The Use Of Antagonist Muscle As A "Catch" In Explosive Movement

by
Peter J. Wellings

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2009

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Abstract

Explosive movements are necessary for many animals to capture prey or escape predators. The movements often require quick bursts of energy that cannot be supplied by muscles alone. Some animals, especially insects, store energy in their tendons by restraining motion with a physical catch, stretching the tendon by flexing the muscle and releasing the energy through the tendon. Since the tendon can release energy faster than the muscle, the peak powers can be much higher. This study asks whether an opposing muscle could be used as the catch in this scenario to restrain the motion. Using a novel apparatus developed in the MIT media lab, a model of this system was simulated using live muscle tissue. It was shown that for loads below 30% of the maximum force of the muscle, using an antagonist muscle as a catch could produce beneficial power amplifications. These amplifications increase as the load and muscle release rates decrease.

Thesis Supervisor: Hugh M. Herr

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Introduction:

Nature demonstrates time and time again how it has perfected its mechanisms. Musculoskeletal systems are no exception. Ambulation is necessary for all animals to survive. For many animals explosive movements are just as important. Many use these explosive movements to capture prey or escape from predators or other dangers. Even humans require explosive movements to protect themselves or for recreational activity.

Nature has optimized muscles to serve the animal's typical ambulatory needs. This has made the muscle a not-so-desirable source of energy for the occasional explosive movements. In many cases, though, Nature has found a way to amplify the power released during these motions, well above powers achievable by the muscle alone, using the tendon. If the muscle can be allowed to expend energy in a way that is most efficient for it, then that energy could be stored and released suddenly for an explosive movement.

This study examines the approach of storing muscle energy in a tendon by examining a "catch". A "catch" is an opposing force (or a reaction force) that immobilizes the joint as the muscle contracts and releases when the explosive movement is desired, soon thereafter. As the joint is immobilized the muscle performs a fixed-end contraction that stretches out the tendon. Using the tendons spring-like properties the muscle's energy can be stored and then released at a much faster rate than the muscle could contract. Since the tendon can expend its energy over a much shorter time, the power is significantly higher than powers producible by the muscle in a typical configuration. A diagram of the "catch" mechanism can be seen in Figure 1.

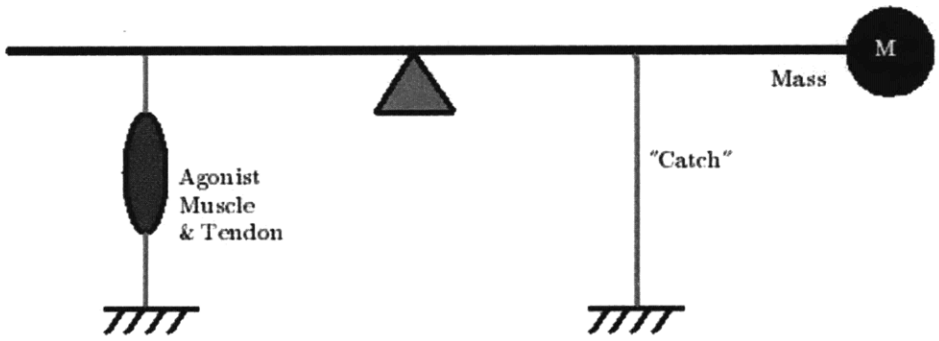

Figure 1: Illustrates the catch system. The catch is shown here as a string tying the lever to ground during activation of the agonist.

Explosive Movements in Nature: "Catch" Systems

There are a few cases in nature where animals employ this mechanism to great benefit. The most obvious cases are insects, such as fleas or locusts, which have the ability jump much higher than their muscles should allow. These insects have developed anatomies that allow them to lock their skeleton and load their tendons. Fleas have been shown to momentarily tense their entire body before jumps; this tensing is the loading of the tendons before a jump. Locusts have been shown to employ the same tactic along with a handful of other jumping insects. Most other animals did not develop the

anatomies that these insects have. Humans, for example, do not have the skeletal configuration that allows them to perform this loading task.

Could An Antagonist Muscle Be A "Catch"?

Considering the obvious jumping capabilities of insects, it is the interest of this study whether catches are at work more subtly in other animals. For the many animals that do not have the capability to lock their joints like the flea, is it possible to instead use an antagonist muscle to hold the joint still? The antagonist muscle would match the force seen in the agonist muscle as the agonist loads the tendon. Then, the antagonist releases its hold and, thus, the energy in the tendon is released.

The question that this study seeks to answer is whether antagonist muscle can relax quickly enough to act as a catch. While muscles are relatively slow to contract, they are often slower to release, especially when fatigued. This lag could rob the catch of its power amplification. In this study, various release rates will be applied to the simulated antagonist force seeking a critical release rate where a catch is no longer advantageous. This rate will then be compared to release rates of natural muscle to determine the efficacy of using an antagonist muscle as a catch.

Additionally, it is likely that a passive version of this catch is at work in most animals. Without using an active catch, the mere force of the load can be enough to hold back the joint as the muscle stretches the tendon a bit (until the muscle-tendon force reaches the force of the load). This is called and inertial catch. This study also looks at the advantages of an inertial catch when compared to an active catch or no catch at all.

Muscle Structure and Function

Due to availability and prevalence in past research, the *plantarus longus* muscles of leopard frogs (*Rana pipien*) are used in this study to act as the agonist muscle. The *plantaris longus* would be the equivalent of the calf muscle in humans; the muscle is responsible for ankle extension. The dissected tissue is comprised of tendon, nerve and muscle. There are two types of tendon in three locations on the muscle after dissection. When the muscle is dissected it is separated at the proximal tendon as close to the muscle as possible; and at the distal end it is removed such that one quarter of the muscle length in tendon remains attached to the muscle. The distal tendon is the tendon that will be loaded to create power amplification in the catch experiment. The third tendon is the aponeurosis. This is a parallel tendon that fans out as a sheath around the distal half of the muscle. It behaves like a tendon, but in parallel. The aponeurosis contributes little to the spring-like behavior of the muscle-tendon when compared to the much larger distal tendon. The dovetail inserts are tied to the proximal and distal tendons using surgeon's suture and the muscle is placed into the receiving slots of the apparatus. The tibial nerve inserts at the proximal end and is trapped inside hook electrodes to stimulate the muscle.

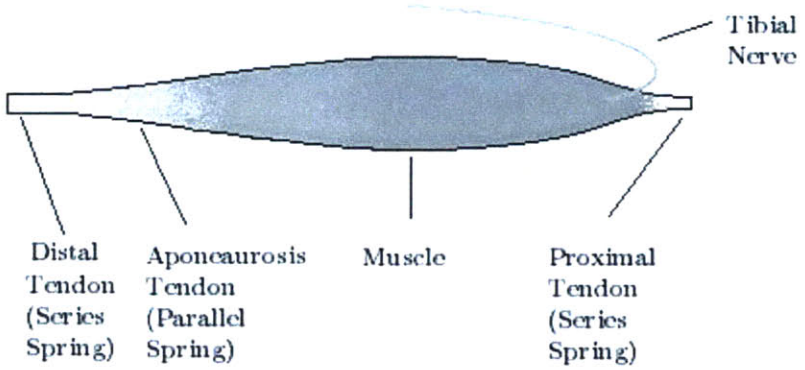

Figure 2: The structure of dissected tissue used in this experiment. Inserts were tied to tendons at each end and the nerve was captured in a hook electrode stimulator.

The "Catch" System

The "catch" mechanism can manifest in many different configurations. The configuration that is discussed in this paper seeks to roughly model the human calf muscle operating on the foot at the ankle joint. The system consists of a lever with the agonist muscle on one side and the antagonist muscle and mass on the other. Initially the mass rests on a table. This is an artifact of the simulation code described later and it is used as a means to prevent negative displacements during the loading phase.

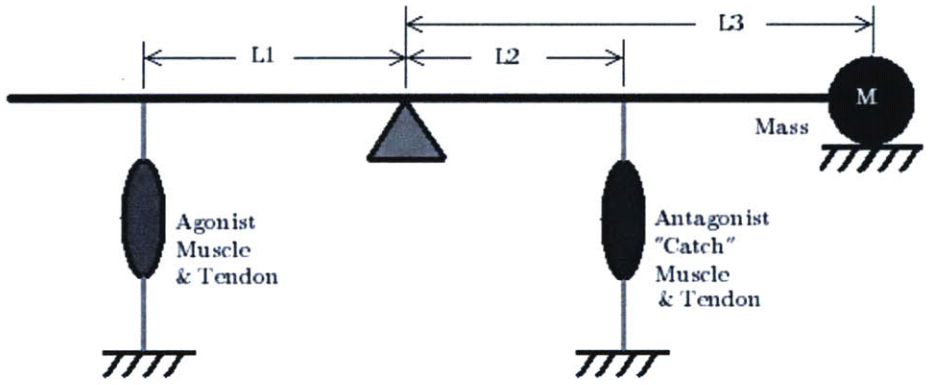

Figure 3: Catch system with antagonist muscle as catch. L1, L2 and L3 are the lever arms of the agonist, antagonist and mass respectively. M is the mass of the load.

This "catch" system can be described by a simple torque balance. From this torque balance a governing equation was created and used as a control algorithm for testing. Equation 1, below, describes the torque balance. Equation 2 shows the acceleration of the agonist muscle assuming a large L_1.

$$F_{agonist}L_1 - F_{antagonist}L_2 - mgL_3 = mL_3^2\ddot{\theta} \tag{1}$$

$$\ddot{x}_{agonist} \approx \ddot{\theta} = \frac{F_{agonist}L_1 - F_{antagonist}L_2 - mgL_3}{mL_3^2} \tag{2}$$

Literature Review

Recent experiments have made the question posed by this study very interesting. The idea of a fleas and locusts loading their skeletons to jump higher is an old one, posited as early as 1967 by Bennet-Clark. Understanding the mechanism happened a bit later. The area of muscle energetics has more recently become flooded with research from groups using apparatuses similar to this one to test the strange behaviors of muscle. Galantis and Woledge were the first to study the catch mechanism's power amplification (but only theoretically) in 2003. They examined the idea of the ideal instantaneous catch and the mechanism that creates its power amplification. Their study predicts a near ten times power amplification for the instantaneous catch. In an unpublished 2009 study, Sheppard and Sawicki tested the advantages of inertial catches (using the mass as the resistive force for small amounts of loading) on bullfrog muscle. Greg Sawicki is an advisor to this study.

The Hypothesis

It is anticipated that a quick releasing catch (roughly over 100 N/s) amplifies power over the non-catch configuration. It is also expected that for low force contractions power amplification is significant even with slower catches. For high force contractions, it is expected that a catch is not a beneficial configuration.

Methods:

Experimental Apparatus

In order to examine the energetics of the catch system it is necessary to use an apparatus with the appropriate components and controls to simulate a virtual mass, lever and antagonist muscle. The apparatus also needs to be able to measure the interesting aspects of these interactions: displacement, force, velocity and power.

The apparatus, designed by Waleed Farahat, consists of a small bath with a fixed dovetail connection on one end, and a moveable stage on the other end, also with a dovetail connection. The stage can move in the horizontal plane relative to the fixed bath. The moveable stage is attached to a voice-coil motor that is used to control the position of the stage. The stage is fitted with a magnetic strip that passes alongside a magnetic position encoder as the stage moves. The encoder is used to provide position feedback. The fixed-end dovetail connection is connected to ground through a load cell to measure the forces placed on the fixed-end by the muscle. The muscle is tied to two dovetail inserts that slide into the dovetail connections on the bath and the stage. The muscle, pinned to the dovetails on each side, is submerged in Ringer's solution as the bath is filled. The nerve of the muscle is then fed into the hooked-end of the stimulator. The stimulator is capable of delivering electrical signals to the nerve of the muscle. The stimulators, shown in Figure 4 are plastic hooks with embedded contacts and wiring to deliver the impulse. The voice-coil motor, the stage, the muscle and the load cell are all connected in one axis of motion as is detailed in Figure 4.

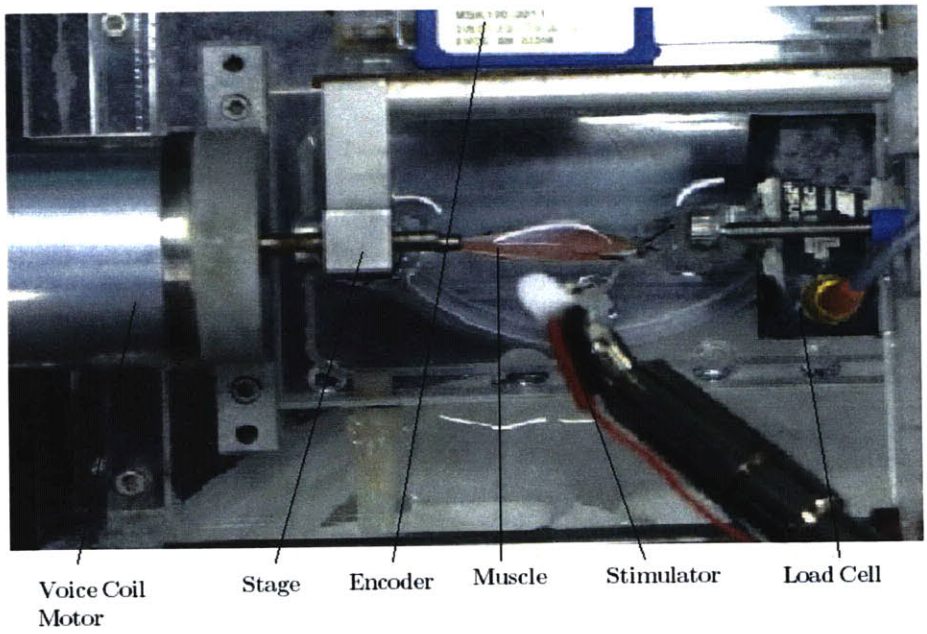

Figure 4: Photo of apparatus setup before a test.

To drive the voice-coil motor and read the encoder and load cell, a computer is fitted with a data acquisition board that interfaced with the basic power electronics on the apparatus. These power electronics are used to amplify the signals sent by the data acquisition board. The data acquisition board communicates with the main control computer through an Ethernet connection. The Ethernet connection allows the main control computer to use Simulink to create control code that can run on the slave computer fitted with the data acquisition board. A Simulink model, created on the main computer, is deposited onto the slave computer and runs each experiment. A user interface, created in MATLAB, allows the experimenter to interact with the Simulink model in-between experiments. A detailed diagram of the flow of information can be seen in Figure 5.

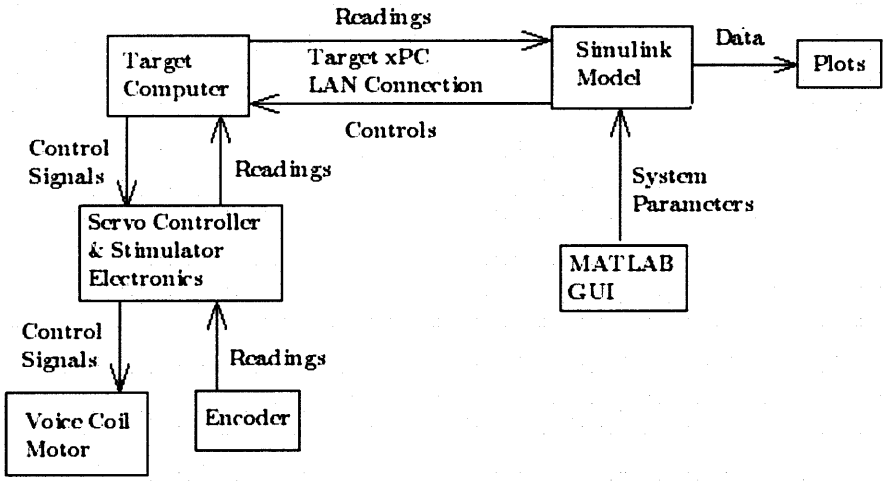

Figure 5: Apparatus information flow diagram.

Simulink allows its user to create simple block diagram control models and run them like computer code. Using this functionality a simple block diagram version of the governing equation was created to simulate the lever, mass and antagonist muscle. The model reads the change in force exerted by the muscle from the load cell, places it in the governing equation, solves for the new position of the lever, compares this to the current position of the muscle and moves the muscle accordingly through the voice coil motor. In addition to the governing equation, a few addition control loops are added to ensure the safety of the muscle and apparatus in case of flyaway. The controlling block diagram can be seen in Figure 6.

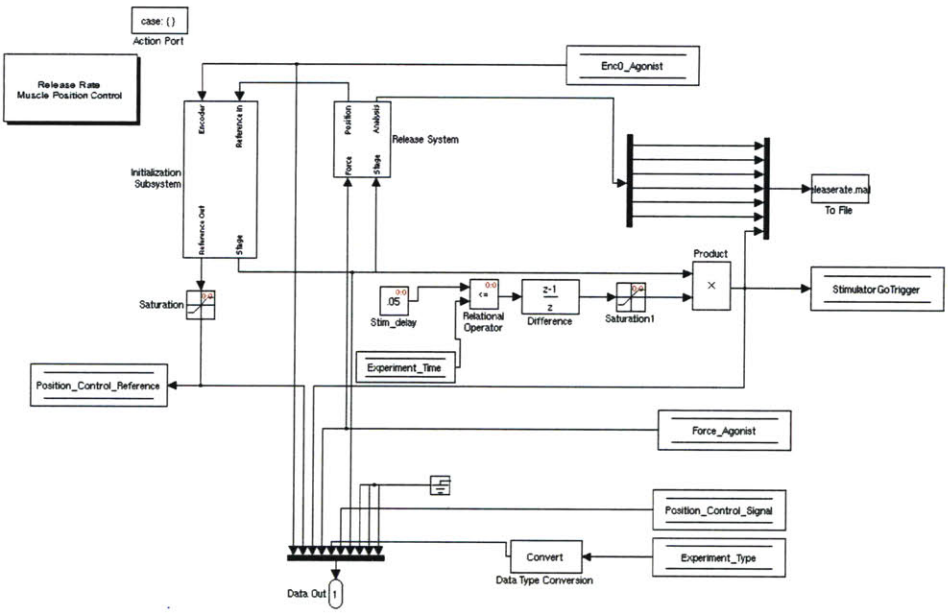

Figure 6: View of the Simulink block diagram model.

The MATLAB user interface, shown in Figure 7, is also designed to take the data from the load cell and encoder and output plots. After each experiment is completed, the MATLAB code reads data stored in Simulink from these devices and outputs plots of muscle displacement versus time, muscle force versus time, and muscle power versus time. The displacement and force readings come straight from the encoder and load cell, but the power is calculated by taking the derivative of the displacement to find the velocity and multiplying it by the force at that instant.

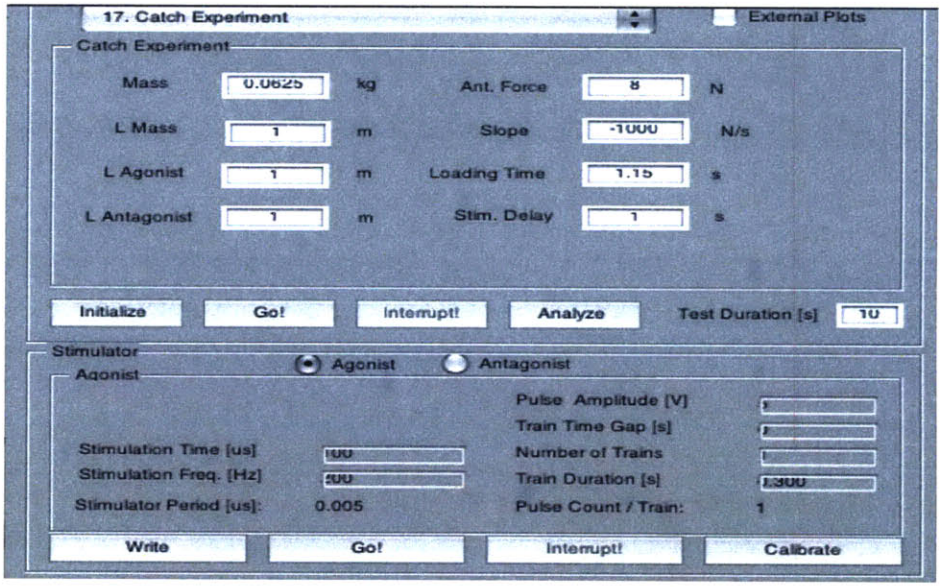

Figure 7: View of the MATLAB graphical user interface.

Live Muscle Testing

To examine the unique behavior of the muscle-tendon complex in this system, it is necessary to use live muscle tissue. Experimenting with the muscles requires that they be preserved as close to their original state as possible for the length of the experiment. Using common practices in the research community, amphibian Ringer's solution (a solution of water and electrolytes) is used to fill the bath and preserve the muscle.

Experimental Procedure

The experimentation consists of three steps: dissecting the muscle, testing its basic characteristics and running the force-velocity and catch experiments.

Characterizing the Muscle

In order to collect meaningful data from the muscle, it is necessary to establish working conditions that are similar to the typical operating conditions for the muscle in-vivo. This requires setting an initial tension in the muscle. The required initial tension is determined by finding the peak force generated by the muscle over a range of initial tensions. Whichever initial tension produced the maximum force is set as the initial tension. The initial tension is determined to be roughly 0.1 Newtons. This initial tension allows the muscle to act in its most efficient capacity and generate its greatest power outputs.

Next, it is necessary to determine the magnitude of the electrical stimulus. The resting tension is applied to the muscle and electrical impulses of 5, 10, 15 and 20 Volts are given to the nerve. The lowest value at which maximal contraction force is observed is determined to be the appropriate stimulation voltage. Typically, this is 15V. A plot of stimulation voltage versus output force can be seen in Figure 3.1 below.

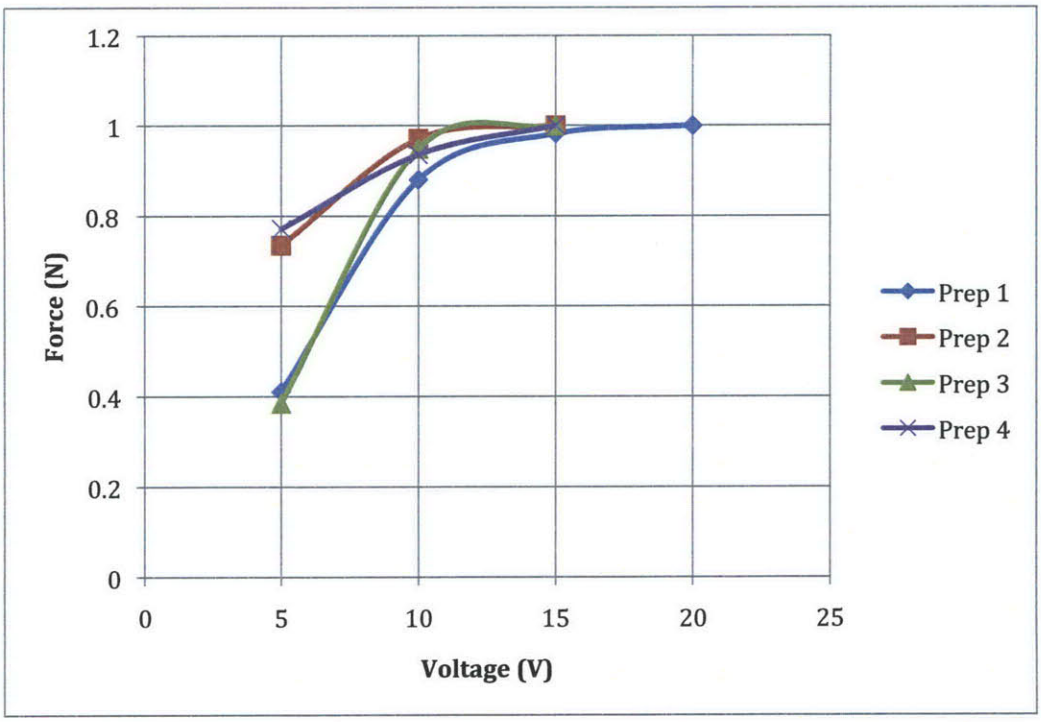

Figure 8: Dependence of output force on stimulation voltage. Force reaches maximum near 15V-20V.

Lastly, it is important to understand the peak force output capabilities of the muscle. Fixed-end contractions (isometric twitches) are performed to establish this value, which typically falls between 5 and 10 Newtons. This value is used later in the procedure to set the force of the simulated antagonist muscle and to determine the extent of muscle fatigue.

The data for the characterization tests are stored and viewed in MATLAB and important values are recorded in Excel for later analysis.

Force-Velocity Tests

One of the most important aspects of this experiment is to compare the power amplification capabilities of the "catch" configuration. In order to do so, a baseline power output must be obtained. The goal of the force-velocity test is to create a force versus velocity curve that shows the maximum velocity the muscle can contract at, given a certain load. Multiplying the force values by their respective maximum velocities gives the peak power the muscle can output for that load. The force-velocity test can be visualized as shown in Figure 9.

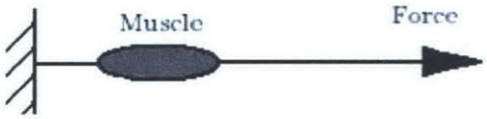

Figure 9: Visual representation of the Force-Velocity Experiment.

The scenario above is simulated by adjusting the position of the voice coil in order to maintain constant force as the muscle contracted. The test consisted of initiating the voice coil position control to simulate a given force then stimulating the muscle and allowing it to pull the load as fast as it can. The muscles are stimulated maximally in order to ensure maximum force output throughout the tests. For each muscle a force velocity test is conducted for 8-10 data points spanning the entire range of forces producible by the muscle. Raw data is collected and viewed in MATLAB, then exported to Microsoft Excel for higher-level analysis. The data is analyzed examining trends in force versus velocity, force versus power and peak power. Below, in Figure 10, are typical data from a force-velocity test.

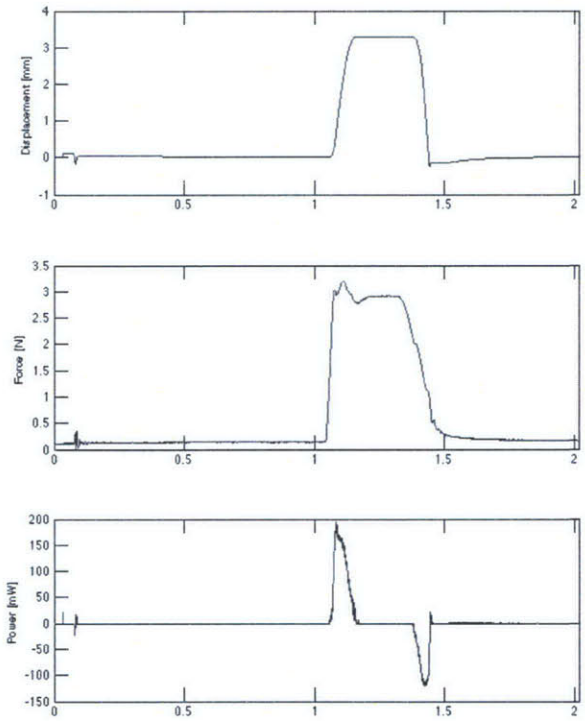

Figure 10: Sample real time data of displacement (top), force (middle) and power (bottom) from a Force-Velocity experiment. Negative displacement is shown positive.

"Catch" Tests

The catch tests are run using the controls described in the apparatus section. The muscle is excised and loaded into the apparatus. Anywhere from 6-15 tests are performed on each muscle varying mass and release rate. Before each test, the most recent isometric contraction force is used to set the initial force of the simulated antagonist. Roughly 0.5 Newtons is added to this value to control for variance in the muscle's force reading; if the initial antagonist force had been exceeded too early in the test, the control algorithm will not run. For simplicity, the lever arms are all set to 1 meter. To allow for the system to initialize, stimulation of the agonist begins 1 second into the test (0.15 seconds before release) and continues for 300 milliseconds (until 1.3 seconds). After 1.15 seconds, the catch is released and the simulated antagonist begins to reduce its force at the specified release rate. The catch test is conducted using masses between 0.01625 and 0.25 kilograms and release rates between 0 and 1000 Newtons per second. A view of the raw data demonstrating the sequence of events can be seen in Figure 11.

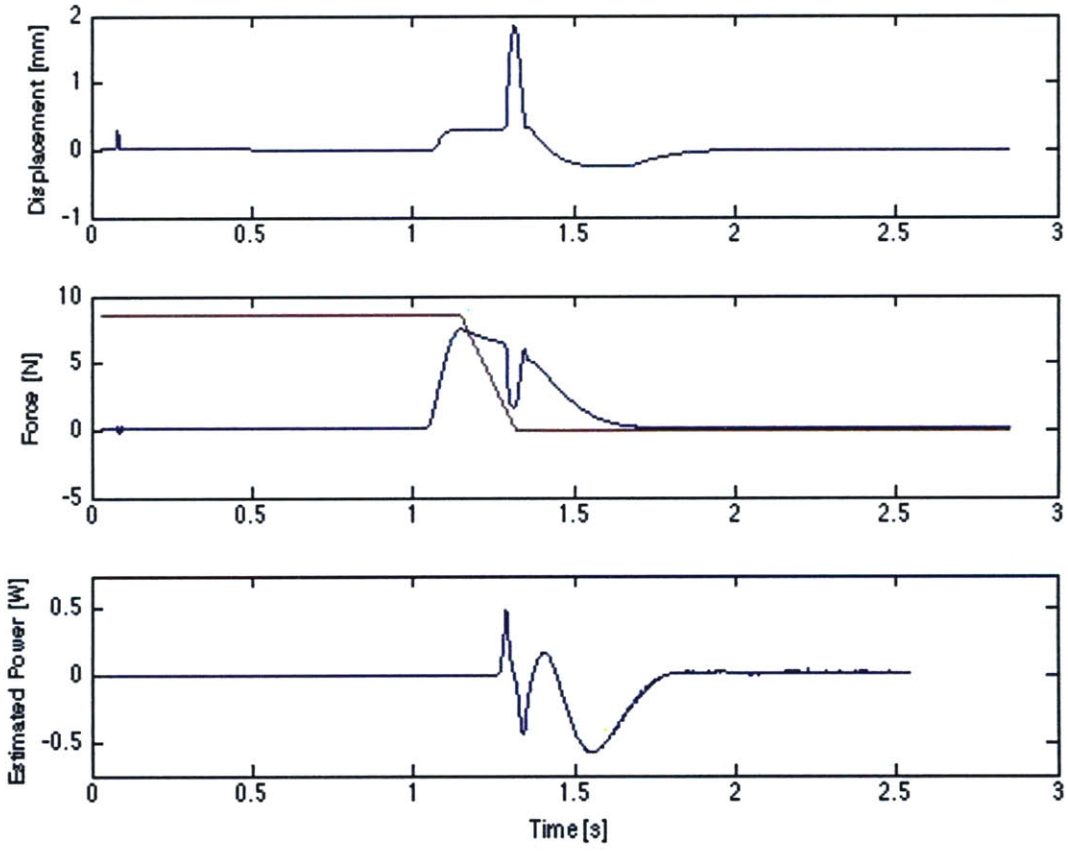

Figure 11: Real time data from a catch experiment. The curve that initially begins higher on the force plot represents the antagonist force versus time. Negative displacement is shown positive. Stimulation occurs between 1 second and 1.3 seconds.

Results:

Data from multiple muscles is gathered and normalized by peak power and peak force to generate the plots shown in the following section.

Muscle Displacement, Force and Power Output

Below you can see the displacement, force and power versus time plots for a typical catch test.

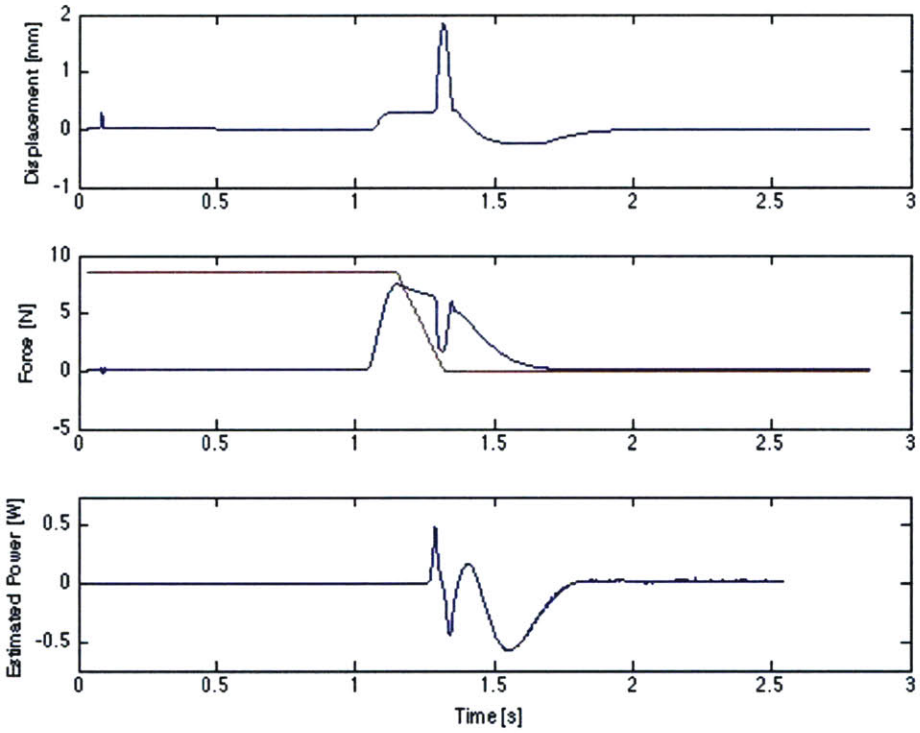

Figure 12: Real time data for a typical "catch" experiment. The curve that begins higher on the force plot represents the antagonist force versus time.

Force-Velocity-Power Curves

Below are the curves representing the force-velocity tests. These curves represent the baseline performance of the muscle. The values from these curves are used to normalize the catch data.

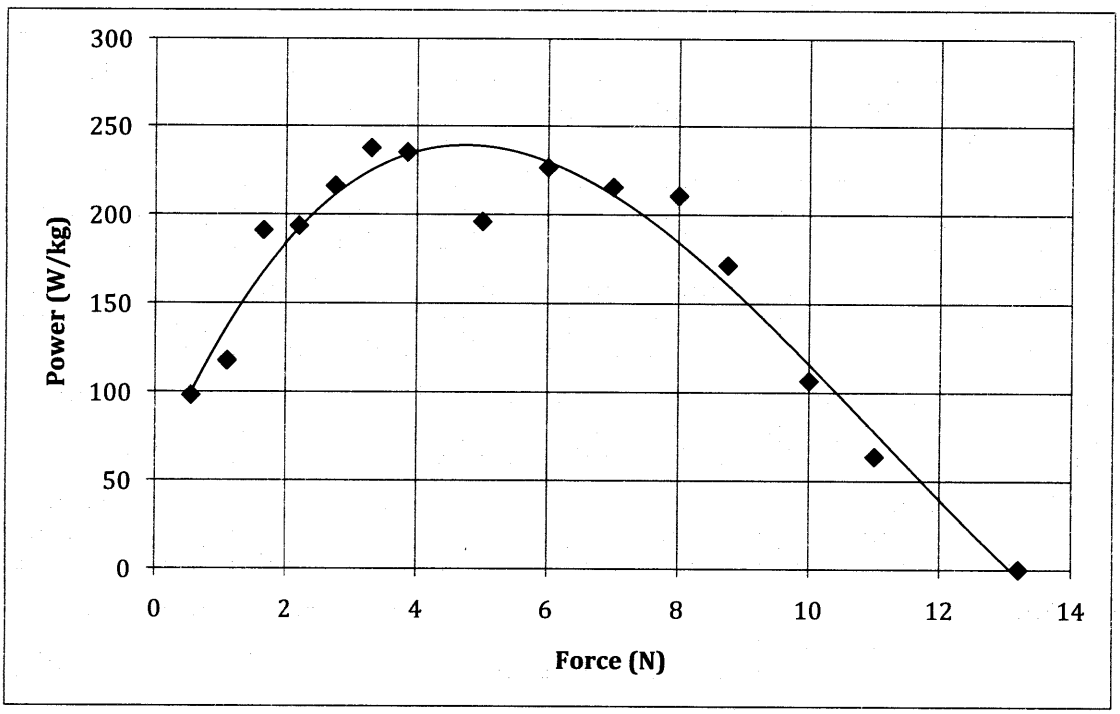

Figure 13: Power versus force from the Force-Velocity tests. Demonstrates peak power at 1/3 of the maximum force.

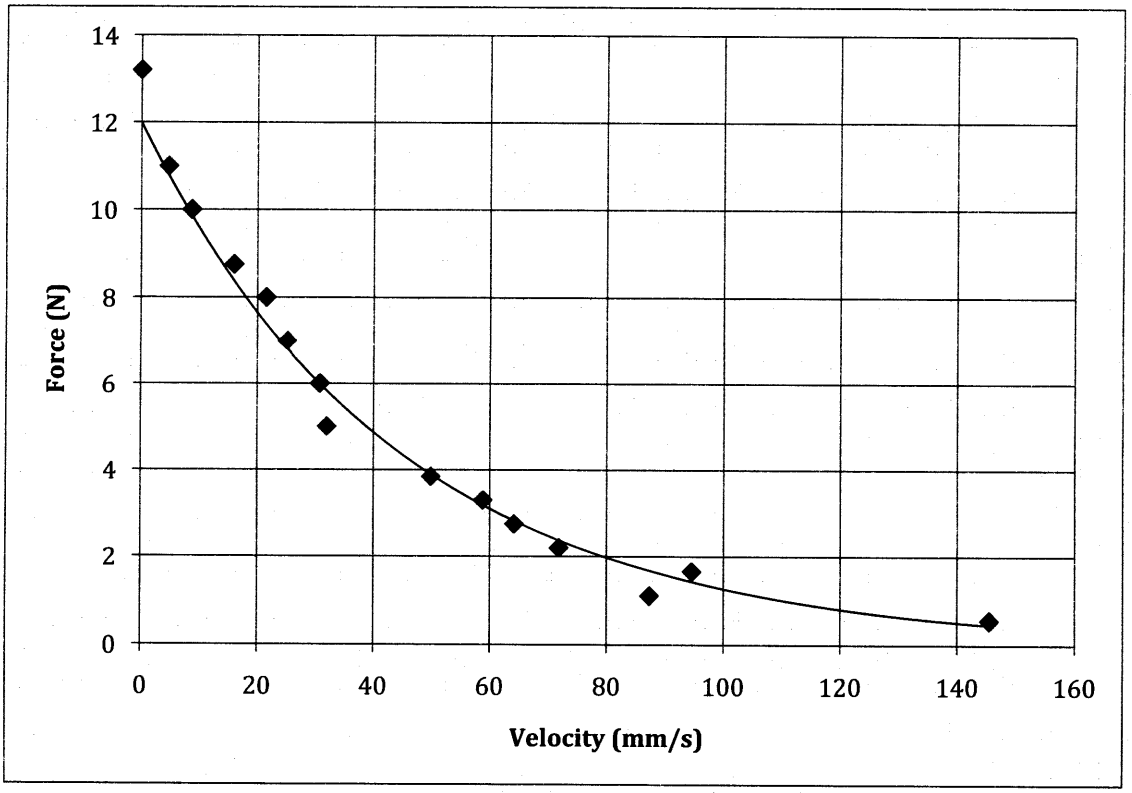

Figure 14: Force versus velocity for the Force-Velocity tests.

"Catch" Power Amplification

The following graphs represent the effectiveness of the catch configuration across a spectrum of loads. The power is normalized by the peak power output for each muscle. The force is normalized by the peak force output for each muscle.

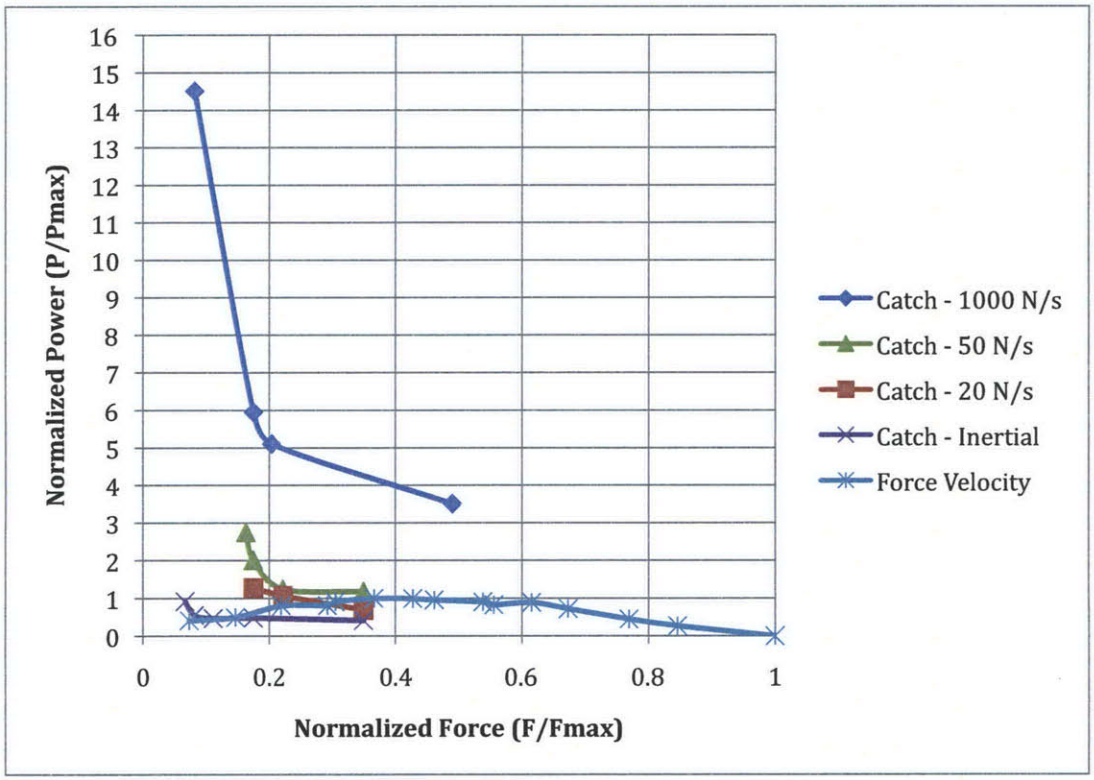

Figure 15: Peak power output versus force normalized by peak values for each muscle. For catch data, force represents the weight of the mass. Intersection with the force-velocity curve indicates a lack of power amplification at that load.

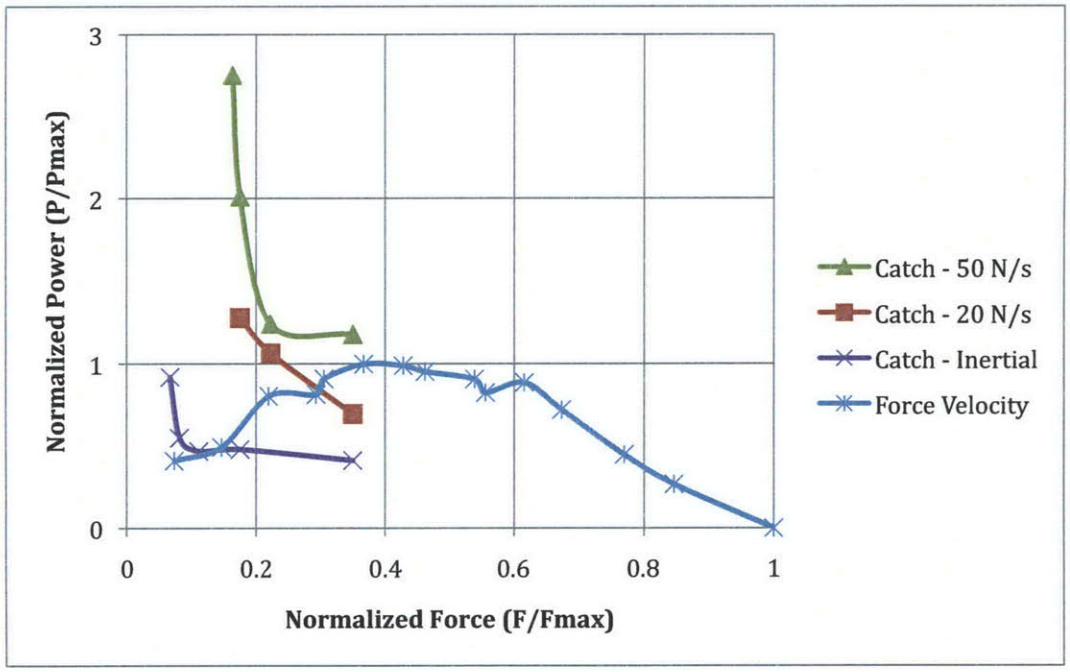

Figure 16: Figure 16 with a focus on the slower release rates.

Power versus Release Rate

To demonstrate the relationship between the release rate and the power output seen, the following plots has been created.

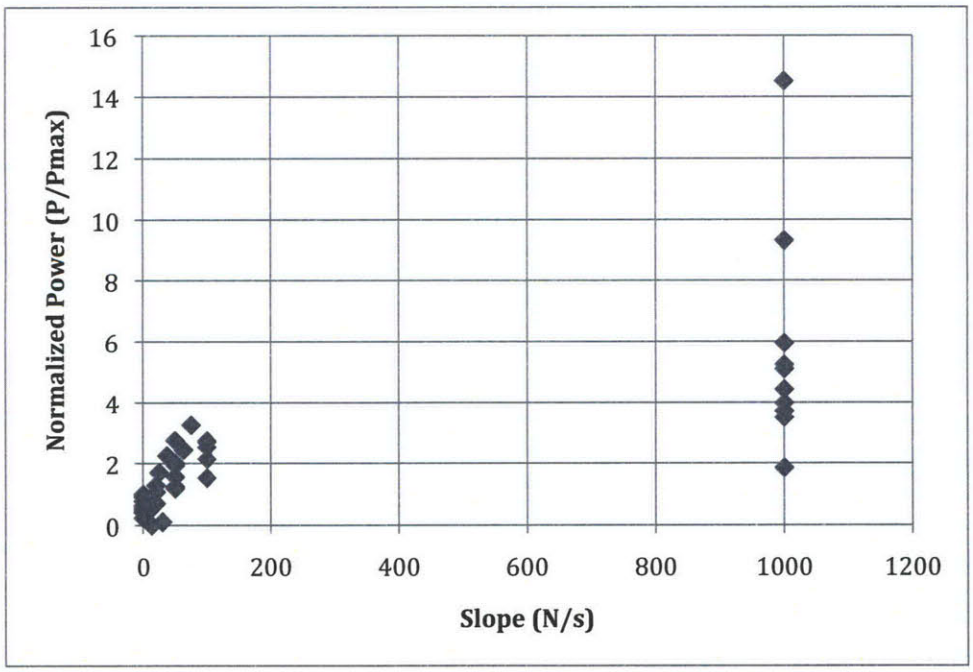

Figure 17: Demonstrates the power amplification at various release rates for various loads. As the slope increases the power approaches large values of amplification for all loads.

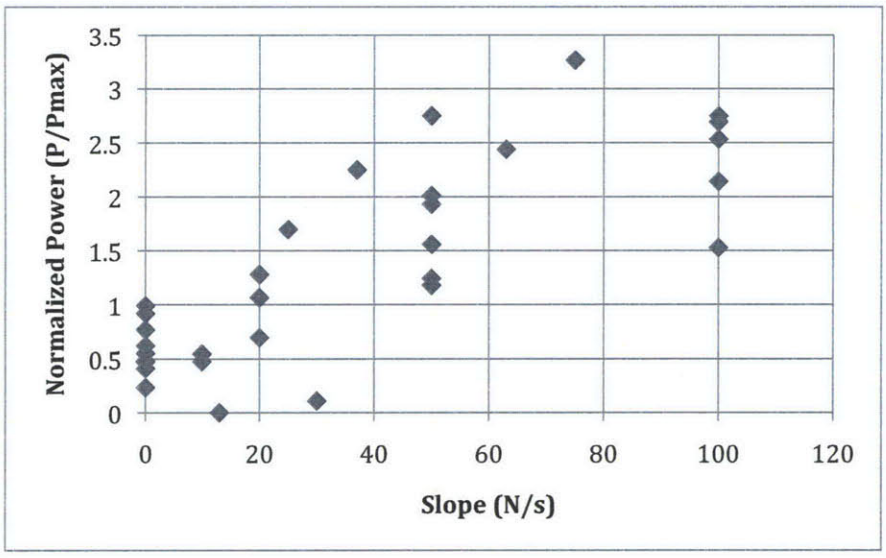

Figure 18: Figure 18 with a focus on slower release rates.

Comparison to Natural Muscle Release Rates

In order to assess the possibility of using a muscle as a catch, the following plot has been generated showing the rate of release for a muscle in an isometric (fixed-end) contraction. The stimulation is 15V for 300ms.

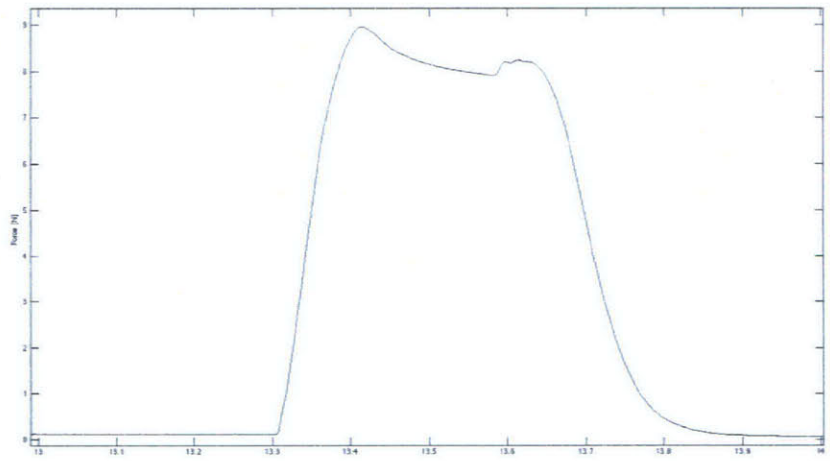

Figure 19: Typical force versus time curve for *plantaris longus*. Release rate here is 63 N/s.

The average release rate for the muscles was determined to be 60 N/s. This value rapidly decreases as the muscle begins to fatigue. Values that are taken from fatigued muscles are not considered. In nature, the animal is expected to use a non-fatigued muscle to perform these explosive movements.

Discussion

Use of the Antagonist Catch

The results from this experiment suggest that it is advantageous to use an antagonist muscle as a catch in certain scenarios. If the catch can be released close to instantaneously, power amplification can be seen for most loads. This is not possible if the catch is an antagonist muscle. If the catch releases slower (less than 100 N/s), the advantage only exists for lighter loads (less than 30% maximum force output). Therefore, using an antagonist muscle as a catch is advantageous for lighter loads. Simply put, if the antagonist muscle is not capable of releasing faster than the agonist tendon can retract, then the power amplification will be less than 1. Power amplification for release rates on the order of the muscle release rate is minimal compared to that of instantaneous releases. Though the benefit is significantly lower for a slower releasing catch, this does not imply that such mechanisms are not at work in these animals. The benefit does exist, however small, and animals could benefit from this capability. The hypothesis underestimates the power amplification capabilities of the catch system, since amplification is seen for release rates below 100 N/s; however, this power amplification is seen only for lighter loads.

Further Considerations and Future Work

The experiment, while answering the question at hand, provides further insight into the scenario that was not available before. The tests also elucidate unseen limitations of the experimental apparatus.

One interesting observation is the vibration of the tendon after the catch release. This vibration is due to mass-spring oscillations after the tendon (spring) is pre-stretched and then released with the mass on the other end of the lever. These vibrations trace the descending force of the antagonist as it limits the amplitude of the oscillations until its force is reduced entirely. This effect can be seen in Figure 12.

One variable that is not explored in this study is muscle morphology. It is reasonable to believe that by altering the relative positions along the lever of the agonist and antagonist muscle, it would be possible to accommodate various muscle morphologies. If a smaller muscle, that would have a faster release rate but lower peak force, could be used at a longer lever arm, then it may be able to amplify power higher than a morphology that matched the agonist. This idea should be examined in future experiments.

Another consideration that may reveal more insights is the use of non-linear release profiles. Muscles tend to release with a more exponential decline and simulating this behavior may more accurate predict the power amplifications seen in nature.

There are a few limitations in the system that become apparent during the experiments. The most obvious is fatigue. With each stimulation, the muscles become weaker and, as the experiment continues, the muscle loses its strength exponentially. As the muscle fatigues, its peak force decreases and this decline is normalized. As the

fatigue continues, though, the power output of the muscle decreases; this can not be normalized. Data from tired muscles are not used, but small declines before the muscle was noticeably tired may confound the data. The order of the tests is randomized from muscle to muscle to lessen this effect through averaging.

The stimulators used in this experiment are hook stimulators, which contact the circumference of the nerve. In order to see full activation of the muscle under these conditions, large voltages need to be used. Since much of the voltage is lost to the Ringer's solution, the voltages used are almost an order of magnitude larger than those necessary to fully stimulate the muscle and these values have to be calibrated often. Future studies will utilize more appropriate stimulators that direct voltages at the head of the nerve to ensure full activation throughout experiments.

Acknowledgements

The author would like to acknowledge his thesis advisor, Professor Hugh Herr, for the freedom and opportunity to design an engaging thesis project. He would also like to acknowledge Greg Sawicki of Brown University for his teaching and guidance throughout the process. He would like to acknowledge Eric Swart for his help and company in designing and carrying out this project. Finally, he would like to acknowledge Waleed Farahat for the development of the apparatus that made this exciting research possible.

Biographical Note

Peter Wellings is a mechanical engineering student with interests in medical device design. He began working in the Biomechatronics group in MIT's media lab in the fall of 2008. There, he assisted Eric Swart under the direction of Professor Hugh Herr in conducting muscle energetics research. He continued this work under the additional advisement of Post-Doctoral Fellow Greg Sawicki of Brown University, culminating in this thesis paper. He plans to continue this research towards the possibility of a published manuscript.

References

Swart, E.F., 2009, "Control of Resonance Shift Via Muscle Activation Using a Novel Antagonist Muscle Testing Apparatus", Harvard-M.I.T. Division of Health Sciences and Technology, Cambridge, MA.

Farahat, W., Herr, H., 2006, "Workloop Energetics of Antagonist Muscles", Proceedings of the 28th IEEE EMBS Annual International Conference, IEEE, New York, pp. 3640-3643.

Farahat, W., Herr, H., 2005, "An Apparatus for Characterization and Control of Isolated Muscle", IEEE Transactions on Neural Systems and Rehabilitation Engineering, 13(4), pp. 473-481.

Farahat, W., 2007, "Optimal Workloop Energetics of Muscle-Actuated Systems", Massachusetts Institute of Technology, Cambridge, MA.

Bennet-Clark, H.C., Lucey, E.C.A., 1967, "The Jump of the Flea: A Study of the Energetics and a Model of the Mechanism", Journal of Experimental Biology, 47, pp. 59-76.

Roberts, T.J., Marsh, R.L., 2003, "Probing the Limits to Muscle-Powered Accelerations: Lessons From Jumping Bullfrogs", Journal of Experimental Biology, 206, pp. 2567-2580.

Ferenczi, M.A., Goldman, Y.E., Simmons, R.M., 1983, "The Dependence of Force and Shortening Velocity on Substrate Concentration in Skinned Muscle Fibres From *Rana Temporaria*", Journal of Phisiology, 350, pp. 519-543.

Galantis, A., Woledge, R.C., 2003, "The Theoretical Limits to the Power Output of a Muscle-Tendon Complex With Inertial and Gravitational Loads", Proc. R. Soc. B, pp. 1493-1498.

Herzog, W., Leonard, T.R., Joumas, V., Mehta, A., 2008, "Mysteries of Muscle Contraction", Journal of Applied Biomechanics, 24, pp. 1-13.eri