Jumper Design Document

ME112

Team Mynock On Wood
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1 Executive Summary

The final project of Mechanical Systems Design challenges us to create a battery-powered jumping robot able to jump one meter and stick to a Velcro ceiling. The robot is inspired by Mynocks, the galactic pests that cling onto and consume the electricity of spaceships. The Mynock's jumping movements mimic those of the earth frog, which serves as biomimetic inspiration.

Our final 3D printed design consists of a body on which we mount our motor and battery, 2 legs each made of 2 limbs compressed by torsion springs, a foot, and a coupled pulley crouching mechanism transfers the motor's energy to compress the springs. The body, legs, and foot make for a 6-bar linkage with 6 pins. Power comes from a 7.4V battery connected to a small DC motor.

In testing, we demonstrate that our jumper, once turned on, can crouch and initiate jumping on its own. We also demonstrate that if extension springs are added to supplement the existing torsion springs, our jumper can reach one meter. However, because of flaws in our pulley design, the jumping is initiated prematurely with this additional loading. On demonstration day on March 16th, 2018, our Jumper reached a height of 0.6 meters.

In further design iterations, we might consider a larger and more robust pulley mechanism to prevent premature jumping, stronger springs to store more energy, adding a linear spring to the jumper's "knee" joints, and geared legs to reduce the degrees of freedom of the system.

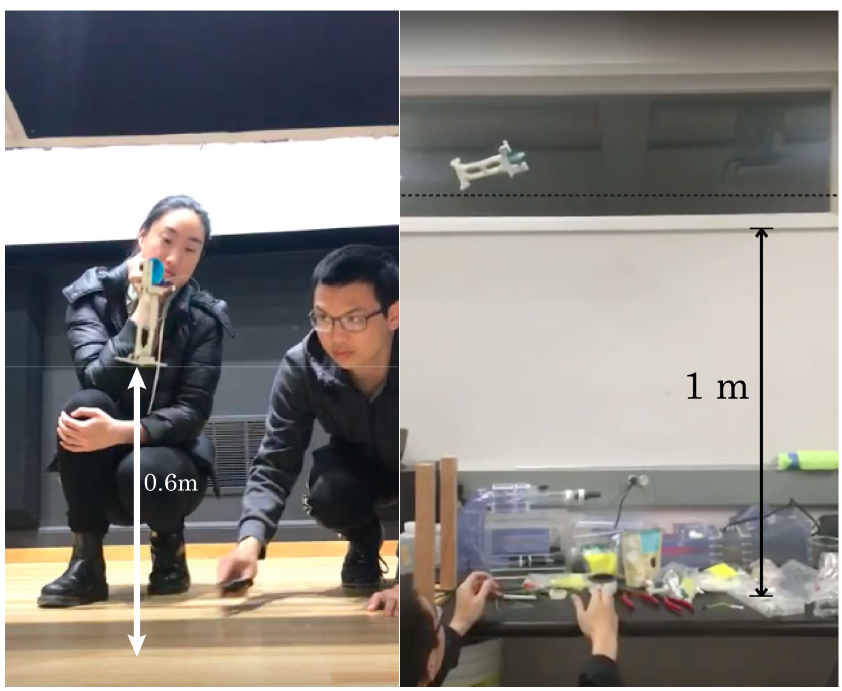

Figure 1.1: *Action shots of our jumper on test day (left) and reaching a meter in height with the addition of an extension spring during testing (right)*

Contents

1 Executive Summary **2**

2 Background **4**
- 2.1 Overview 4
- 2.2 Design Requirements 4

3 Design Description **5**
- 3.1 Motor, Gearbox, and Battery 5
- 3.2 Energy Storage 6
- 3.3 Degrees of Freedom and Leg Geometry 6
- 3.4 Crouching Mechanism 7
- 3.5 Materials and Manufacturing 8
- 3.6 Free Body Diagrams 9

4 Analysis of Performance **11**
- 4.1 Performance Requirements 11
- 4.2 Motor and Transmission Characterization 11
- 4.3 Momentum Analysis 12
- 4.4 Energy Storage 12
- 4.5 Motor to Spring Relations 13
- 4.6 Force Plate Data 15
- 4.7 Flight 16
- 4.8 Actual Performance 17
- 4.9 Comparison to Model 18

5 Jumper Redesign **20**

Bibliography **21**

A Appendices **22**
- A.1 Previous Iterations 22
- A.2 MATLAB 23

2 Background

2.1 Overview

The goal of this project is to design a "mock Mynock" that will, in a fashion similar to the fictional creatures from Star Wars, jump upwards and be able to stick to a surface directly above them. To realize this goal, we begin by studying the biomimetic motion of jumping animals (such as frogs or grasshoppers). Endeavouring to mimic this behaviour, we design a mission statement to be the following: design a robot with linkages which, when powered by a motor, can jump vertically and affix itself to a horizontal plane.

Our research begins with an analysis of small creatures' jumping mechanics. We look at grasshoppers and fleas because they are light, as we also intend our robot to be, and because their jumping mechanics seem readily replicable. Both creatures begin the jumping process by storing energy over a "charging period" in the muscles in their legs, which can be mechanically simulated as a pinned set of links. Once sufficient energy is stored, the muscles release their stored energy, the legs impart a force to the surface on which the creature is situated, and the creature launches into the air.

With these insights, we set out to develop a jumping robot that would, over a period of time, store energy in springs; have links of constraint level l_1 or l_2 acting as legs; and rapidly discharge the spring energy, imparting a large propulsive force downward whose equal and opposite force would launch the robot upward.

2.2 Design Requirements

The final robot was subject to the following design requirements:

- Jump at least one meter in a biomimetic fashion
- Stand no taller than ten centimeters in a fully crouched position, and have a horizontal footprint of no longer than thirty centimeters
- Jump within five seconds of power first being supplied to the motor
- Be fully autonomous (including being battery powered)
- Not use any energy pre-stored in energy storage mechanisms
- Stick to a ceiling positioned one meter above the launching platform

Robots are evaluated on successfully jumping one meter; sticking to the ceiling; launching within five seconds; and on the degree to which they mimic the biomimetic motion of a common frog.

3 Design Description

This section outlines the mechanical design choices that went into the final design of our Mynock pictured below.

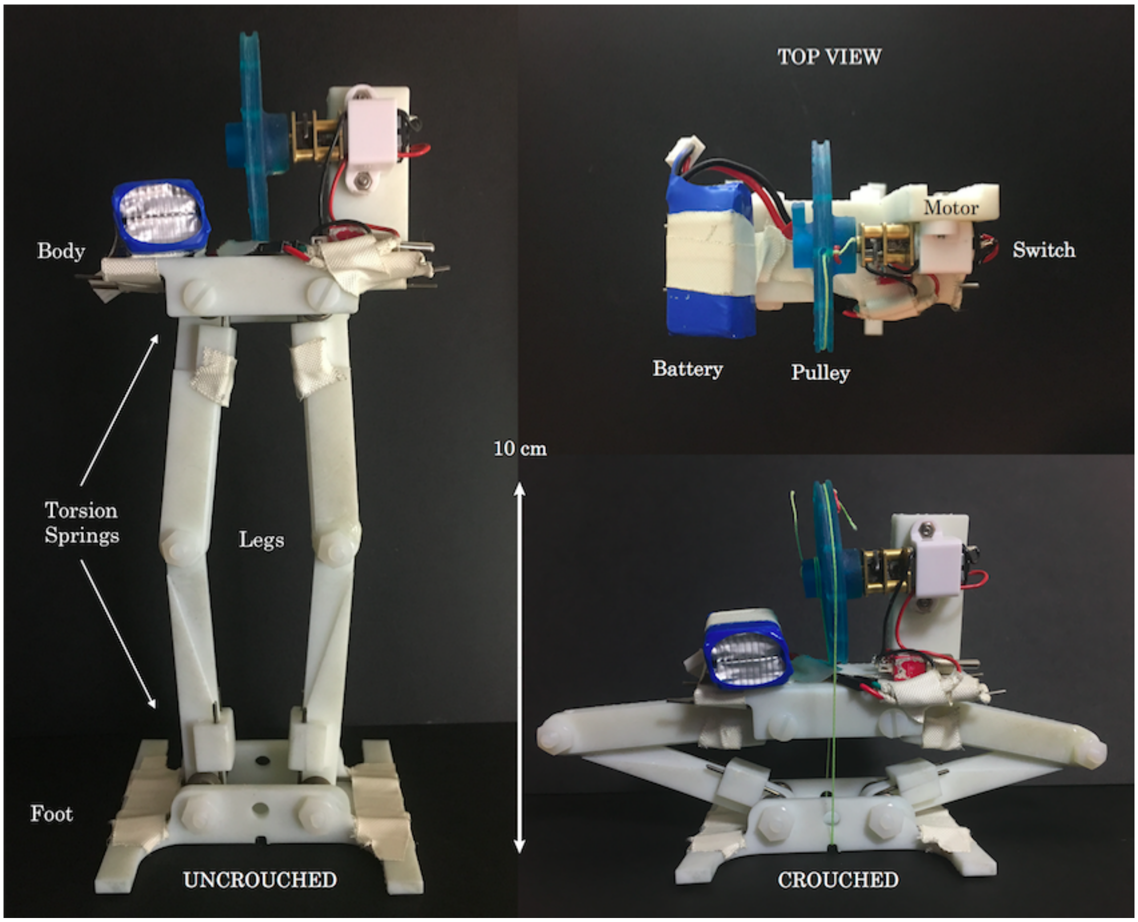

Figure 3.1: *Our Mynock consists of 2 legs, a body, foot, 8 torsion springs, a pulley, string, motor, battery, and switch. It measures 10cm in height it its crouched position.*

3.1 Motor, Gearbox, and Battery

Our Mynock is powered by a lightweight micromotor from Banana Robotics. This motor drives a gearbox with a 1000:1 reduction ratio which turns the output shaft at 15 RPM at 6V. The motor can be driven from a voltage range of 1.5V to 12V DC and is about an inch long and weighs about one half ounce. We select this motor because of its light weight design to reduce the mass of our jumper.

For our power supply, we use a $7.4V$ battery as it is the highest voltage we can get in a battery that can be easily purchased, is relatively light, and is reasonably sized.

More information about the operating voltage and motor performance can be found in section 4.2.

3.2 Energy Storage

We transform the rotational energy from the motor to linear motion through the use of torsion springs as they provide a light weight method of storing energy. Through some preliminary analysis of the energy required to lift the Mynock one meter detailed in 4.5, we sourced springs with the required spring constants.

The addition of a linear extension spring between the two pairs of legs allows for our Mynock to reach beyond the one meter requirement when released by hand. However the placement of this spring as the robot is currently designed interferes with our charging and release mechanism, so we decide to leave it out of the final design.

3.3 Degrees of Freedom and Leg Geometry

To analyze the degrees of freedom in our design, seen in Figure 3.2, we utilize the Kutzbach-Gruebler's equation. Since the design can be analyzed in a single plane, we can use the equation

$$F = 3(N - 1) - 2f_1 - f_2 \tag{3.1}$$

where F is the mechanism's degrees of freedom, N is the number of links, f_1 is the number of type-1 links, and f_2 is the number of type-2 links. In this case, $N = 6$, $f_1 = 6$, and $f_2 = 0$. Thus,

$$F = 3(6 - 1) - 2 \cdot 6 - 0 = 3. \tag{3.2}$$

These three degrees of freedom manifest themselves in translation in the $\hat{x}$ coordinate direction, up and down motion in the $\hat{y}$ coordinate direction, and rotation about the $\hat{z}$ axis (directed orthogonal to the plane in which the legs rest).

Ideally we would like to eliminate at least one of these degrees of freedom. We consider inserting a gearing mechanism between the two links that attach to the upper body to eliminate a degree of freedom. However, a simpler solution that does not require mechanical alterations is to use torsion springs to severely limit $\hat{z}$ rotation so the top body stays parallel to the base. Symmetry about the vertical axis bisecting the jumper also ensures that crouching is symmetric, thus eliminating even more rotation and ensuring that the dominant degree of freedom is in the vertical direction.

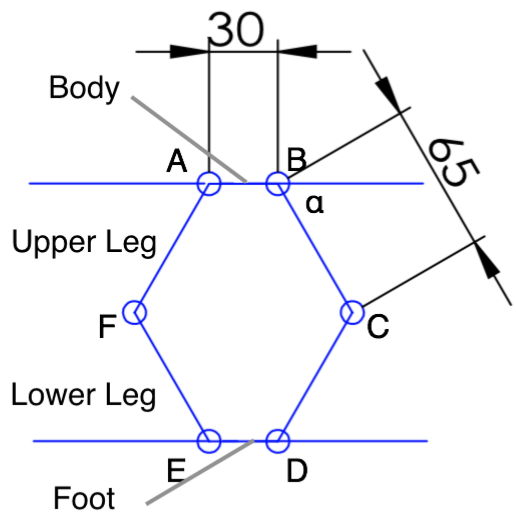

Figure 3.2: *Linkage diagram showing body, foot, upper and lower legs, and pins. The body and foot links are both 30mm long and the upper and lower leg links are both 65mm long. Angle α is the angle between the legs to the horizontal which corresponds to the angle of the torsion springs.*

The legs are designed to maximize the distance the jumper can crouch down and thus minimize α and maximize the compression in the springs. At the jumper's standing height, the height of the body relative to the foot is 130mm. In the crouched position, the distance between the body and foot reduces to 25mm. Using trigonometry, we find that the angle of the compression springs go from $\alpha_{standing} = 90°$ in the standing position to $\alpha_{crouched} = 11°$.

3.4 Crouching Mechanism

Some the major design requirements are to design a system that is fully autonomous, not use any presorted energy, and jump within five seconds of the motor being turned on. To accomplish this we require a mechanism to crouch and release our Mynock. Our initial design consisted of a crank with an escapement feature (Figure A.2), while this meets the requirement of quick release it limits the charging phase to half a rotation which does not provide enough energy for our Mynock to launch a meter. In order to obtain more rotations and further crouching the robot, we opt for a coupled pulley mechanism illustrated in Figure 3.3. The pulley consists of a large outer radius which the string winds around and a smaller radius which the pre-wound string unwinds. The end of the strings is tied to a post that it slips off of when the Mynock is fully crouched and the post is pointing toward the ground. The string is secured to the foot by threading it through holes in the foot.

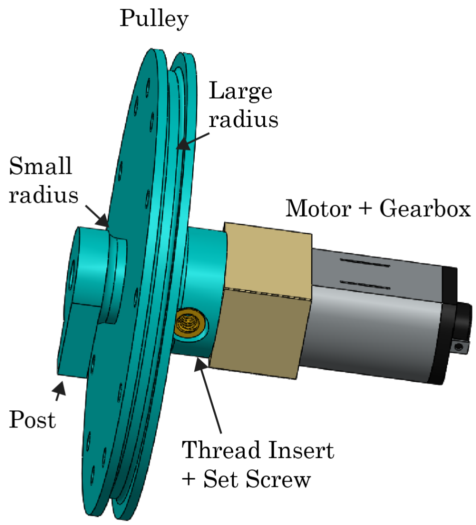

Figure 3.3: *Schematic of the pulley winding mechanism for crouching.*

With this mechanism, our Mynock is able to fully crouch in about 8 seconds. While this slightly over the design requirements, changes to the motor gear ratio and the ratio between the small and large pulleys could be modified to reach the goal.

3.5 Materials and Manufacturing

All of the designed components are made from additive manufacturing processes. This allows us to create complex geometries, including braced joints and spring and motor mounts, while minimizing the weight of our jumping robot. However, with the advantages of 3D printing come some caveats, including the time required for each iteration which slows the design process. For the final Mynock, we use a stereolithography (SLA) 3D printer to cure our photopolymer resins. The pulley, subject to high torques and loads, is printed out of a tougher resin.

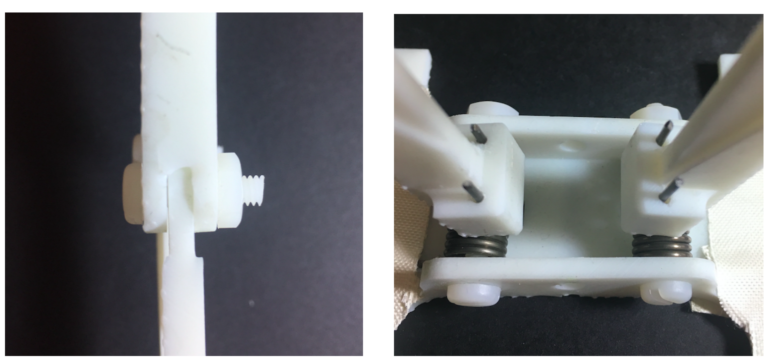

Figure 3.4: *3D printed features.Braced joint between top and bottom legs (left) and Spring mounting boxes on the foot (right).*

Apart from the major parts such as the body, legs, and foot, other materials we will be using include music wire torsion springs, steel screws for the motor mount, a steel set screw to mount the pulley, and nylon screws and nuts as pins.

3.6 Free Body Diagrams

In order to inform our design and the required materials and sizing, we find it useful to model the forces on the body, legs, and joints.

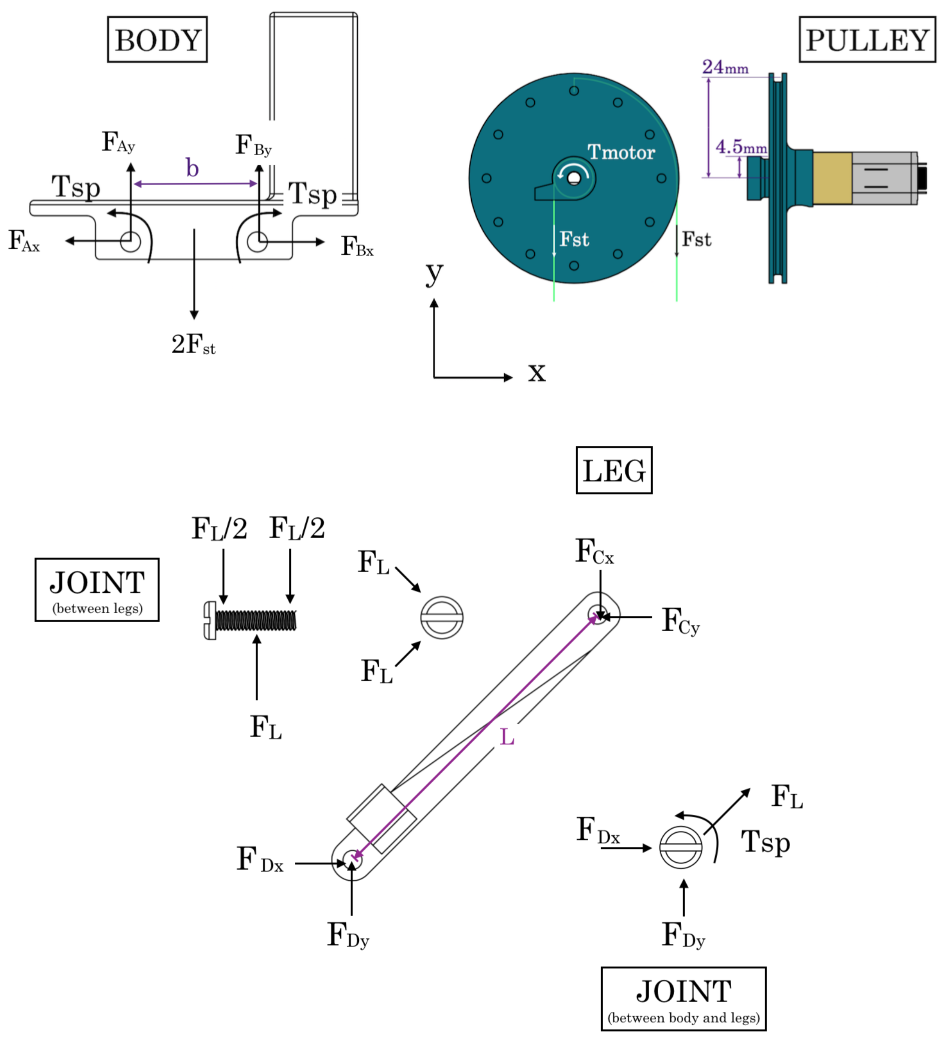

Figure 3.5: *Pictured are the force-body diagrams for various parts of the jumper: Leg, Top Body, Joint (between the legs), Joint (between body and legs), and Pin (side view).*

Based on Figure 3.5, F_{Dy} is the upward component of the force exerted upwards on the top body component. There are two contributions of F_y that can be found exerting force upwards, accounting for the left and right side of the jumper. F then refers to the required force needed to charge the energy. When equating the two, their relationship is as follows:

$$F = 2F_{Dy}$$

We know that the spring follows Hooke's law from equation 4.4. In addition, α is also the angle between the leg and the horizontal. Thus, looking at the right side of the jumper, we create an equation, where τ_{spring} is tension of the spring, k is the spring constant, and α is the spring deflection angle:

$$\tau_{spring} = 2k(\frac{\pi}{2} - \alpha)$$

Solving the moment equation around point D of the"Leg" free-body diagram from Figure 3.5 results in the following, where L is the length of a jumper leg:

$$\tau_{spring} = LF_{Dy}cos(\alpha) - LF_{Dx}sin(\alpha) \tag{3.3}$$

Since our jumper is symmetric in both leg length and body width, solving the moment equation for the angle of the leg at the top of the body results in an equation identical to Equation 3.3. Using the equations which we have just solved, we find that force F results in

$$F = \frac{2k(\pi - 2\alpha)sin(\alpha)}{Lsin(2\alpha)} \tag{3.4}$$

As previously mentioned, $F = 2F_{Dy}$. We refer to Figure 3.5's "Body" free-body diagram to solve for the relation between F_{Dy} and F_{string}. Solving the moment equation around point A in that particular figure, using b as the length of the top body, we find that:

$$\sum M_A = -\tau_{spring} + \tau_{spring} + bF_{Dy} - 2F_{string}(\frac{1}{2}b) = 0 \Rightarrow F_{Dy} = F_{string}$$

Looking at that same free-body diagram with regards to the summation of the forces in the x and y direction as well as the equation $F = 2F_{Dy}$, we find that:

$$F_{string} = \frac{k(\pi - 2\alpha)sin(\alpha)}{Lsin(2\alpha)} \tag{3.5}$$

4 Analysis of Performance

4.1 Performance Requirements

When the Mynock jumps, it converts potential energy stored in the energy storage mechanism into kinetic energy. The amount of energy we can store in the energy storage mechanism is limited by what the battery and motor can output in the 5 seconds allowed to input energy into the system before having to jump. As a thought experiment, we will analyze a simplified system to determine if it is even possible to store enough energy in the given amount of time. The energy needed to jump a meter high, without taking into account any losses, is equal to $E_{min,required} = mgh$. With a Mynock mass of 119g, this equates to approximately at least 1.2 Joules of energy needed to jump a meter. Assuming we run the motor at peak efficiency at approximately 7.4V, which can be supplied using a store-bought battery that is reasonably sized, the motor can provide about 1W of power (Figure 4.1). If the motor is run for 5 seconds, this corresponds to 5 Joules of energy, several times more than the minimum required energy needed to make our idealized Mynock jump a meter. Using this thought experiment, we find that the motor can provide enough energy to meet the performance requirements.

Further analysis of various factors including the energy storage mechanism and losses such as air drag can be explored by breaking down the jump into loading and flight phases.

4.2 Motor and Transmission Characterization

The motor we chose to use is a "Micro Metal Gear Motor" purchased from Banana Robotics. It came mated to a 1000:1 gearbox and has a total mass of $18g$. The motor has an internal resistance of 7.17Ω, motor constant $k = 3.26 \cdot 10^{-3} \frac{N \cdot m}{A}$, and torque due to friction $T_f = 2.06 \cdot 10^{-4} N \cdot m$. From these values, we can make motor characterization plots of motor output power and torque as a function of motor rotational speed (Figure 4.1). The motor is rated to run anywhere between $1.5V$ and $12V$. We operate with a $7.4V$ battery.

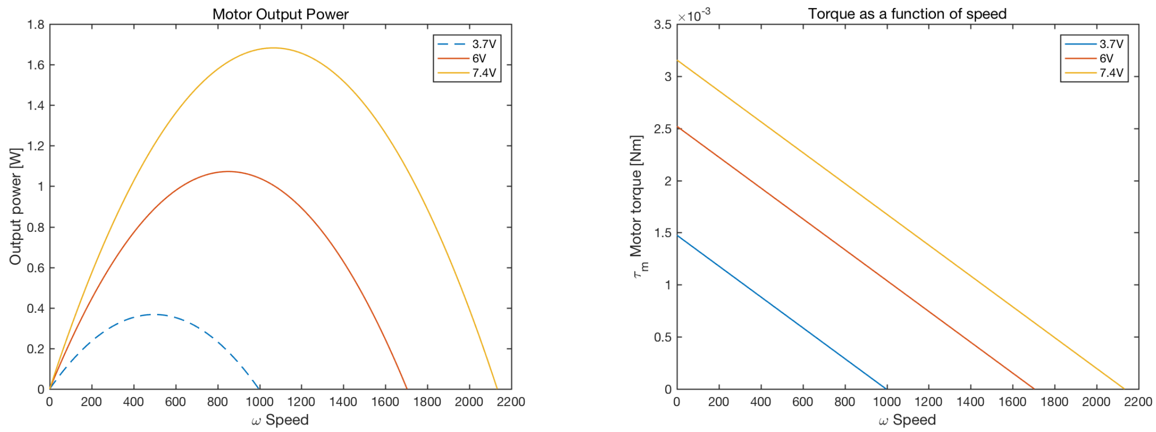

Figure 4.1: *(Left) Motor output power as a function of rotational speed ω of the motor. (Right) Motor output torque as a function of rotational speed ω of the motor.*

4.3 Momentum Analysis

Zhao, Yang, et. al.[1] claim that biomimetic jumping can be separated into two main points of analysis: the period of time in which the base of the animal remains in contact with the ground while the top accelerates, and the period of time when the entire animal is in the air. The former can be described accurately as a perfectly inelastic collision once maximum on-ground height is reached, while the latter can be described by projectile motion. To describe the first phase of jumping, the following analysis, which utilizes the formula for kinetic energy, is used.

$$v_{top} = \sqrt{\frac{2E_{0,spring}}{m_2}} \Rightarrow m_{body}v_{body} = m_{tot}v_{launch} \tag{4.1}$$

Where $E_{0,spring}$ is the energy stored in the springs, v_{body} is the velocity of the body as it is rising but while the feet are still touching the ground, m_{body} is the mass of the body, m_{tot} is the total mass of the jumper, and v_{launch} is the velocity of the jumper immediately after the inelastic collision and the feet leave the ground. Solving for v_{launch}, we find that

$$E_{launch} = \frac{m_{top}}{m_{tot}} E_{0,spring} \tag{4.2}$$

This analysis suggests that in the limit as $m_{top} >> m_{bottom}$, $E_{launch} = E_{0,spring}$. However, as m_{tot} gets larger, energy analysis in the previous sections show that maximum achievable height falls. Thus, an optimized design minimizes total mass while concentrating as much as possible in the top portion of the jumper.

4.4 Energy Storage

Potential energy is stored in 8 torsional springs. The springs are loaded by running the motor and winding the string around a large pulley and unwinding the string from a smaller pulley

(Figure 3.3). Once the string unwinds completely from the small pulley, the string is released and the Mynock jumps. The number of rotations and how far the body of the jumper lowers itself while winding down is related by equation 4.3, where ΔY is how far the jumper squats down, ΔL is how much the length of the string shortens as it is wound around the pulleys, R an r are the radii of the large and small pulleys respectively, and n is the number of rotations the motor makes to load the springs by squatting down.

$$\Delta Y = \Delta L/2 = \pi(R - r)n \tag{4.3}$$

The legs and pulleys are designed such that $R = 22mm$, $r = 4.35mm$, and $\Delta Y = 100mm$. Solving equation 4.3 for n we find that $n = 1.8$. This means that the motor needs to make 1.8 rotations in order for the jumper to squat down the designed distance to compress the spins.

The torsional springs were purchased from McMaster and each have a spring constant $k = 3 \cdot 10^{-3} Nm/deg = 0.17Nm/rad$. For symmetry, 4 of the springs are right-hand wound while the other 4 are left-hand wound. These springs obey Hooke's law:

$$\tau = -k\theta \tag{4.4}$$

where τ is the torque exerted by the spring, θ is the angle of deflection from the equilibrium position, and k is the spring constant. Another useful equation for U, the potential energy in joules stored in a torsion spring is:

$$U = \frac{1}{2}k\theta^2 \tag{4.5}$$

In section 4.4 we found that the jumper crouches down such that spring deflection angle $\theta = 79^\circ = 1.38\text{rad}$. Using equation 4.5 we find that in the crouched position, the energy stored in each spring is $U = 0.16J$. With 8 springs, the total potential energy stored in the crouched position is $U_{total} = 1.3J$. From the performance requirements outlined in section 4.1, we see that this is barely enough energy to reach 1m in an idealized situation and likely will not be sufficient when unaccounted losses such as friction and air drag are are factored in. To supplement the torsion springs, we added extension springs between pins C and F (Figure 3.2). With these additional springs, the jumper has enough stored energy to jump to 1m and successfully does so in testing if the jumper is compressed and released by hand. The jumper has trouble crouching with the additional springs; as the jumper crouches and winds the string around the pulley, the pulley begins to warp to the point that the string falls off the pulley and the jumper jumps prematurely. Fixing this problem would require us to increase the size and improve the robustness of the pulley, but we did not have enough time to reprint new parts before the final demonstration. For the sake of this paper, we will continue the analysis without the additional extension springs.

4.5 Motor to Spring Relations

We now look at the relationship between F_{string} and motor torque, or τ_{motor}. The following is the equation for torque:

$$\tau = Fd \tag{4.6}$$

We take into account that the distance over which the motor works is the difference between the pulley's outer and inner radii, or $2.4 \cdot 10^{-2}m - 4.5 \cdot 10^{-3}m = 1.95 \cdot 10^{-2}m$. Our F_{string} is obtained from Equation 3.5. To calculate the motor torque going through the gearbox before it reaches the pulley, we scale the motor torque equation by a factor of 1000 since the gearbox has a ratio of 1000:1. The final equation we obtain for motor torque is Equation 4.7.

$$\tau_{motor} = \frac{(1.95 \cdot 10^{-5}m)k(\pi - 2\alpha)sin(\alpha)}{Lsin(2\alpha)} \tag{4.7}$$

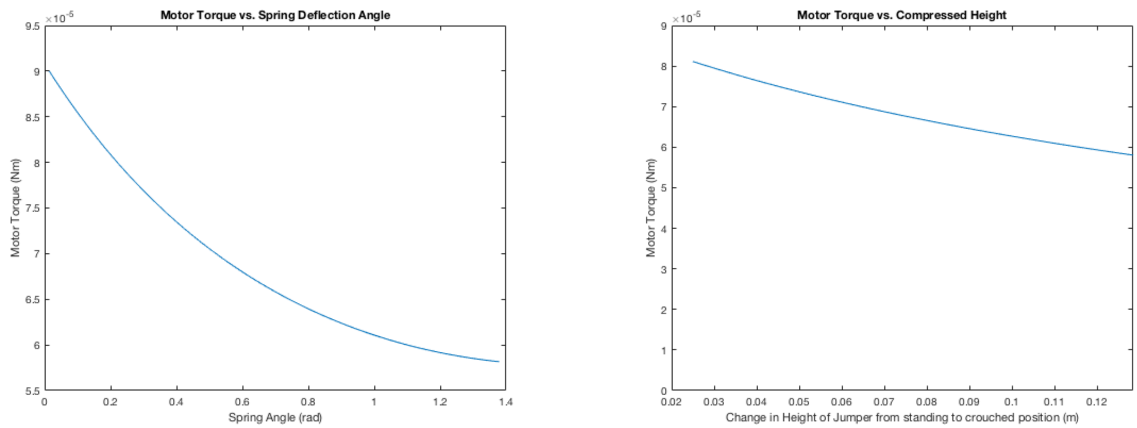

Figure 4.2: *(Left) Graph of relation between motor torque and spring deflection angle. (Right) Graph of relation between motor torque and height of the jumper, from a standing to a crouched position.*

The left graph of Figure 4.2 describes how the motor torque begins at $9.0 \cdot 10^{-5}Nm$ and decreases as the jumper crouches lower and lower until its max deflection of angle of 79 degrees. In the right graph of Figure 4.2, the torque increases up to a maximum of $9.0 \cdot 10^{-5}Nm$, which forces the jumper to crouch from a standing height of $0.13m$ to a crouched height of $0.025m$.

A useful graph is Figure 4.3, which demonstrates the relationship between tension of the string and compressed height of the jumper. This graph allows to visualize the intuitive release of the mechanism: as the tension of the string increases to a maximum of $4.0 \cdot 10^{-3}N$, the jumper crouches down to its maximum crouched height of $2.5 \cdot 10^{-3}m$. The area under this plot's curve is proportional to the energy being put into the elastic system of our jumper design and the variation in tension with height tells us where the motor is working the hardest. Thus, based on the area under this graph, the jumper used $0.3432J$ of energy across the process.

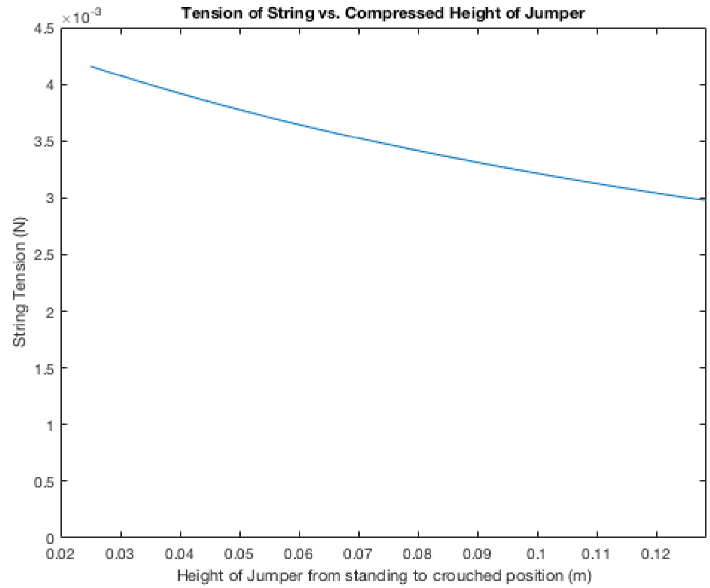

Figure 4.3: *Graph of relation between tension of the string versus the height of the jumper, from a standing to a crouched position.*

4.6 Force Plate Data

We attempt to measure the normal force the jumper makes with the ground by using a force plate with capacitive sensors. By releasing the jumper from the crouched position on the force plate, we find the normal force the jumper makes with the force plate over time (Figure 4.4). We can find the impulse J that the jumper imparts onto the ground using Equation 4.8.

$$J = \int F dt \tag{4.8}$$

Where F is the normal force the jumper makes with the ground. Evaluating this integral using data in Figure 4.4, we find that the impulse $J = 0.127kg\frac{m}{s}$. Using the value and knowing that impulse corresponds to a change in momentum, we can calculate the velocity of the jumper as it leaves the ground $v_{launch} = J/m_{tot} = 1.1m/s$. Using an energy balance, according to the force plate data, our jumper only jumps 5cm. Since this height less than a tenth of what was achieved during the demonstration, we note that significant errors likely exist in the force plate data. We will neglect this data until a more accurate test can be performed.

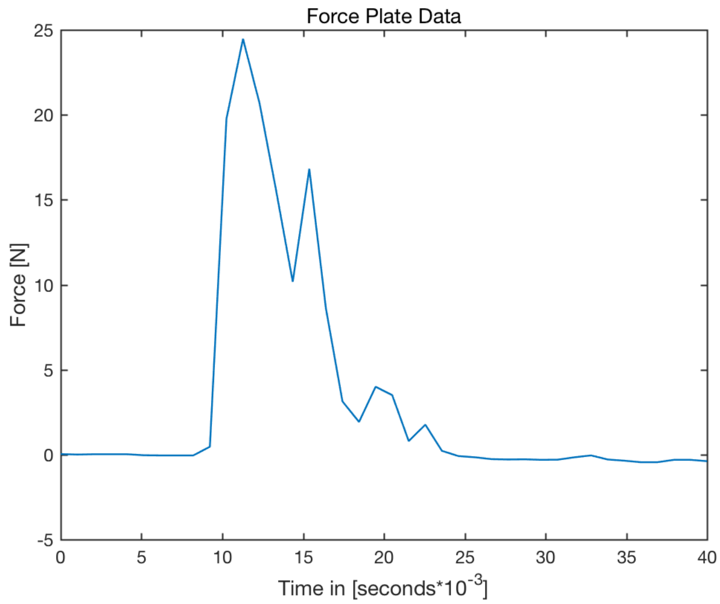

Figure 4.4: *Force the jumper exerts onto the force plate as it jumps off of it.*

4.7 Flight

During the flight phase, the jumper experiences losses to air drag. This can be modeled using equation 4.9, where air density $\rho \approx 1.23 kg/m^3$, drag coefficient $C_d \approx 1$, cross-sectional area $A \approx 0.01 m^2$, and V is the vertical velocity of the jumper. In order to reach a meter in height, the jumper must be traveling vertically at about 5m/s at the beginning of the jump. This translates to a maximum aerodynamic drag of $F_{aero} \approx 0.15N$ at launch.

$$F_{Aero} = \frac{1}{2}\rho C_d A V^2 \tag{4.9}$$

The drag force equation can also be used to determine necessary takeoff velocity needed to take the jumper to 1m. Equation 4.9 becomes helpful when we have v as a function of the independent variable time. To do this, we start with $F = ma$ to determine that

$$m\frac{dv}{dt} = -mg - F_{Aero} \tag{4.10}$$

we can use differential calculus to determine that, for purely vertical motion,

$$v_y(t) = v_t \frac{v_o - v_t tan(\frac{g}{v_t}t)}{v_t + v_o tan(\frac{g}{v_t}t)} \tag{4.11}$$

Where

$$v_t = \sqrt{\frac{2mg}{\rho A C_d}} \tag{4.12}$$

Thus,

$$v_o = \frac{v(t) + v_t tan(\frac{g}{v_t}t)}{1 - \frac{v(t)tan(\frac{g}{v_t}t)}{v_t}} \tag{4.13}$$

and

$$y_{max} = \frac{v_t^2}{2g} ln(\frac{v_0^2 + v_t^2}{v_t^2}) \tag{4.14}$$

Rearranging to the most useful form, we see

$$v_0 = \sqrt{v_t^2 e^{\frac{2gy_{max}}{v_t^2}} - v_t^2} \tag{4.15}$$

Using the parameters $\rho = 1.23\frac{kg}{m^3}$, $A = 1.76 \cdot 10^{-3}m^2$ (the area of the body of the jumper), $C_d = 1$, $g = 9.8\frac{m}{s^2}$, and assuming a y_{max} of 1 m, we see that

$$v_{o,min} = 4.44\frac{m}{s} \tag{4.16}$$

It is important to note that this is an initial vertical velocity that assumes that air drag is the only source of resistance/energy loss in the projectile motion of the jumper. To counter additional losses that present themselves in jumping (such as rattling of parts), and to make sure that the jumper impacts the aircraft wing with a greater force, we must have a takeoff velocity greater than this minimum theoretical velocity.

Transitioning to force analysis, knowing that $F = ma$ and that the velocity of the jumper's foot while on the ground $v_{contact} = 0\frac{m}{s}$, we see as the jumper accelerates due to transmission of force to its mounting surface,

$$\int_{\tau=0}^{t} a d\tau = v_0 = \frac{1}{m}\int_{\tau=0}^{t} F_c d\tau = 4.44\frac{m}{s} \tag{4.17}$$

where F_c is force transmitted to the ground while the jumper stays in contact with the ground.

If the springs charge for 5 seconds,

$$P = \frac{E}{t} = \frac{5.86J}{5sec} = 1.17W \tag{4.18}$$

Looking at the motor characterization plots, we see that the motor is theoretically able to provide the assumed required power of $1.17W$ if run at certain conditions.

4.8 Actual Performance

Looking at video from testing, we find the crank's average rotational speed as it is making the jumper crouch by winding the pulleys under load is $\omega_{crank} = 1.57rad/s$. Knowing that the motor is connected to a 1000:1 gearbox, the motor's average rotational speed is $\omega_{motor} = 1570rad/s$. At 1570 rad/s and 7.4 Volts, we see from Figure 4.1 that the motor is outputting an average torque $\tau_{motor} = 8.29 \cdot 10^{-4}Nm$ and power of $P_{motor} = 1.30W$. The τ_{motor} we find here is significantly higher than what we found in Section 4.5 because here, we are analyzing a real system with significant losses, including warping of parts and friction.

Looking at footage from our final demonstration, the motor was run for $t = 8seconds$. Using the average power, we find that energy put into the system is $E_{in} = Pt = 10.4J$. Also from the final demonstration footage, we see that the Mynock jumps approximately 0.6m. From this, we can find the energy used to jump, $E_{jump} = mgh = 0.7J$. Using the energy balance found in Equation 4.19, we find that 9.7J of energy did not contribute to jumping and was therefore lost elsewhere, including rotational kinetic energy, collisions of the legs after they fully extend, internal dissipation within the springs, air resistance, the 'collision' between the body and foot when the legs fully extend, friction in the joints, springs, and pulleys.

$$E_{in} = E_{loss} + E_{jump} \tag{4.19}$$

We can define the jumping efficiency of the Mynock as the proportion of energy that went into jumping to the total energy that went into the system.

$$\eta_{total} = \frac{E_{jump}}{E_{in}} = 6.5\% \tag{4.20}$$

We find that our jumping efficiency $\eta_{jumping} = 6.5\%$. We can further break down the energy lost during different stages by figure out how much energy was stored in the springs. We found in Section 4.4 that a total of $E_{springs} = 1.3J$ is stored in the springs. This means that the majority of the energy, $9.1J$ is lost during the crouching phase. Another $0.6J$ of energy is lost during the jumping phase. We can define crouching efficiency as

$$\eta_{crouching} = \frac{E_{springs}}{E_{in}} = 12.5\% \tag{4.21}$$

and jumping efficiency as

$$\eta_{jumping} = \frac{E_{jump}}{E_{springs}} = 53.8\% \tag{4.22}$$

By breaking up the jumping sequence into crouching and jumping phases, we get that

$$\eta_{total} = \eta_{crouching}\eta_{jumping} = 6.5\% \tag{4.23}$$

4.9 Comparison to Model

Since we wanted to mainly analyze the height the jumper reaches, we ignored the jumper's release mechanism. The Working Model results in a model jumper that is able to leap to a height of 3.5 meters, which is significantly higher than the actual performance of the jumper. This is because Working Model ignores various effects such as friction and warping of parts.

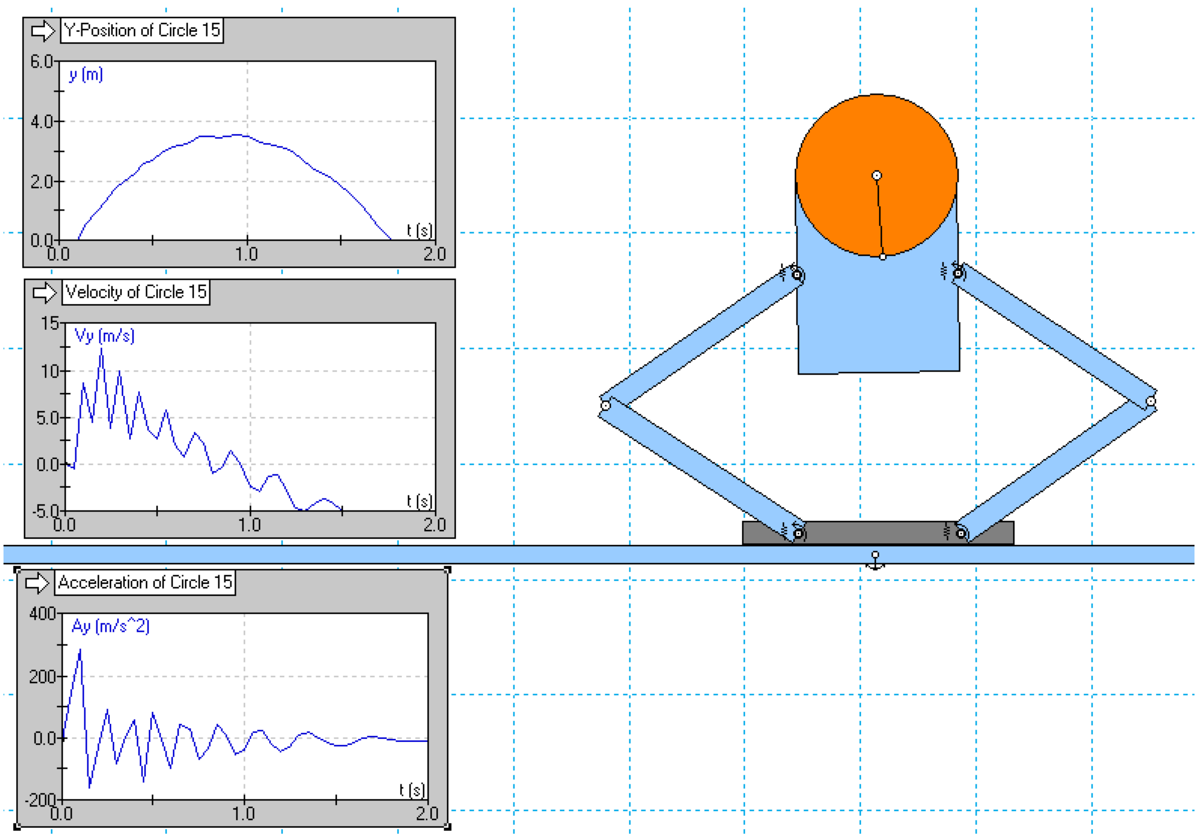

Figure 4.5: *Pictured is Working Model 2D's model of the jumper leaping to a height of 3.5 m.*

5 Jumper Redesign

While our Mynock is able to jump off the ground and do so autonomously, more stored energy is required to reach a meter and stick to the spaceship. We identify areas of improvement to reduce losses and increase energy storage in the Mynock legs.

1. Longer legs: A challenge we face with the current design is a limited amount of extension that the Mynock legs can achieve. By increasing the length of the legs, we can increase our moment arm and transmit more of the energy stored in the springs.

2. Increase spring constant: Our current design has $1.3J$ stored in the torsion springs, which is much less than the motor can output and just enough energy to get the robot to 1 meter with almost perfect efficiency. As our Mynock encounters many frictional losses, stronger springs or more springs or even other forms of energy storage (ie: rubber bands) could prove useful.

3. Lighten up: While our robot was not too heavy, weighing in at $119g$, reducing the mass further would decrease the energy required for the Mynock to jump.

4. Degrees of freedom: Our current design uses a 6-bar linkage, which allows for 3 degrees of freedom. Although our torsion springs limit the movement of the body and foot and keep the robot on a relatively vertical trajectory, elimination of any additional translation or rotation through gearing the legs together or reducing to a 4-bar linkage may be worth exploring.

5. Extended foot: In increasing the foot's contact with the ground at liftoff, we can increase the impulse time and the momentum transfer as our Mynock takes off. Redesigning the foot so that it flexes and remains in contact before leaving the ground could increase the efficiency.

6. Reduce gear ratio: Our robot took 8 seconds to wind on test day. In order to increase the speed at which the robot crouches to fully meet the design requirement, we may want to reduce the gear ratio of the transmission and increase the voltage of the battery.

7. Reduce friction: Our final efficiency is 6.5%. While all the redesign options mentioned above could help increase this, reducing friction at the joints by using smoother and smaller pins and reducing air drag by creating a more aerodynamic shape would directly reduce some losses.

Bibliography

[1] J Zhao. Biologically inspired approach for robot design and control. 2015. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=6481459&tag=1.

A Appendices

A.1 Previous Iterations

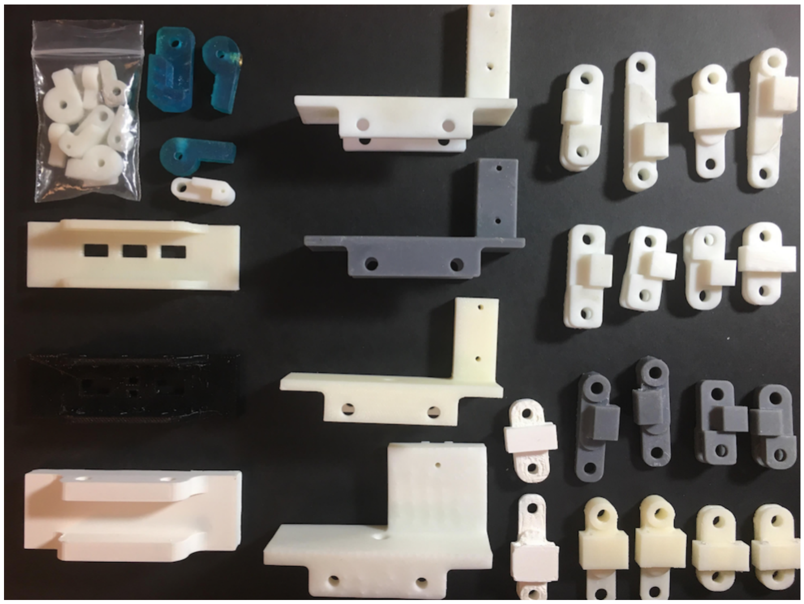

Figure A.1: *3D printed iterations of legs, crank, body, and foot.*

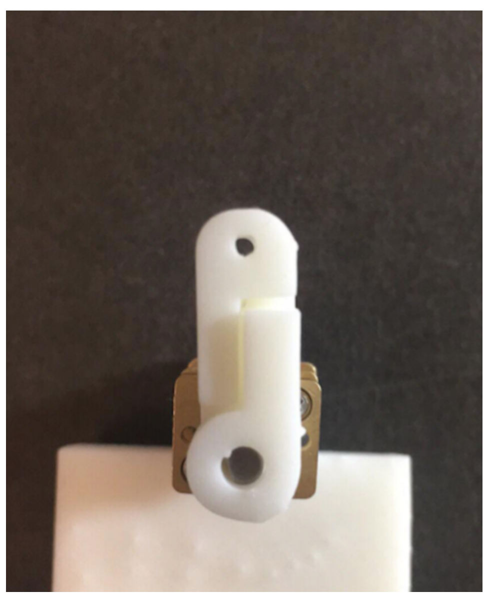

Figure A.2: *Old crank powered mechanism limited by half a rotation.*

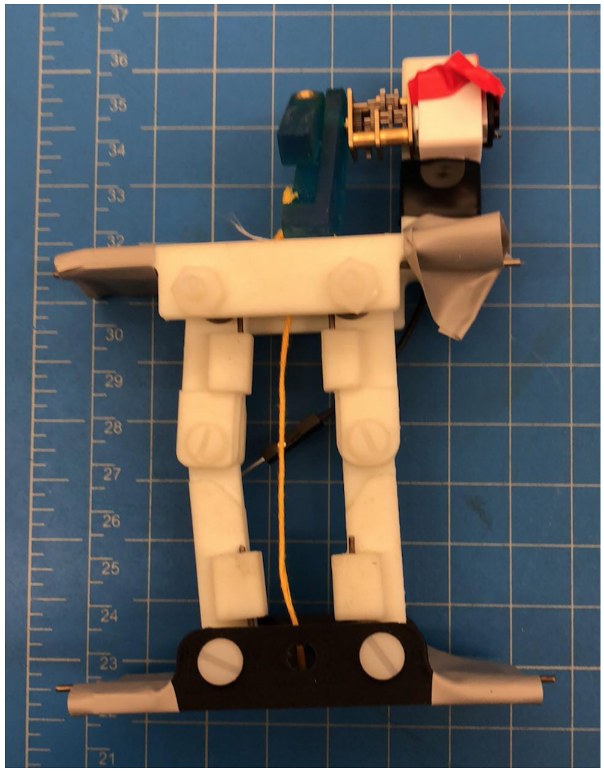

Figure A.3: *Old Mynock with much shorter legs, fewer springs, and crank.*

A.2 MATLAB

```
%% MATLAB script to create motor characterization plots

R = 7.17;             % [ohms]
k = 3.2568e-3;        % [Nm/Amp] or [Volts/(rad/sec)]
Tf = 2.06e-4;         % [Nm]
inl = Tf/k;           % i no load
Va = 3.7; Vb = 6; Vc = 7.4;
omega_nl_a = (Va-inl*R)/k; omega_nl_b = (Vb-inl*R)/k;
i_stall_a = Va/R; i_stall_b = Vb/R; i_stall_c = Vc/R;

i_a = linspace(i_stall_a,inl); i_b = linspace(i_stall_b,inl); i_c = linspace(i_stall_c,inl);
omega_a = (Va-i_a*R)./k; omega_b = (Vb-i_b*R)./k; omega_c = (Vc-i_c*R)./k;
P_in_a = Va*i_a; P_in_b = Vb*i_b; P_in_c = Vc*i_c;
Tl_a = k*i_a-Tf; Tl_b = k*i_b-Tf; Tl_c = k*i_c-Tf;
P_out_a = Tl_a.*omega_a; P_out_b = Tl_b.*omega_b; P_out_c = Tl_c.*omega_c;
Efficiency_a = P_out_a./P_in_a; Efficiency_b = P_out_b./P_in_b; Efficiency_c = P_out_c./P_in
Omega_rpm_a = omega_a*30/pi; Omega_rpm_b = omega_b*30/pi; Omega_rpm_c = omega_c*30/pi;

plot(omega_a, P_out_a, '--'); hold on;
```

```
plot(omega_b, P_out_b);
plot(omega_c, P_out_c);
xlim([0,2200])
ylim([0,1.8])
legend('3.7V','6V','7.4V')
xlabel('\omega Speed'); ylabel('Output power [W]')
title('Motor Output Power')
plotfixer

P_max_a = max(P_out_a)
P_max_b = max(P_out_b)
P_max_c = max(P_out_c)

figure
plot(omega_a, Efficiency_a, '--'); hold on;
plot(omega_b, Efficiency_b);
plot(omega_c, Efficiency_c);
xlim([0,2200])
ylim([0,0.6])
title('Motor Efficiency')
legend('3.7V','6V','7.4V')
xlabel('\omega'); ylabel('motor efficiency')
plotfixer

figure
plot(i_a, Efficiency_a'); hold on;
plot(i_b, Efficiency_b');
plot(i_c, Efficiency_c');
xlim([0,1.1])
ylim([0,0.6])
title('Efficiency vs. Current')
xlabel('Current [A]')
ylabel('Efficiency')
legend('3.7V','6V','7.4V')
plotfixer

figure
plot(omega_a,Tl_a); hold on;
plot(omega_b,Tl_b);
plot(omega_c,Tl_c);
xlim([0,2200])
ylim([0,3.5e-3])
title('Torque as a function of speed')
xlabel('\omega Speed')
ylabel('\tau_m Motor torque [Nm]')
legend('3.7V','6V','7.4V')
```

```
plotfixer


[Efficiency_max_a,i_a] = max(Efficiency_a)
[Efficiency_max_b,i_b] = max(Efficiency_b)
[Efficiency_max_c,i_c] = max(Efficiency_c)

Peak_a_omega = omega_a(i_a)
Peak_b_omega = omega_b(i_b)
Peak_c_omega = omega_c(i_c)

%% MATLAB script to read in and plot force plate data and determine height that jumper jumps

data = xlsread('force_plate.xlsx');     %reads in data
data = data+29.73;                      %index offset of force plate
data = data(1120:end);                  %parses the data
data = data(1:300);
time = linspace(0,length(data),length(data));
plot(time,data)
title('Force Plate Data')
xlabel('Time in [seconds*10^{-3}]')
ylabel('Force [N]')
impulse = 0;
dt = 0.001;
for i = 1:length(data)
    impulse = data(i)*dt + impulse;
end
m = 0.119;
vi = impulse/m;
KE = 0.5*m*vi^2;
h = KE/(0.119*9.8);


%% MATLAB script for plot of motor torque v. angle

angle = linspace(1.37881,0);   %pi/2 rad to 0.191986 rad (90 deg to 11 deg)
y = zeros(1,100);
leg = 0.065;
k = 0.192696;   % in nm/rad
for i = 1:100
    torque_m = (.0195*k*(pi - 2*angle(i))*sin(angle(i)))/(leg*sin(2*angle(i)))./1000;
    y(i) = torque_m;
end
max(y)
figure
plot(angle,y)
```

```
xlabel('Spring Angle (rad)')
ylabel('Motor Torque (Nm)')
title('Motor Torque vs. Spring Deflection Angle')

%% MATLAB script for plot of motor torque v. height

height = linspace(0.13,0.025);
k = 0.192696;   % in nm/rad
leg = 0.065;

for i = 1:100
    alpha = asin(height(i)./2./leg);
    torque_m = (.0195*k*(pi - 2*alpha)*sin(alpha))/(leg*sin(2*alpha))./1000;
    y(i) = torque_m;
end
max(y)
figure
plot(height,y)
ax = gca;
axis([0.02 0.1285 0 9*10^-5])
xlabel('Height of Jumper, from standing position to crouch (m)')
ylabel('Motor Torque (Nm)')
title('Motor Torque vs. Compressed Height')

%% MATLAB script for plot of tension in string vs crouched height

height = linspace(.025,0.13);
k = 0.192696;   % in nm/rad
leg = 0.065;    % in m

for i = 1:100
    alpha = asin(height(i)./2./leg);
    tension = (k*(pi - 2*alpha)*sin(alpha))/(leg*sin(2*alpha))./1000;
    y(i) = tension;
end
Q = trapz(y)
max(y)
figure
plot(height,y)
axis([0.02 0.1285 0 4.5*10^-3])
xlabel('Height of Jumper from standing to crouched position (m)')
ylabel('Spring Tension (N)')
title('Tension of Spring vs. Compressed Height of Jumper')
```