accelerate itself and the load at greater than 1551 rad/s².

1.2 Moment Generated by Rat

Large male rats can generate a force of up to 120N. In order to determine the moment this produces about the shaft the distance from the shaft to the point where force is measured must be determined. A diagram showing the current foot plate and location of load cell is shown below.

Figure 1.2A – Rat Force Moment Arm

$$M = F \times d = (120N) \times (11.113mm) = 1.34 \text{ N} \cdot m$$

From the above figure it was seen that the moment arm for the force generation was 11.113mm. The maximum moment produced by a large male rat was found to be 1.34N·m.

1.3 Moment of Inertia Calculations

The moments of inertia of the shaft and foot holder were determined by modeling the shaft and foot holder as basic shapes with homogeneous material properties. Both the shaft and foot holder were constructed from aluminum making this possible. The shaft consisted of a hollow cylinder connected to a solid cylinder as shown in the following figure.

Figure 1.3A – Shaft Diagram

Using the dimensions from the shaft, the properties of aluminum, and the following equations, the moment of inertia of the shaft was calculated with the x-axis being the centerline of the shaft.

For cylinders:

$$I_x = \frac{md^2}{8}$$

For hollow cylinders:

$$I_x = \frac{m}{8} (d_o^2 + d_i^2)$$

The basic shape of the foot holder is shown in the following figure.

Figure 1.3B- Footholder

Using the dimensions of the foot holder, the properties of aluminum, and the parallel axis theorem shown in the following equations, the moments of inertia of the foot holder were calculated.

$$I = I_{xCG} + md^2$$

$$I_{xCG} = \frac{m}{12}(a^2 + b^2)$$

All of the moments of inertia from the foot holder and shaft were then summed as shown in the following table.

Table 1.3A – Summation of Moments of Inertia

Shaft	Foot Holder
$I_1=8.2 \times 10^{-9} \text{ kg-m}^2$	$I_1=5.9 \times 10^{-6} \text{ kg-m}^2$
$I_2=1.7 \times 10^{-7} \text{ kg-m}^2$	$I_2=2.3 \times 10^{-6} \text{ kg-m}^2$
$I_3=2.35 \times 10^{-6} \text{ kg-m}^2$	$I_3=1.4 \times 10^{-5} \text{ kg-m}^2$
$I_4=1.7 \times 10^{-7} \text{ kg-m}^2$	$I_4=2.35 \times 10^{-6} \text{ kg-m}^2$
$I_5=2.4 \times 10^{-8} \text{ kg-m}^2$	$I_5=5.33 \times 10^{-6} \text{ kg-m}^2$
	$I_6=1.067 \times 10^{-5} \text{ kg-m}^2$
	$I_7=1.067 \times 10^{-5} \text{ kg-m}^2$
	$I_8=8.134 \times 10^{-5} \text{ kg-m}^2$
$I_{\text{Total}}=2.7 \times 10^{-6} \text{ kg-m}^2$	$I_{\text{Total}}=1.32 \times 10^{-4} \text{ kg-m}^2$

From table 1 it was seen that the total moment of inertia of the system was $1.35 \times 10^{-4} \text{kg} \cdot \text{m}^2$.

1.4 Torque Calculations

The peak torque the motor must overcome is the summation of the moment produced by the rat, and the product of the inertia of the system and the acceleration of the system.

The maximum acceleration the motor must achieve to meet the requirements of the project was found in Section 1.1 of Appendix A to be 1551 rad/s^2 . Therefore the maximum torque produced due to the inertia of the system was:

$$T = I \times \alpha = (1.35 \times 10^{-4} \text{kg} \cdot \text{m}^2) \times (1551 \text{ rad} / \text{s}^2) = 0.209 \text{N} \cdot \text{m}$$

The maximum torque the motor had to overcome was the summation of the moment produced by the rat and the total torque of the system. The moment produced by the rat was found in Section 1.2 of Appendix A to be $1.34 \text{N} \cdot \text{m}$. Therefore the maximum torque the motor had to overcome was:

$$T_{\text{max}} = 1.34 \text{N} \cdot \text{m} + 0.209 \text{N} \cdot \text{m} = 1.545 \text{N} \cdot \text{m}$$

After the gearbox was added to the system the torque that the motor saw was decreased to:

$$T = 1.545 \text{N} \cdot \text{m} / 12 = .129 \text{N} \cdot \text{m}$$

which is well below the peak torque of the motor ($1.68 \text{N} \cdot \text{m}$). The maximum torque the gearbox was able to output was also taken into consideration. The maximum

output torque of the gearbox was 4.2N-m, which was well above the maximum torque of the system of 1.545N-m.

Appendix B – Diagrams and Drawings

1 Mechanical Drawings

1.1 Overall Layout

1.2 Base Plate

1.3 Bearing Mount 1

Side View

Top View

1.4 Bearing Mount 2

1.5 Gear Box Mount

1.6 Motor Mount

1.7 Shaft

1.8 Load Cell Mount

Load Cell Mount
Side View

Load Cell Mount
Top View

1.9 Limit Switch

Unit Switch Plate

Coupler

1.10 Screw Device

Slide Bearings

Need 2

Top View

Drill to pass 1/4"-20 screw
Counterbore for 1/4"-20
screw +.05"

Side View

Drill for 3/8" diameter
nylon bearing

Middle Bearing

Top View

Side View

Threaded Rod

Turn down extra 1/2" of threaded rod to 1/4" O.D. on left end.

2 Wiring Diagrams

2.1 UMI-7764 Diagrams

The UMI 7764- was the breakout box to which almost all of the dynamometer components were wired. A diagram of the UMI-7764 is shown in the following figure.

Figure 2.1A – UMI 7764 Manual Diagram (57)

The UMI-7764 was connected to the PCI-7344 card by a cable that was run from the back of the UMI-7764 to a Motion I/O port located on the back of the computer.

2.2 Motor Wiring

Axis 1 was the axis used to control the motor. The motor wiring consisted of 2 cables: a 9 pin high power D connector and a 25 pin D connector. The 9-pin connector was attached to the motor connections port labeled A, B, C, ground on the BA Sinedrive amplifier as shown in the following figure.

Figure 2.2A – BA Sinedrive Connections

The 25-pin connector was attached to the BA Sinedrive in the slot labeled P3 ENC. A 9-pin cable was run from the BA Sinedrive slot P2 COMM to communications port 1 on the computer. A 25-pin cable was also run from P1 I/O slot on the BA Sinedrive to the UMI-7764. The cable that ran to the UMI-7764 was split and the proper pin colors and functions were determined as shown in the following table.

Table 2.2A - Pin Color Code

Pin	Color	Function (UMI-7764)
1	Brown	Shield
2	Red	Forward Limit(FWDLIM1)
3	Orange	Reverse Limit(REVLIM1)
4	Pink	Home Limit
5	Yellow	(INHOUT1-N)
6	Green	Input Common
7	Seagreen	MRKR-N (INDEX1-N)
8	Dark blue	MRKR (INDEX1)
9	Purple	Output Common
10	White – with ink	Fault Out
11	White – no ink	
12	Black	
13	Brown/white	
14	Red/white	
15	Red/black	Ground(GND)required input
16	Orange/white	(+5V)required input
17	Orange/black	(AOUT1)
18	Pink/black	(A0GND)
19	Yellow/black	Thermistor
20	Green/white	Restore/Reset
21	Green/black	SIN (ENCA1)
22	Blue/white	SIN-N (ENCA1- N)
23	Purple/white	COS (ENCB1)
24	Light blue	COS-N (ENCB1-N)
25	White/black	Ground

The correct wires were then matched to their designated function on axis 1 of the UMI-7764. It must be noted that the red/black and orange/white wires were not run to axis 1 but to the required inputs at the bottom of the UMI-7764.

2.3 Load Cell Wiring

The load cell had four output wires that were connected to the back of the load cell signal conditioner according to the following table.

Table 2.3A – Load Cell Wiring

Load Cell	Signal Conditioner
Red	+Exc.
Black	-Exc.
White	+Signal
Green	-Signal

The load cell signal conditioner was then connected to the analog input section of the UMI-7764 by the following table.

Table 2.3B – Signal Conditioner/UMI-7764 Wiring

Signal Conditioner	UMI-7764
-Output	AIGND
+Output	AIN1

2.4 Limit Switch Wiring

The four output wires from the limit switch were connected to the UMI-7764 axis 1 according to the following table. The red wire was connected in series with a 330ohm resistor.

Table 2.4A – Limit Switch Wiring

Limit Switch	UMI-7764
Red	+5V
Black	GND
Green	GND
White	FWDLIM1

Appendix C – Calibration

1.0 Load Cell Calibration

- 1.) Zero Adjustment – Make sure no load is applied to the load cell (Remove the footplate from the footholder). Next remove the front panel of the signal conditioner. Apply power to the signal conditioner and let it warm up for at least 10 minutes. Once warm up is complete use a screwdriver to adjust the coarse and fine zero shown in figure until they provide a zero reading on the display.

Figure 1.0A – Signal Conditioner Adjustment Diagram (62)

- 2.) Calibration – The values needed to properly calibrate the load cell are:

$$\text{Shunt Calibration Output} = 1.492\text{mv/v}$$

$$\text{Full-Scale Output} = 2.002\text{mv/v}$$

$$\text{Full – Scale Output} = 5V$$

Using these values the full scale output during shunt calibration can be found using the following equation:

$$\frac{\text{Shunt Calibration Output } \text{mv/v}}{\text{Full – Scale Output } \text{mv/v}} \times 5V = \text{Full Scale Output}$$

$$\frac{1.492 \text{ mv/v}}{2.002 \text{ mv/v}} \times 5V = 3.726V$$

This is the value that should be read by a voltmeter attached to the $\pm$ Output terminals (Figure 1.0B) located on the back of the amplifier when the shunt calibration button is pressed.

4.0 Initial Adjustments/Setup

Figure 1—GM Control Locations

Figure 1.0B – Amplifier Wiring Diagram (62)

If this is not the value read by the voltmeter when the shunt calibration button is pressed then the coarse and fine span on the front of the amplifier must be adjusted until they produce this value.

- 3.) Scaling – The amplifier can be scaled to display the load on the front panel in any form of units (lbs, N, kg, etc.). In order to display the load in a desired measurement unit the shunt calibration display value for that unit must first be calculated using the following equation:

$$\frac{\text{Shunt Calibration Output } mv / v}{\text{Full Scale Output } mv / v} \times \text{Full Scale Display Value} = \text{Shunt Cal Display Value}$$

The full-scale display value is the maximum load the load cell can read. This particular load cell has a maximum load of 50lbs. Therefore the full-scale display value is 50lbs converted to the desired units. For example if the scale were set to kilograms the full-scale display value would be 22.68kg. The value displayed on the front panel when the shunt calibration button is pressed should then be:

$$\frac{1.492 \text{ mv} / \text{v}}{2.002 \text{ mv} / \text{v}} \times 22.68 \text{ kg} = 16.9 \text{ kg}$$

If this is not the value displayed while the shunt calibration button is depressed, the scaling potentiometer shown in the following figure must be adjusted until this value is displayed.

2.0 LabVIEW Load Cell Scaling

The load cell amplifier sends a 0-5V signal to LabVIEW with 0V representing a zero load and 5V representing the full-scale load of 50lbs. LabVIEW then converts the voltage into a number between 0 and 4095, once again with 0 representing a zero load and 4095 representing a full-scale load of 50lbs. In order to be useful this number must be converted to a weight measurement equivalent to what is displayed on the load cell amplifier. Since LabVIEW converts the 0-5V from the load cell into a number from 0-4095 which is equal to a zero to full-scale load the following equation was found.

$$\frac{0V}{5V} = \frac{0}{4095} = \frac{\text{Zero Load}}{\text{Full - Scale Load}}$$

When the load is desired at some point other than zero the equation becomes:

$$\frac{\text{Unknown Voltage}}{5V} = \frac{\text{Number read by Labview}}{4095} = \frac{\text{Displayed Load}}{\text{Full - Scale Load}}$$

The equation can then be rearranged to find the load for any units.

$$\text{Displayed Load in Desired Units} = \frac{(\text{Number read by Labview}) \times (\text{Full - Scale Load in Desired Units})}{4095}$$

For units in pounds:

$$\text{Displayed Load in Pounds} = \frac{(\text{Number read by Labview}) \times (50\text{lbs})}{4095} = \frac{\text{Number read by Labview}}{81.9}$$

For units in kilograms:

$$\text{Displayed Load in Kilograms} = \frac{(\text{Number read by Labview}) \times (22.68\text{kg})}{4095} = \frac{\text{Number read by Labview}}{180.6}$$

For units in Newtons:

$$\text{Displayed Load in Newtons} = \frac{(\text{Number read by Labview}) \times (222.4\text{N})}{4095} = \frac{\text{Number read by Labview}}{18.4}$$

Once the load is converted to the proper units in LabVIEW the weight of the footplate must be converted into the same units and subtracted from the load measurement. This allows the LabVIEW program to display only the weight that is applied to the load cell from external loading by weights or rat force. The foot plate weighs 64g, which is equal to 0.06kg, 0.588N, or 0.13lbs.

3.0 Load Cell Calibration Results

3.1 Test 1 Results

Table 3.1A– Test 1 Weight Measurements

Known Weight (kg)	Measurement 1 (kg)	Measurement 2 (kg)	Measurement 3 (kg)	Standard Deviation (kg)
.01	.01	.01	.01	±0
.02	.02	.02	.02	±0
.05	.05	.05	.05	±0
.1	.1	.1	.1	±0
.2	.21	.19	.2	±0.01
.3	.29	.29	.29	±0.01
.4	.39	.39	.39	±0.01
.5	.49	.49	.52	±0.02
.6	.6	.58	.6	±0.01
.7	.7	.69	.69	±0.01
.8	.79	.81	.79	±0.01
.9	.91	.9	.9	±0.01
1	1	1	.98	±0.01
1.1	1.09	1.1	1.12	±0.02
1.2	1.17	1.18	1.21	±0.03
1.3	1.31	1.29	1.31	±0.01
1.4	1.46	1.39	1.37	±0.03
1.5	1.49	1.51	1.54	±0.03
1.6	1.6	1.61	1.64	±0.03
1.7	1.71	1.7	1.73	±0.02
1.8	1.81	1.8	1.83	±0.02
1.9	1.91	1.9	1.95	±0.04
2.0	2	2.01	1.98	±0.02
2.1	2.09	2.11	2.08	±0.02
2.2	2.2	2.21	2.18	±0.02
2.3	2.3	2.3	2.26	±0.03
2.4	2.4	2.41	2.37	±0.02
2.5	2.49	2.51	2.49	±0.01
2.6	2.59	2.6	2.57	±0.02
2.7	2.66	2.71	2.71	±0.03
2.8	2.8	2.81	2.82	±0.02
2.9	2.92	2.91	2.92	±0.02
3.0	3.01	3.02	3.05	±0.04
3.1	3.1	3.13	3.11	±0.02
3.2	3.19	3.23	3.23	±0.03

3.3	3.3	3.33	3.32	±0.02
3.4	3.4	3.43	3.45	±0.04
3.5	3.5	3.53	3.54	±0.03
3.6	3.59	3.62	3.64	±0.03
3.7	3.7	3.73	3.73	±0.03
3.8	3.79	3.82	3.78	±0.02
3.9	3.89	3.92	3.96	±0.04
4.0	4	4.02	4.06	±0.04
5.0	4.95	4.98	5	±0.04

Table 3.1B– Weight Positioning Data

Weight (kg)	Forward Position	Middle Position	Back Position	Standard Deviation
0.01	0.01	0.01	0.01	±0.0
0.02	0.02	0.02	0.01	±0.01
0.05	0.04	0.05	0.06	±0.01
0.1	0.1	0.11	0.09	±0.01
0.2	0.2	0.21	0.19	±0.01
0.5	0.52	0.5	0.48	±0.02

3.2 Test 2 Results

Table 3.2A – Isovelocity Load Cell Data Test 2

Known Weight (kg)	Zero Weight on Amplifier(kg)	Zero Weight in LabVIEW(kg)	Weight on Amplifier(kg)	Weight in LabVIEW (kg)
.01	0.02	0.0297	0.03	0.064
.05	0.02	0.057	0.06	0.103
.1	0.02	0.049	0.12	0.158
.25	0.02	0.051	0.26	0.291
.5	0.01	0.042	0.52	0.558
1.0	0.02	0.063	1.02	1.035
1.5	0.01	0.044	1.51	1.535
2.0	0.01	0.042	2.01	2.015
2.5	0.01	0.043	2.54	2.544
3.0	0.01	0.057	3.02	3.03
3.5	0.01	0.049	3.58	3.562
4.0	0.01	0.055	4.04	4.024
4.5	0.01	0.049	4.53	4.52
5.0	0.01	0.038	5.08	5.06

Table 3.2B – Error in Force Readings from Isovelocity Test

Known Weight (kg)	Zero Error Standard Deviation	Weight Error Standard Deviation
.01	$\pm .01$	$\pm .03$
.05	$\pm .04$	$\pm .04$
.1	$\pm .03$	$\pm .04$
.25	$\pm .03$	$\pm .03$
.5	$\pm .03$	$\pm .04$
1.0	$\pm .04$	$\pm .02$
1.5	$\pm .03$	$\pm .02$
2.0	$\pm .03$	$\pm .01$
2.5	$\pm .03$	$\pm .00$
3.0	$\pm .05$	$\pm .01$
3.5	$\pm .04$	$\pm .02$
4.0	$\pm .04$	$\pm .02$
4.5	$\pm .04$	$\pm .01$
5.0	$\pm .03$	$\pm .02$
Average	± 0.03	± 0.02

Table 3.2C – Isometric Load Cell Data Test 2

Known Weight (kg)	Zero Weight on Amplifier(kg)	Zero Weight in LabVIEW(kg)	Weight on Amplifier(kg)	Weight in LabVIEW (kg)
.05	0.01	0.26	0.06	-.059
.5	0.01	0.046	0.51	0.498
1.0	0.01	0.039	1.0	0.947
2.0	0.01	0.052	1.98	1.867
3.0	0.01	0.047	3.06	2.74
4.0	0.0	0.029	4.12	4.10
5.0	0.01	0.041	5.15	5.131

Table 3.2D – Error in Force Readings from Isometric Test

Known Weight (kg)	Zero Error Standard Deviation	Weight Error Standard Deviation
.5	± 0.04	± 0.01
1.0	± 0.03	± 0.05
2.0	± 0.04	± 0.11
3.0	± 0.04	± 0.32
4.0	± 0.03	± 0.02
5.0	± 0.03	± 0.02
Average	± 0.04	± 0.09

Table 3.2E – Concentric Isotonic Load Cell Data Test 2

Known Weight (kg)	Weight on Amplifier(kg)	Zero Weight in LabVIEW(kg)	Weight on Amplifier(kg)	Weight in LabVIEW (kg)
.05	---	---	0.06	0.105
.5	---	---	0.5	0.542
1.0	---	---	0.99	1.026
2.0	---	---	2.02	2.045
3.0	---	---	3.1	3.105
4.0	---	---	4.11	4.110
5.0	---	---	5.14	5.122

Table 3.2F – Error in Force Readings from Concentric Isotonic Test

Known Weight (kg)	Zero Error Standard Deviation(kg)	Weight Error Standard Deviation (kg)
.05	---	± 0.04
.5	---	± 0.04
1.0	---	± 0.04
2.0	---	± 0.03
3.0	---	± 0.01
4.0	---	± 0
5.0	---	± 0.02
Average	---	± 0.02

Table 3.2G – Eccentric Isotonic Load Cell Data Test 2

Known Weight (kg)	Weight on Amplifier(kg)	Zero Weight in LabVIEW(kg)	Weight on Amplifier(kg)	Weight in LabVIEW (kg)
.05	---	---	0.06	0.102
.5	---	---	0.51	0.555
1.0	---	---	1.02	1.048
2.0	---	---	2.04	2.058
3.0	---	---	3.07	3.084
4.0	---	---	4.08	4.078
5.0	---	---	5.11	5.097

Table 3.2H – Error in Force Readings from Eccentric Isotonic Test

Known Weight (kg)	Zero Error Standard Deviation (kg)	Weight Error Standard Deviation (kg)
.05	---	± 0.04
.5	---	± 0.04
1.0	---	± 0.03
2.0	---	± 0.02
3.0	---	± 0.02
4.0	---	± 0.0
5.0	---	± 0.01
Average	---	± 0.02

4.0 Motor Calibration Results

Table 4.0A – Velocity Results

Velocity (rpm)	Target Position (Counts)	Time Elapsed (Seconds)	Voltage (V)
2.5	10,000	30	0.005
10	40,000	30	0.05
30	120,000	30	0.075
50	200,000	30	0.125
100	800,000	60	0.225
500	2,000,000	30	1.25
1000	4,000,000	30	2.5
1500	6,000,000	30	3.75
2000	8,000,000	30	5
2500	10,000,000	30	6
3000	12,000,000	30	7.5
3500	14,000,000	30	8
4000	16,000,000	30	10

Figure 4.0A – Isovelocity Test Results at 600°/s

Figure 4.0B – Isometric Test Results at 15°/s

Figure 4.0C – Isometric Test Results at 600°/s

Appendix D – Software Programs

1.0 MAX Settings

The program that is used to setup the PCI 7344 board is called Measurement and Automation Explorer and is a product of National Instruments that comes with the motion control card. In order for the programs to function properly Max must be setup with the proper values. These values are shown in the following figures.

Figure 1.0A – MAX Axis Configuration

Figure 1.0B – MAX Axis Settings (Motion I/O)

Figure 1.0C – MAX Axis Settings (Breakpoint and Trigger)

Figure 1.0D – MAX Axis Settings (Control Loop)

Figure 1.0E – Axis Settings (Static Friction)

Figure 1.0F– MAX Axis Settings (Misc.)

Figure 1.0G– MAX Trajectory Settings (Trajectory Settings)

Figure 1.0H – MAX Trajectory Settings (Move Complete Criteria)

Figure 1.0I – MAX Find Reference Settings (Home)

Figure 1.0J – MAX Find Reference Settings (Forward Limit)

Figure 1.0K – MAX Find Reference Settings (Reverse Limit)

Figure 1.0L – MAX Gearing Settings

Figure 1.0M – MAX ADC Settings

Figure 1.0N – MAX Encoder Settings

2.0 BAS MMI Settings

In addition to the National Instruments software, a program also came with the BA Sinedrive called BA MMI. This program downloads values to the BA Sinedrive to insure that it runs properly. The necessary inputs are shown in the following figures.

Figure 2.0A – BA MMI (System Parameters)

Figure 2.0B – BA MMI (Option Parameters)

Figure 2.0C – BA MMI (Loop Parameters)

In addition to the parameters shown in the above figures the operation mode must also be set to velocity in the toolbar under operation mode.

3.0 LabVIEW Programs

Figure 3.0A – Initial Positioning Diagram

Figure 3.0B – Isovelocity Program Diagram

Figure 3.0C – Isometric Program Diagram

Figure 3.0D – Concentric Isotonic Program Diagram

Figure 3.0E – Eccentric Isotonic Program Diagram