Force Reflecting Pneumatic Hand Tools

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Abstract

Pneumatic hand tools have been used for many decades. These tools help users accomplish tasks with much less effort than is required with manual tools. However, one significant drawback of pneumatic tools compared with manual hand tools is that the user is disconnected from the output forces the tool is creating. This has various safety and functionality issues.

A pair of pneumatic powered loppers was developed to demonstrate the potential of force-multiplying, pneumatically powered hand tools with haptic control. A purely mechanical control system was tested and found to provide proportional feedback over the range of operating conditions.

The work required to cut through different sizes of dowels and branches was also calculated and tested against the prototype to determine the amount of compressed air needed to operate the loppers. It was determined that the loppers could have an onboard, high pressure tank that could provide enough energy for average homeowner use. For commercial use a larger external tank would be required.

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1.0 INTRODUCTION

1.1 Background

Many homeowners enjoy having a multitude of different trees and bushes in their yards, but with these trees and bushes comes the need to trim and prune them. The size of what the homeowner trims can vary from a small twig to a large branch, though most of what they trim is less than one inch in diameter.

There are also commercial businesses that provide cutting and trimming services to homeowners and businesses. They cut a wider variety of branch types and diameters. Most of what they trim is still under one inch in diameter but they do cut branches up to several inches in diameter on a regular basis.

Vineyards and orchards are another example of businesses with a need for trimming and pruning. The average diameter of what and orchard trims is larger than what a homeowner or a commercial business trims because they are primarily cutting trees rather than bushes. They would typically cut branches from one half to two inches in diameter.

There are many ways to go about the task of cutting and trimming shrubs and branches. A chain saw is one example. It can get the job done quickly but not always accurately. Some drawbacks of chainsaws are that they can be expensive, noisy, and potentially dangerous. Hand saws are another example. They can be precise and safer than a chainsaw but they can also be labor intensive, especially when the branch being cut is thick. Another example is a pair of loppers. Loppers are safe and precise but can require a great amount of force when dealing with thick branches. If a power assist mechanism was added to the loppers, they could provide safe and precise operation with only a minimal amount of effort to operate.

Pruners and loppers (pruners are one-handed tools, loppers require two hands) are common tools for anyone who takes care of plants, from the home gardener to the professional landscaper and orchard operator. Loppers trim bushes, cut small branches off trees, and harvest fruit. To make the job of operating loppers easier, fluid power has been incorporated into pruners to assist users.

Fluid powered loppers are not a new technology. They have been around for decades. They are mostly used in orchards, vineyards, and by professional landscapers. They are designed with a handheld or pole-mounted pneumatic cylinder which actuates a small set of jaws. Figure 1 shows examples of pneumatic and hydraulic pruners currently on the market. There are no pneumatic or hydraulic two handled loppers currently on the market because the point of loppers is to increase the input force with the use of two hands. The power assist removes the need for the increased input force.

Campagnola SE-4 pruner[1] Felco Pneumatic Shear Head[2]

Limb-Lopper Hydraulic Orchard Pruner[3]

Figure 1. Various pneumatic and hydraulic pruners.

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These loppers and pruners are usually powered by a portable air compressor (Fig. 2) or a compressed air tank mounted on the operators back (Fig. 3). Some of the pruners can be hydraulic powered which are known for their durability compared to pneumatic tools. Hydraulic tools are also more powerful than pneumatic tools because they use pressurized liquid (oil) which does not compress like air does. The downside of hydraulic tools is that they can be messy. A leak in a hydraulic tool will spray hydraulic fluid whereas a pneumatic tool will just leak air. Another downside of hydraulic tools is that they are more expensive than pneumatic tools.

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[1] Camp.se4.jpg. 9 July 2009 <http://www.turfeagle.com/products/husqvarna.html>
[2] Felco 70.jpg. 9 July 2009 <http://www.felcousa.com/felco/pages/product.page?name=FELCO%2070>
[3] hydrpruner1.jpg. 9 July 2009 <http://www.peachridge.com/pruning/pruning/hydrpruner1.jpg>

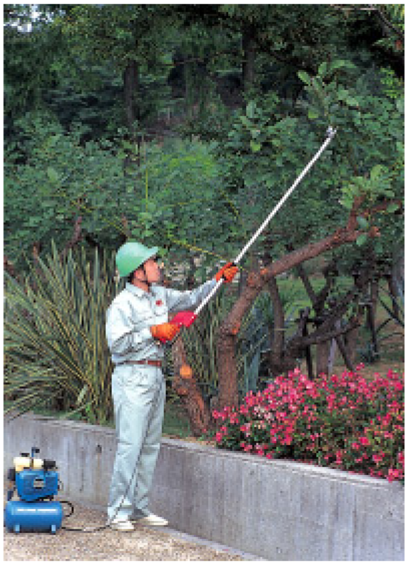

Figure 2 Portable air compressor.[4]

Figure 3 Back mounted air tank.[5]

All fluid powered pruners on the market today have one thing in common. The actuator on these pruners is like a switch. It is either fully on or fully off. This means the operator can only give the pruners full power or no power at all. If the output force could be varied some air could be saved because low pressure can be used for small branches and high pressure used for thick branches. If the user could also get some feedback on the force which the pruners were producing it would greatly improve the safety of the system, as discussed later.

The use of a haptic control mechanism on a pair of loppers would be a way to give the user of the loppers a large variable output force with a small variable input force. Haptic feedback describes sensory feedback involving both tactile and force information [8]. A control mechanism for the loppers could act like a force multiplier. The operator could put in a certain force and the loppers would multiply that force to the lopper cutting head. If the operator puts in twice as much force at the handle, there will be twice as much force applied at the cutting head. This would allow the user to cut through thick branches by only inputting a small variable input force.

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[4] 04_mainpic_005.jpg. 9 July 2009 http://www.ars-edge.co.jp/world/02products/product_04longpru.html

[5] pruner-man 14 Oct 2009 http://www.winebusiness.com/content/Image/pruner-man.jpg

The force multiplication works the opposite way as well. The object that the loppers are trying to cut through would provide a resistance that would vary depending on what is being cut. The user would be able to feel the varying degrees of resistance when they are actuating the loppers.

Haptics has been used in a variety of applications, including robotic exoskeletons for soldiers [5], emergency responders [5], and rehabilitation of those who have had a stroke [6]. Commercially available devices like the PHANTOM[6] and the WAM Robotic Arm[7] have been using haptic feedback for over 15 years. These products however, have advanced feedback mechanisms that would be too expensive to be feasible on a consumer pruning tool. The haptic controls for these proposed loppers are much more simplistic and cost effective.

Haptic control has also been used in the auto industry [1]. There are many parts of a car on an automotive assembly line that are too heavy or awkward for one person to lift or to do so repeatedly without injury. This is where robots or push button assisted lifting can help out. These aids do have their limitations though. Robots move only according to programmed instructions and do not adapt to different circumstances. Push button assisted lifts can move a heavy object with ease but they do not give the operator a feel for how well the object is aligned or if there is something not fitting quite right. The operator must then rely on visual or audio cues to determine fit. A haptic controlled assist device on the other hand can respond to human intent and therefore adapt to changing circumstances. The human operator can interact with the machine in an intuitive manner. With haptic controls, the operator can feel how things are fitting together. This haptic way of interfacing with the machines has been shown to reduce assembly time in some cases and this in turn makes the process more efficient [1].

The use of haptic controls has also been used as a safety mechanism. Tactile feedback can be used in the development of warning systems for drivers [3]. For instance, they can be used to awaken sleepy drivers, get the attention of drivers who are visually overloaded, or get the attention of distracted drivers. There was a study done on the usefulness of a feedback mechanism installed in the steering wheel of a car [4] or on

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[6] PHANTOM Premium 3.0 Haptic Device, Sensable Technologies, Inc, http://www.sensable.com

[7] WAM robot, Barrett Technology, Inc, http://www.barretttechnology.com

the driver's arm [2]. These systems were used to alert the driver of possible problems while driving. There is a great deal of multitasking that goes along with driving a car and this study measured the diver's reaction time to various stimuli. The reaction times of the drivers were found to be greatly reduced when using the tactile feedback. This same principle can be used with a pair of loppers. If the person using the loppers is not paying enough attention to what they are doing, the haptic controls could alert them to a problem that they would not have otherwise noticed until it was too late. For example, if the user is repeatedly cutting through small branches and feeling little resistance, and then they try to cut though another small branch and they feel a much larger amount of resistance, it would signal to them that there is something wrong. There could be a piece of wire they do not see behind the branch or a piece of their clothing or equipment that got caught in the lopper cutting head.

There are other automotive applications where haptics can be used for comfort as well as for safety. In [7], an actuated car door using haptics is proposed. The door is controlled by a force sensor on the door handle or located in another place on the door. There is a motor in the door hinge which assists the user in opening and closing the door. If a user has difficulty opening or closing a heavy door, especially if the car is on an incline, the haptically controlled door helps them complete the task. If the door is combined with a sensor system for detection of obstacles, a collision prevention system can be realized. The system would be able to give the user feedback if the door is going to hit something. The haptic system can also make the door safer for the user. The door would not be able to shut on its own and risk closing on a finger. It would not be able to close unless the user is pushing or pulling on the force sensors.

Power steering and power brakes are similar force multiplying haptic devices. They take an input from the driver and multiply that force to provide a powerful output. Power brakes, for instance, use a varying amount of vacuum provided by the engine to assist the driver in pushing the piston in the brake master cylinder. The harder the driver pushes on the brake pedal, more vacuum is allowed in the brake booster and the more the diver is assisted in braking.

Haptics can also be used in the medical field. The da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA) is a surgical robotic system that allows a surgeon to manipulate robotic arms during surgery. The da Vinci system does not currently have haptic feedback so the surgeon must rely exclusively on visual cues [9]. Tactile feedback may help surgeons to operate and grasp tissue more naturally and with greater control [10], [11]. It can also help in the detection of hard and soft tissues [12]. This tactile feedback is something that can be applied to the pneumatic loppers.

There are no powered loppers or pruners on the market that have a feedback mechanism on the actuator to give the operator a feel for what they are cutting through. There are many reasons why the addition of a feedback mechanism can be beneficial. First of all, the lack of feedback can prove to be a safety hazard. If there is just an on/off switch on the actuator it is possible to accidentally hit the switch and cut through something you do not intend to cut through, such as the operator's equipment or even a finger. It is also beneficial to know how difficult it is to cut through a branch. If the branch looks small and there is a large amount of resistance, the user can realize that something is wrong. There could be a hidden metal wire behind the branch or a piece of equipment could be in the way of the cutting head.

Another idea for improved loppers is to house the compressed air inside the loppers themselves instead of having to haul around an air compressor or wear a compressed air tank on your back. This would make the pneumatic loppers much more convenient to use. It will also allow people who are not physically capable of hauling an air compressor around to use the loppers.

1.2 Patent Search

A patent search was performed to generate ideas for new lopper designs as well as to avoid any possible patent infringements. The primary resource used to conduct the patent search was the on-line USPTO website. The search was done using keywords such as "lopper", "trimmer", "shears", "pneumatic", "hydraulic", "control system", and "haptic". The classes and sub-classes of the lopper patents were reviewed and it was determined that the following class and sub-classes were the most relevant to the search.

Class 30 – CUTLERY

Sub-class 188 –

One movable blade

Sub-class 189 –

Lever and cam

Sub-class 190 –

Lever and link

Sub-class 237 –

Compound blade movement

Sub-class 243 –

Toothed lever and slide

Sub-class 249 –

One movable blade

Sub-class 251 –

Lever and connecting link

Most of the patents that were found in this search were related to the cutting head of the loppers. There were no patents that were found that related to a control system for any kind of lopper, pneumatic, hydraulic or otherwise.

There were quite a few patents found for manual loppers such as Davis 4644652 (1987), Linden 5570510 (1996), Linden 5689888 (1997), and Van Den Hout 5894667 (1999). There were also many pneumatic powered loppers such as J.S. Goodman Re 21347 (1934), E. Landaro 3373490 (1966), Michelson 5341562 (1994), and Sun 6901665 (2005). There was also an interesting patent (Merwe 4949461 (1990)) that comprises a pneumatic lopper with two switches that both need to be depressed by the operator's two hands for the lopper to function. This is a safety feature that could be incorporated into future lopper designs.

There was nothing that was found in the patent search which would indicate that this proposed lopper design with a haptic control system would infringe on any current patents. A full list of the relevant patents from the patent search can be seen in Appendix A.

1.3 Objective

The goal of this project was to demonstrate the potential of force-multiplying, pneumatically powered hand tools. This was done through the development of a pair of pneumatic powered loppers, which have a force multiplying mechanism on them which is purely mechanical. The amount of force and work needed to cut through various branches were tested. From this data a proper tank size and pressure for powering the loppers was determined.

2.0 POWER AND FORCE REQUIREMENTS

2.1 Purpose

The purpose of this test was to determine the amount of work required in the operation of a standard lopper and the maximum force needed during a cut. The objects that were cut were wooden dowels and tree branches of various sizes. These were used to simulate a wide variety of cutting situations an operator of a pair of loppers could encounter.

2.2 Method

2.2.1 Apparatus

The lopper that used in the experiment was a Corona Bypass 26" lopper. One handle of the lopper was fixed and the other was allowed to move. The moving handle had a pivoting female threaded piece on the end of it. There was a long threaded rod which was fixed at one end and went through the female threaded piece on the moving handle. The turning of this threaded rod was the mechanism that actuates the jaws of the lopper. The setup can be seen in Figure 4.

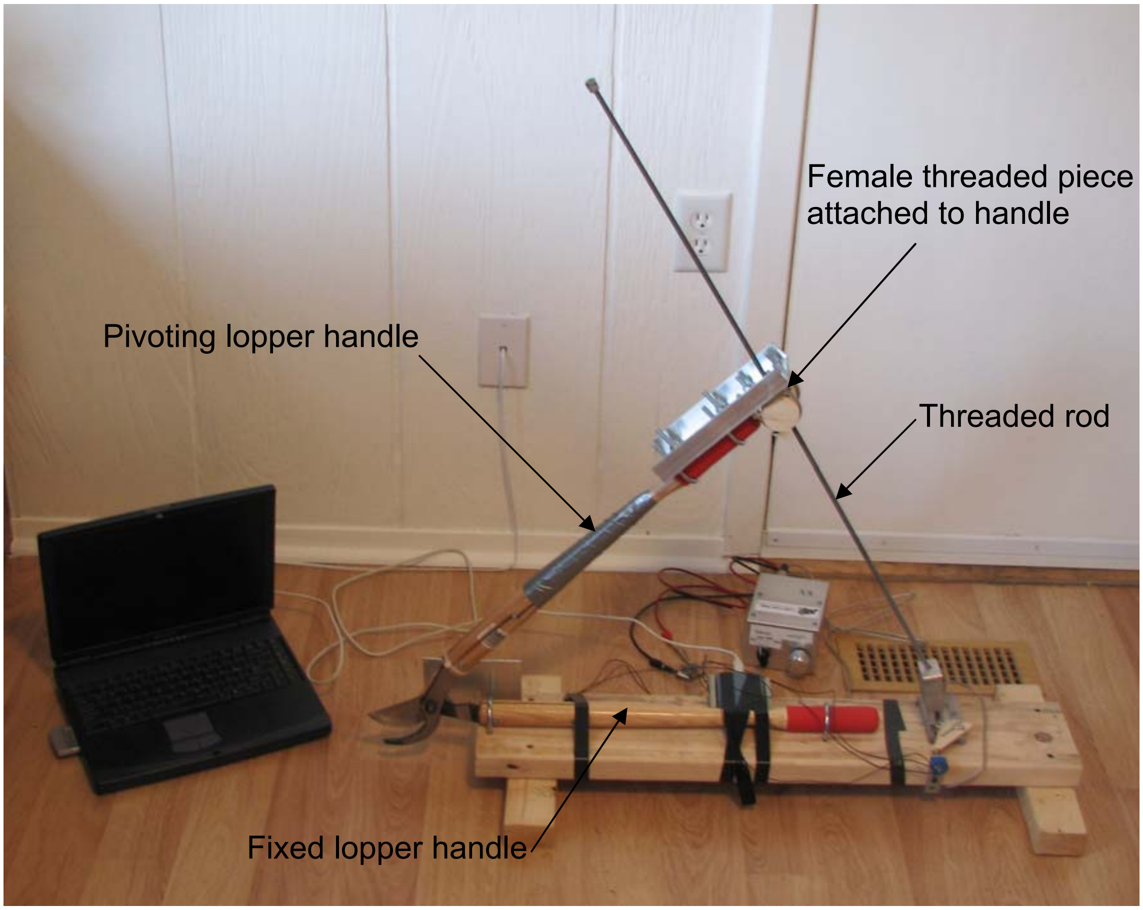

Figure 4. Lopper test setup

In this test setup one handle of the lopper was fixed to a wooden base using U-bolts. To the end of the other handle there was fixed a short piece of large diameter dowel that was free to rotate (Fig. 5). A slot was cut into the dowel and a T-nut was epoxied into it (Fig. 6). As the lopper handle was actuated, the dowel rotated to keep the axis of the T-nut pointed at the fixed end of the threaded rod.

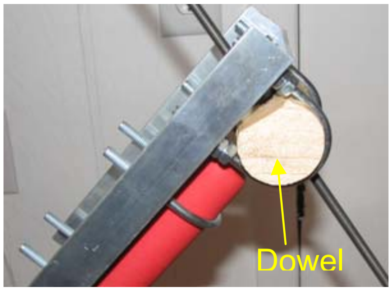

Figure 5. Pivoting dowel on upper handle.

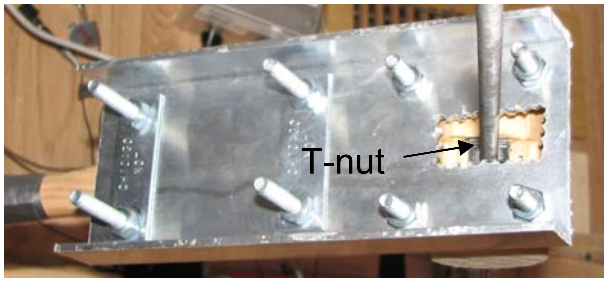

Figure 6. T-nut on upper handle.

The other end of the threaded rod was attached through a load sensor (Omega LCEB-150, 150 lb) to the wooden base. Thrust washers were used to allow the threaded rod to rotate. A metal bracket attached the threaded rod to the load sensor which measured the force needed to cut through the test pieces. The load sensor was mounted on a hinge to allow the load sensor and threaded rod to always be aligned. These parts can be seen in Figure 7.

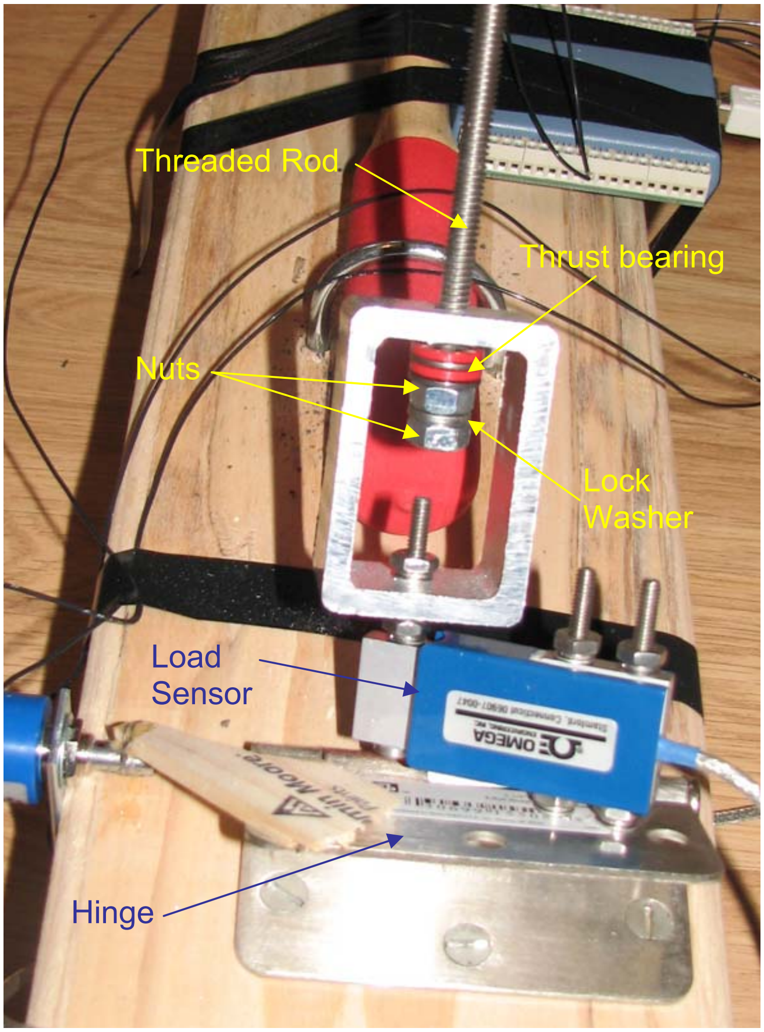

Figure 7. Load sensor end of threaded rod.

At the free end of the threaded rod there was a nut, lock washer, and another nut. This allowed the threaded rod to be driven by a cordless drill (Fig. 8).

Figure 8. Driving the mechanism

There was a potentiometer on the test setup (Bourne 6639S-1-103) to measure angles along with the load sensor (Figure 9). The potentiometer was aligned with the cutting head's pivot point and was used to measure the angle of the handle as it was actuated. This angle data was used to calculate the distance over which the force was applied. Since this was a single degree of freedom system, the angle between the fixed handle and the threaded rod was calculated and used to measure the force which was perpendicular to the handle. The load sensor was used to determine the force needed to cut through the test pieces.

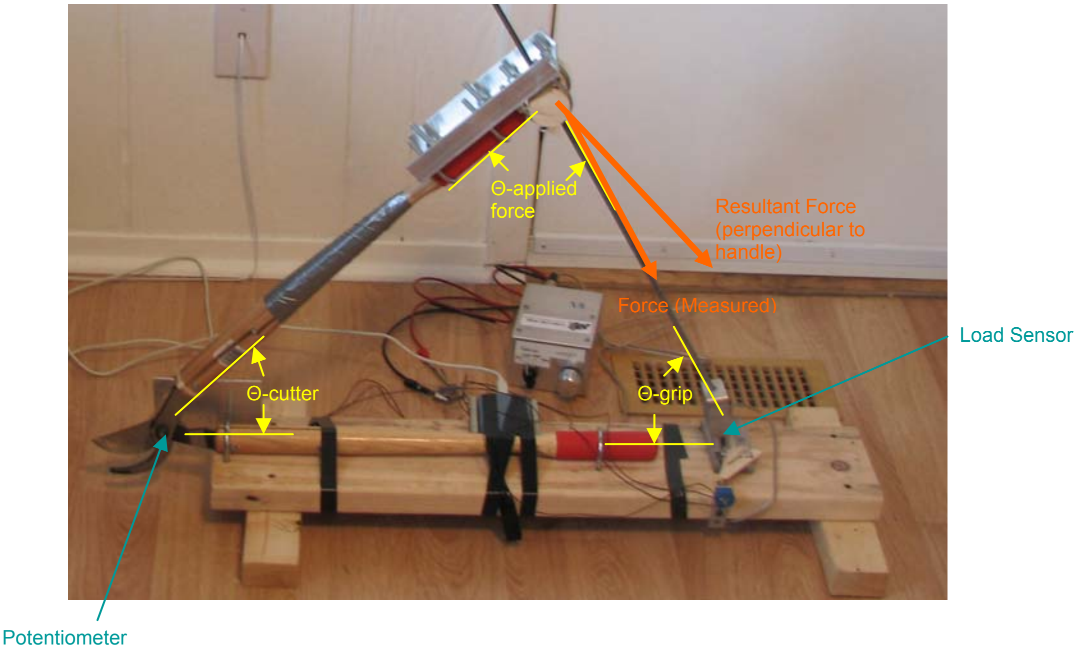

Figure 9. Sensors.

The sensor data was read into a PC using a Measurement Computing USB-1208FS data acquisition unit. The data acquisition unit has a range of 0 to 4.096 volts, a sampling rate of 10 kS/s, and a resolution of 12-bits. The sampling rate for these tests was 1 sample per second.

2.2.1 Sensor Calibration

The sensors needed to be calibrated before any data could be taken. The potentiometer that was used was a Bourn precision rotary potentiometer. When given a 5 volt input, supplied by the data acquisition unit, the output voltage varies linearly with shaft angle

The potentiometer was locked in place mechanically so the angles could be repeated. The θ_{cutter} angle was set to $90^{o}\pm1^{o}$ using a carpenter's square and the output voltage was measured. Then the θ_{cutter} angle was set to $25^{o}\pm1^{o}$, the fully closed position of the lopper handles, and the output voltage was measured. This was repeated three times and the values are shown in Table 1.

θ_{cutter} = 90°	θ_{cutter} = 25°
voltage	**voltage**
0.278	1.256
0.251	1.273
0.24	1.273
average	**average**
0.26	1.27

Table 1. θ_{cutter} calibration values.

The table shows that for a change of 65° the voltage will change by 1.01 volts. A change in one degree will result in a change of .016 volts. The equation for θ_{cutter} is then

$$\theta_{cutter} = \frac{(1.67 - V(x))}{.016\frac{V}{{}^{o}F}}$$

The load sensor has an output in mv/V. A load cell amplifier was used to boost the output signal with a gain of 200 to give an output voltage from -2.5V to +2.5 V. The sensor was calibrated by first fixing the body of the sensor to a board. Then a bolt was placed through the sensing arm mounting hole. The direction of load can be seen in Figure 10.

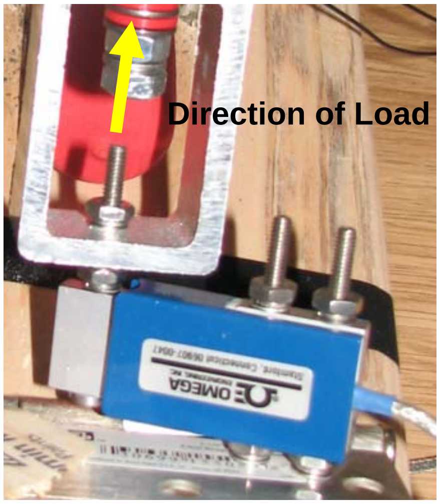

Figure 10. Load sensor.

The bolt was then placed on a bathroom scale and loaded to 100 lb while making sure the sensor body was parallel to the bathroom scale. The voltage was then read at 0 lb as well. This was then repeated and the data is shown in Table 2.

100 lb load voltage	0 lb load voltage	Voltage Difference	lb/volt
0.88	-1.12	2	50.0
0.83	-1.14	1.97	50.8

Table 2. Load sensor calibration.

There is 1.99 volts difference for 100 lb so the equation for the force is

$$F = V(x) * 50\frac{lb}{V}$$

2.2.2 Test Procedure

Each test was performed in the following way. The jaws of the lopper were opened to the angle needed so that the sample piece could be inserted into the jaws. There was a mark on the cutting jaws that was lined up with the centerline of each sample piece so that the force vs. angle graphs would be comparable. If one of the samples was placed farther into the jaws, the forces would be less but it would have to work over a greater distance. Conversely, if one of the samples was placed farther out toward the tip of the jaws, the forces would be greater but it would have to work over less of a distance.

Then the data acquisition unit was started and the jaws of the lopper were driven closed by turning the threaded rod with a cordless drill. The data acquisition was stopped when the sample was completely cut in half. The samples that were tested can see seen in Table 3.

Diameter	Material	Source	Sample #
1/2"	hardwood dowel	Home Depot	1
3/4”	hardwood dowel	Home Depot	2
1.0”	hardwood dowel	Home Depot	3
1.25”	hardwood dowel	Home Depot	4
1.0”	Oak dowel	Home Depot	5
1.0”	Pine Branch	Backyard	6
1.5”	Pine Branch	Backyard	7

Table 3. Test samples.

Each sample was tested twice except for #5. There was only one test of sample #5 because the lopper handle broke during the second test.

2.2.3 Data Analysis

Work:

To get the work (W) done by the loppers the handle force (F) and Distance (D) were used in the equation

$$W = F * D$$

where F was the force being applied perpendicular to the handle (Fig. 11) and D was the distance traveled by the point on the handle where the force is applied.

Distance:

The distance traveled (D_T) by the end of the handle was calculated using the length of the handle (L_H) in the equation

$$D_T = L_H * 2\pi * \Delta\theta_{cutter} \div 360$$

where $\Delta\theta_{cutter}$ is in degrees.

Load:

To get the portion of the force which was perpendicular to the handle, $\theta_{\text{applied force}}$ needed to be calculated. Since the length of the handle and the length of the base were both known, $\theta_{\text{applied force}}$ could be calculated. Then the force perpendicular to the handle could be calculated by

$$\text{Force}\perp_{\text{handle}} = \text{Load measured} * \cos(90 - \theta_{\text{applied force}})$$

The work was calculated for each time increment and summed up to get the total amount of work required.

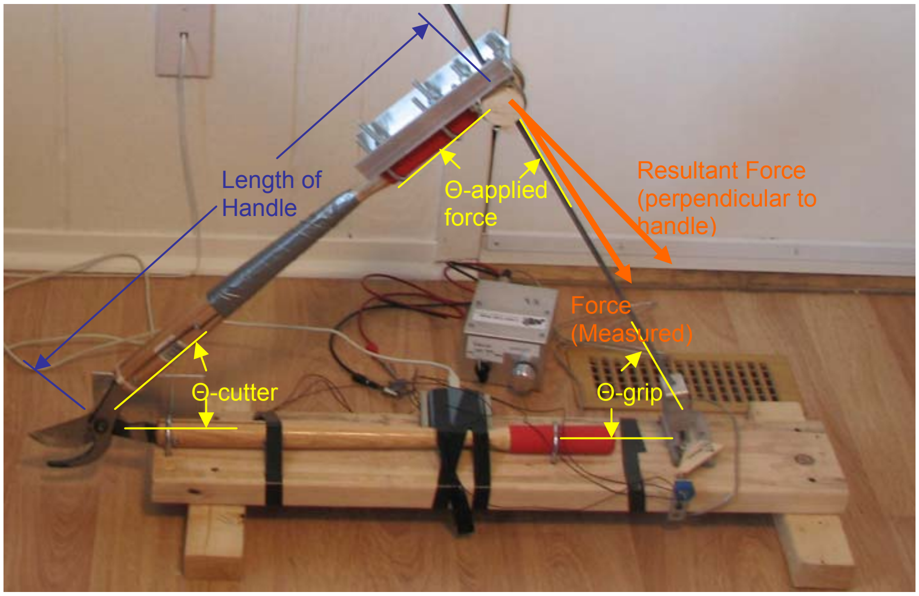

Figure 11. Calculations.

2.3 Results

Figures 12 and 13 show typical plots for force and angle versus time.

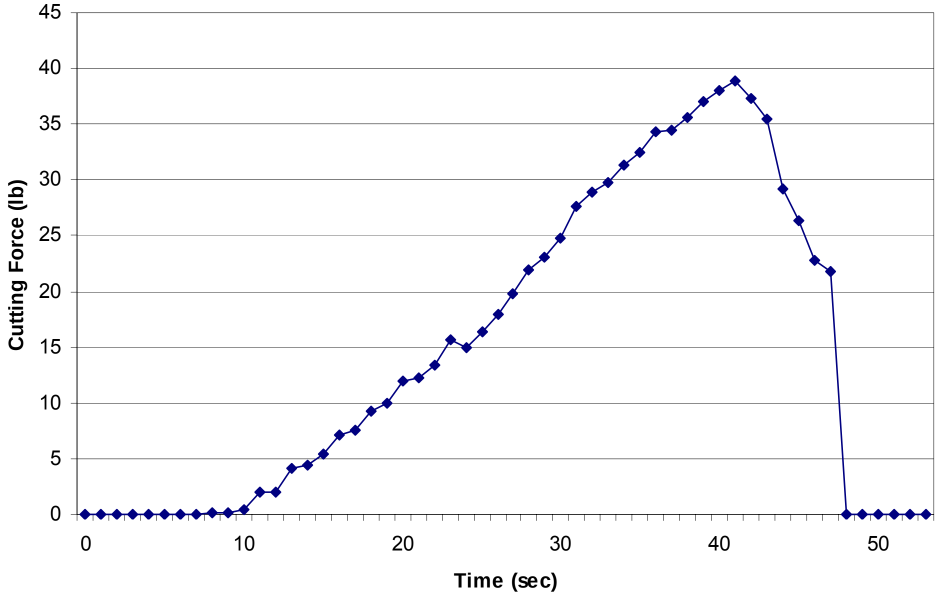

Figure 12. Input force vs. time.

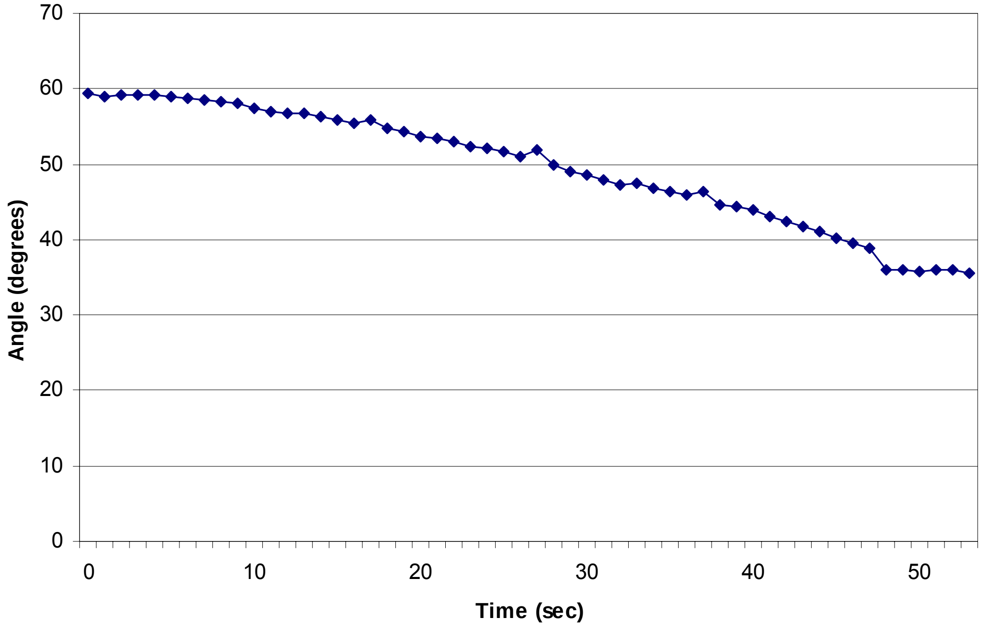

Figure 13. Cutting angle vs. time.

Figures 14 and 15 show the work and maximum handle force required to cut through the various test pieces.

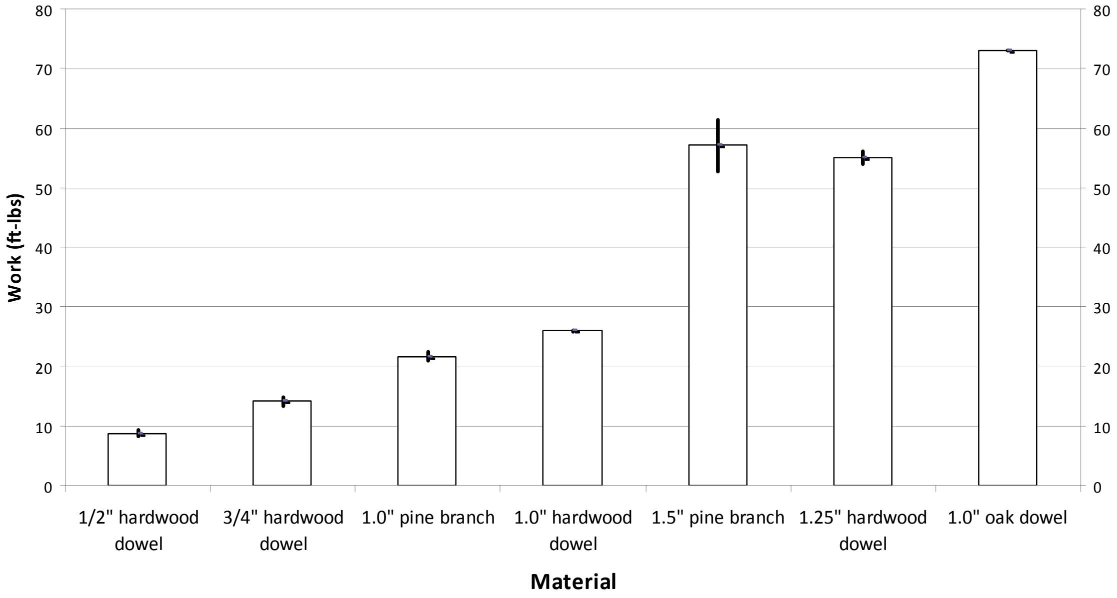

Figure 14. Average work required.

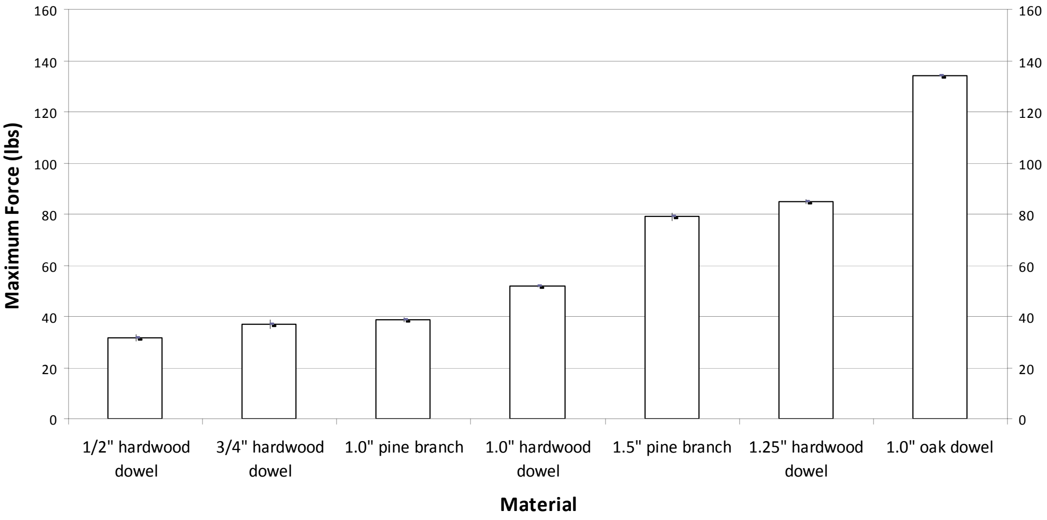

Figure 15. Maximum force required.

Figure 16 shows what angle the cutter head is at the point of maximum force.

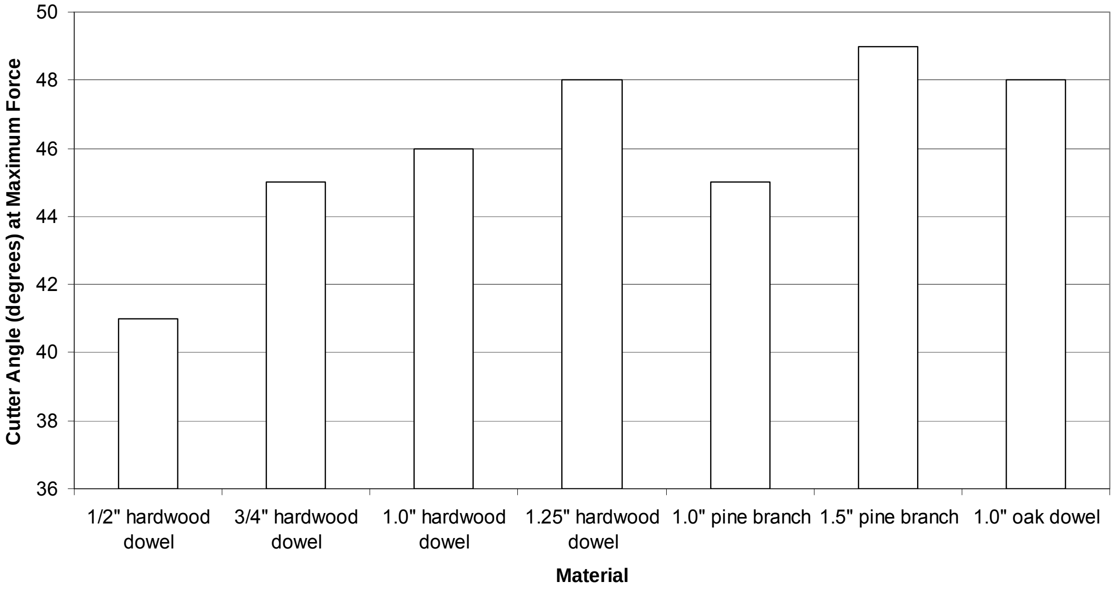

Figure 16. Cutter angle at point of maximum force.

2.4 Discussion

The testing shows a 2^{nd} order polynomial curve for the work required to cut though the dowels as the diameter increases (Fig. 17). This makes sense because the work required is based on cross sectional area and the cross sectional area increases with the square of the diameter.

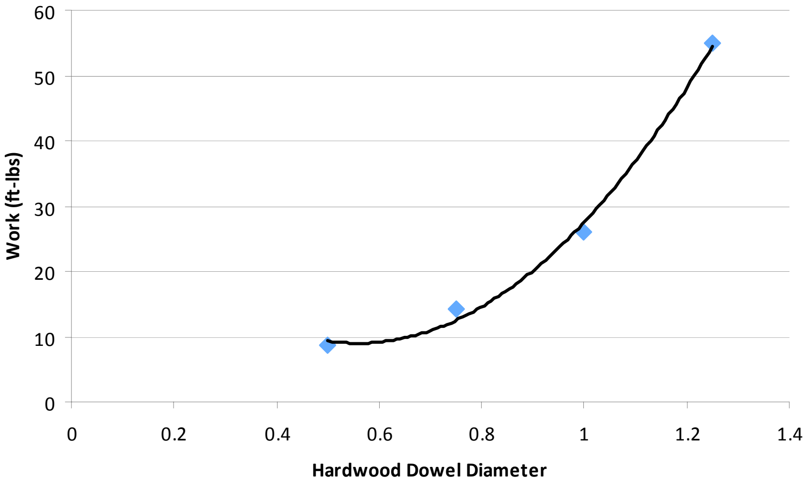

Figure 17. Work required to cut through different diameters.

There were two tests performed to find the work required to cut through each size of dowel and branch. The average variation between the two tests of each size of hardwood dowel was 7%. This confirms that the data taken for each size sample was consistent.

Since the handles on the test lopper broke on the second test of the oak dowel, only one data set was collected for that size.

3.0 PROTOTYPE DEVELOPMENT

3.1 Prototype Description

The prototype was designed to test the cutting mechanism and control system, not power storage, so it was designed to run off of an air compressor with no onboard storage of compressed air. Because of this, the supply pressure was limited to 100 psi. There was no need to reengineer a new cutting head so a pair of Corona Bypass 26”loppers was purchased from Home Depot and retrofitted with two pneumatic cylinders to provide the cutting force.

3.1.1 Pneumatic Cylinders

First of all, the proper size of cylinder needed to be determined as well as where to place them on the loppers. To determine the size of pneumatic cylinder needed, the torque required was calculated. This was calculated using the data from the initial tests on wooden dowels. The ¾” hardwood dowel was used as the maximum size to cut through with the prototype lopper. The maximum force perpendicular to the handle needed to cut through the ¾” dowel was almost 40 lb. This was applied on a lever arm of 23.6” which gives the needed torque of 944 in-lb shown below.

$$40 \text{ lb} * 23.6\text{in} = 944 \text{ in-lb}$$

The mounting locations for the pneumatic cylinders also needed to be determined. There were two existing mounting points on the lopper’s metal cutting head (Fig. 18).

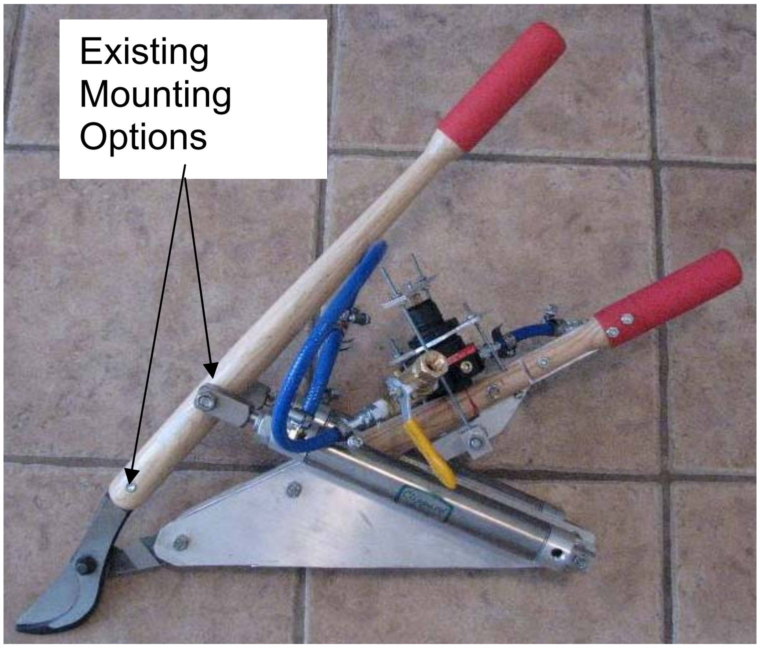

Figure 18. Pneumatic cylinder mounting point possibilities.

These existing mounting holes were a convenient place to mount the cylinders. Since the supply pressure was only going to be 100 psi, the mounting hole that would provide a greater moment arm was chosen to keep the pneumatic cylinder diameter to a minimum. The shorter moment arm mounting hole is approximately 3” from the cutting head pivot point. The more desirable attachment point was approximately 7” from the cutting head pivot point.

To minimize the force needed, the cylinder was oriented such that the angle between each handle and the cylinder are equal, forming an isosceles triangle (Fig. 19). This maximizes the lever arm between the cutting head pivot point and the cylinders.

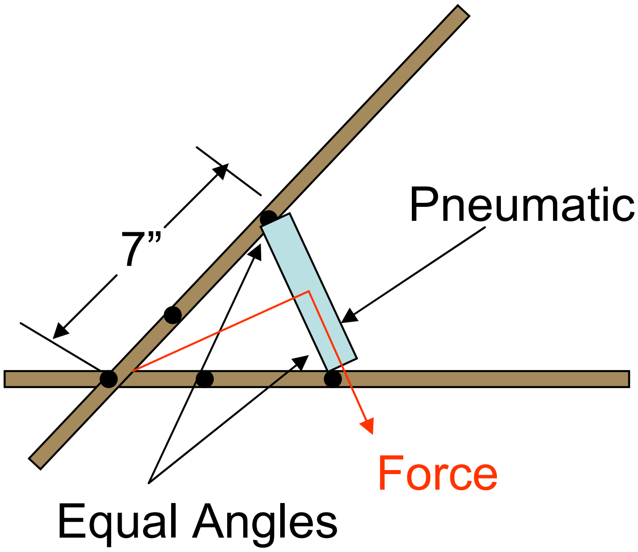

Figure 19. Pneumatic cylinder forces.

This geometry should occur at the point in the cutting stroke where the maximum amount of force is needed. The test data shows that the maximum force is needed when the angle between the two handles is approximately 45º. The mounting hole is approximately 7 inches from the pivot point. The calculation of the lever arm is shown below.

$$7" * \sin(45/2) = 5.9" \mathit{lever\_arm}$$

With a lever arm of 5.9 inches and a required torque of 944 in-lb, the force required is 160 lb. Some margin was added to take into account friction and other losses, so the target force was 200 lb. With 100 psi of air to work with, the area of the cylinder needed to be at least 2.0 in^2. This would require either one 1.75" diameter cylinder or two 1.25" diameter cylinders. These numbers take into account the area taken up by the rod because the force is acting on the side of the piston where the rod is attached. Having one cylinder in between the two handles would have been ideal from a reduction in complexity standpoint but there was not enough room to provide the stroke length that was needed. The cylinder needed to extend past one or both of the handles. This pushed the cylinder off to one side. To make the loppers symmetric two cylinders were used, one on each side, which would extend past one of the handles (Fig 19). The loppers therefore have two 1.25” diameter cylinders providing a maximum of 1,300 in-lb of torque to the cutting head.

The approximate stroke length of the pneumatic cylinders needed to be determined as well. The distance from the pneumatic cylinder mounting point on the upper handle to the corresponding mounting hole on the lower handle was measure and found to be 4”. The loppers were then opened to 75° which corresponds to the widest the loppers had to open to cut the 1.5” diameter pine branch. The distance was measured again and found to be 10”. Thus the stroke length of the pneumatic cylinders needed to be approximately 6”.

The cylinders that were chosen were Clipppad Minimatic, part number UDR-20-6, purchased from McMaster-Carr. These have a bore of 1.25 inches and a stroke length of 6 inches. Due to the stroke length needed to actuate the loppers, the other end needed to be fixed below the lower handle. A bracket was made to connect the cylinder to the handle (Fig. 20).

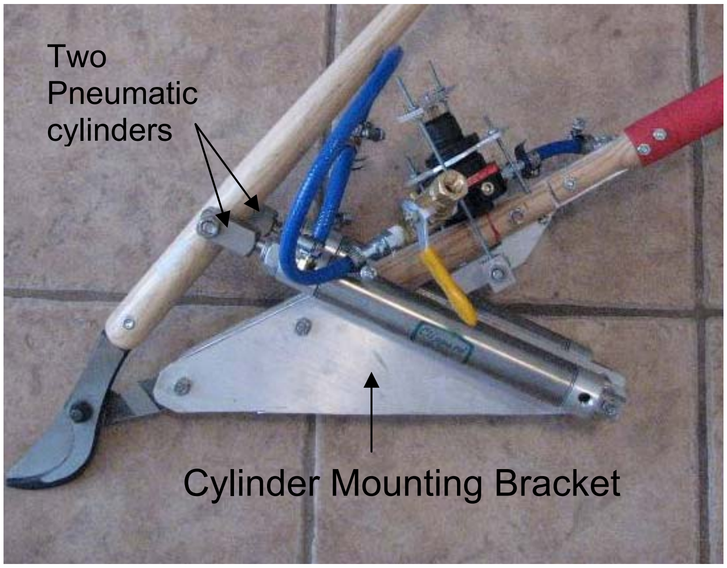

Figure 20. Cylinder mounting bracket.

3.1.2 Control System

A mechanical control system was developed to provide proportional control for the user. The theory behind the control system was to use a pressure regulator to vary the air pressure supplied to the pneumatic cylinders. The basic components of the system were a pressure regulator (Husky model #HDA70503AV) purchased from Home Depot, a pivoting handle, and a link from the handle to the pressure regulator (Fig. 21).

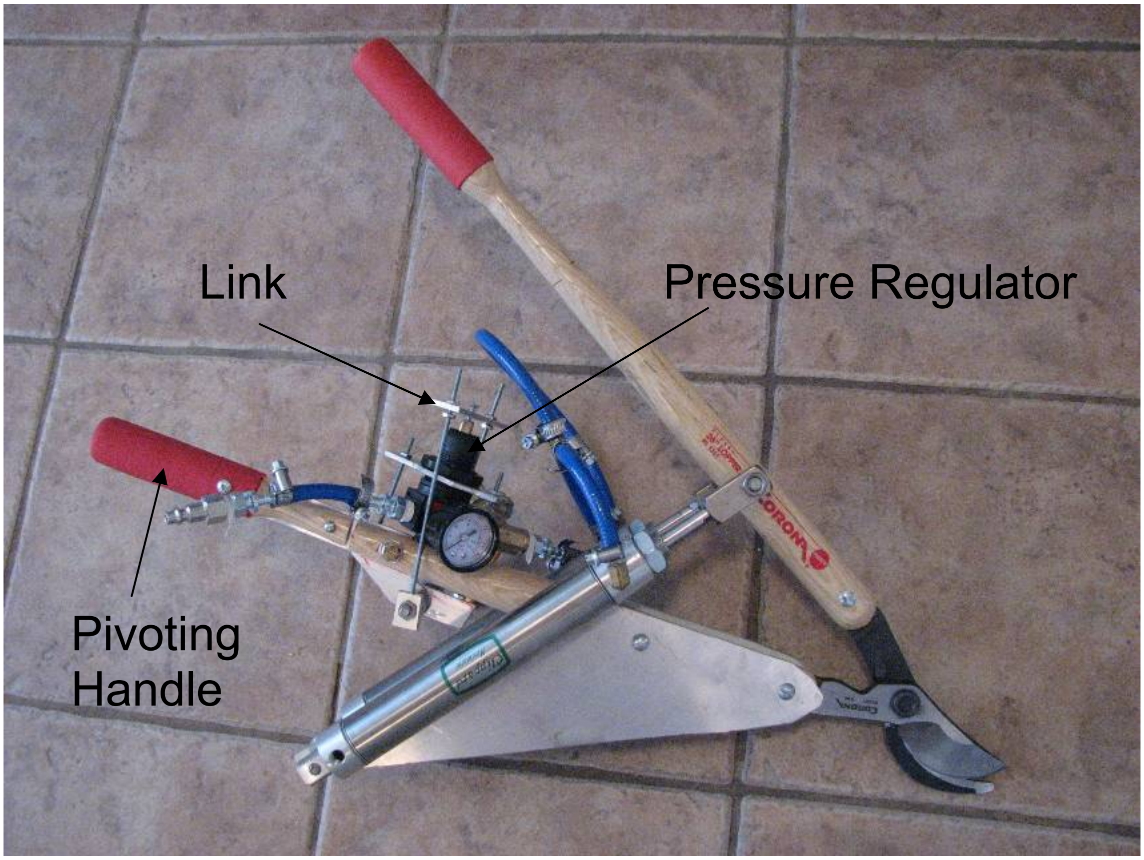

Figure 21. Mechanical control system parts.

Figure 22 shows a diagram of the mechanical control system.

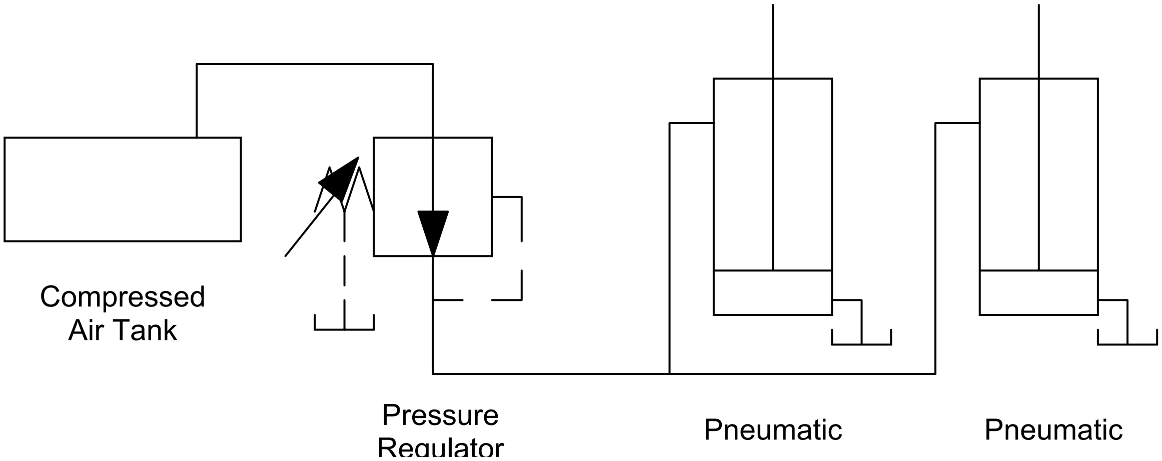

Figure 22. Mechanical control system diagram.

The pressure regulator is a standard air compressor pressure regulator purchased at Home Depot. It is normally actuated by turning a threaded knob. As the threaded knob is turned it moves down depressing the spring loaded valve actuator. As the valve actuator is depressed the pressure allowed to pass through is increased. For this controller the threaded knob is removed in favor of a direct force pressing on the actuator. Because the actuator is spring loaded, the harder one pushes on it the more pressure it lets through, providing the proportional force reflection.

When the user pushes the two handles together, the lower handle pivots slightly (Fig. 23). This pulls the link down and depresses the spring loaded actuator on the pressure regulating valve.

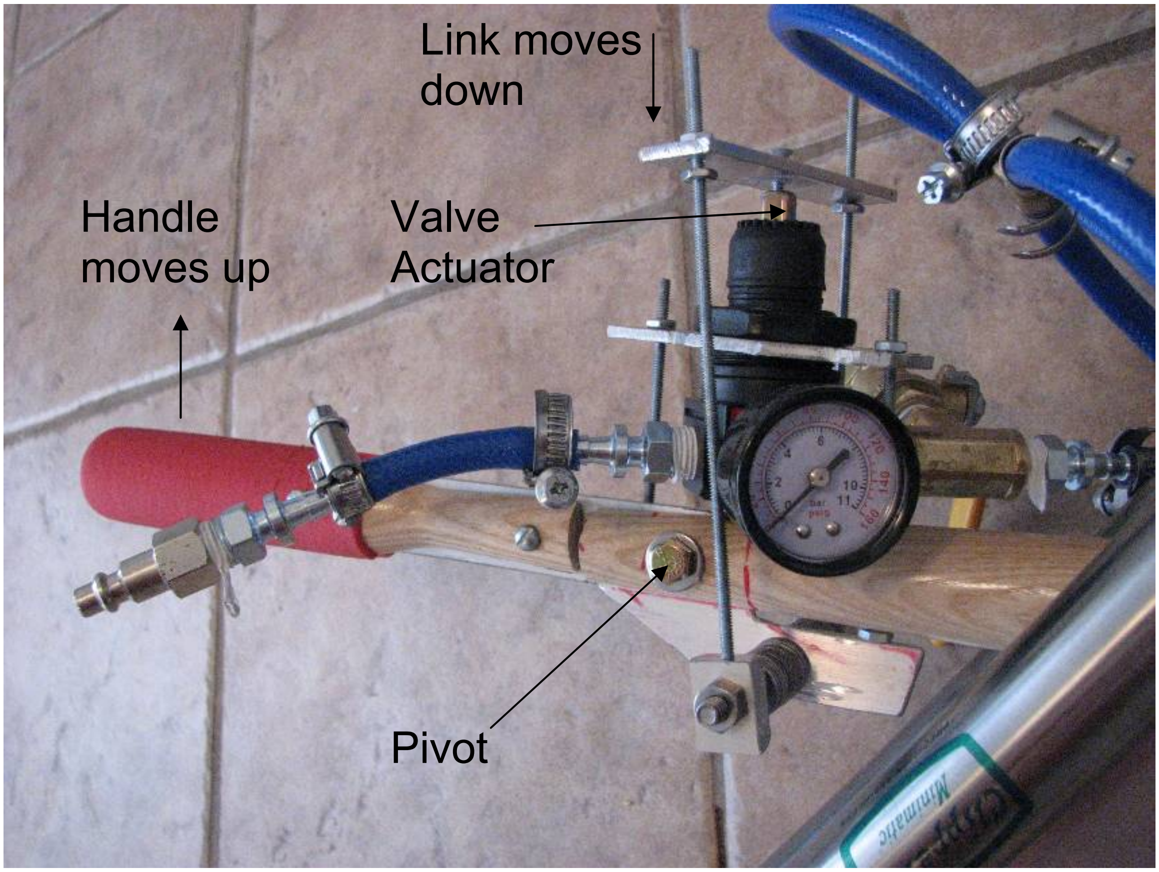

Figure 23. Mechanical controller actuation.

The pressure regulator has an over-pressure vent which allows the user to pull the handles apart when the system is connected to a pressure vessel. This is due to the fact that when the user pulls the handles apart the pressure regulator actuator is under no load so it is set to allow zero pressure at the outlet. As the user pulls the handles apart, the piston rod extends compressing the air in the cylinder and raising the pressure. Since the pressure is raised above the over-pressure limit, which is now at zero, the pressure regulator vents off the excess pressure.

3.2 Performance Evaluation

Once the prototype loppers were built they were tested to see if they could cut through dowels with a small amount of input force. During the initial trials all parts of the loppers were in working order. A test was then devised to see if the input to the loppers was proportional to the output.

3.2.1 Apparatus

The test setup can be seen in Figure 24. The loppers were clamped to the bench. A string was then tied to the pivoting handle of the loppers and run through a pulley in the ceiling. At the other end of the string were two plastic milk jugs. The milk jugs were filled with water to provide the weight needed for the input force.

Figure 24. Prototype proportionality test setup.

3.2.2 Test Procedure

The test was preformed for a variety of different supply pressures and cutting head angles. For each test, the lopper cutting head was fixed at a certain angle by putting a piece of metal in the jaws of the lopper. Then, water was added to the milk jugs, one cup at a time, until the pressure in the cylinder reached the supply pressure from the air compressor. After each cup of water was added, the cylinder pressure was measured along with the moment arms of the input and output forces.

The tests were run at cutting angles of 25°, 40°, 55°, and 70°. The 25° cutting head angle is the fully closed position and 70° is the widest the jaws will open before the pneumatic cylinders bottom out. For each of these angles the supply pressure was set at 100, 75, 50, and 25 psi for a total of sixteen different test cases. These different tests were used to represent the range of operating conditions the loppers would be used in.

3.2.3 Data Analysis and Results

After the data was collected, the input and output torques were calculated and plotted against each other. The graphs in Figures 25 and 26 are representative of how all of the graphs looked. All of the graphs can be seen in Appendix D.

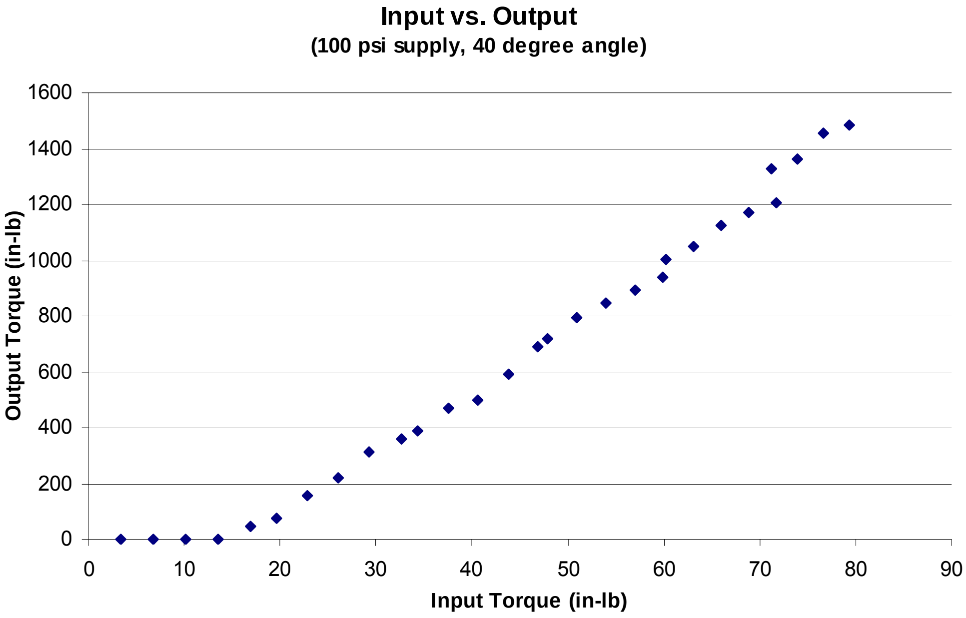

Figure 25. Proportionality test 1.

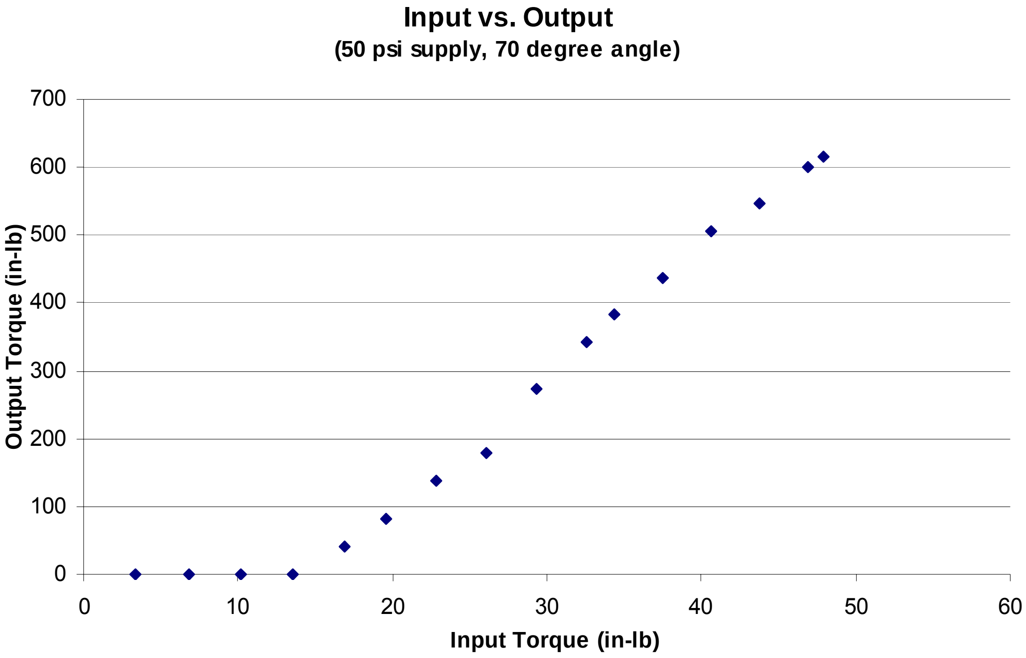

Figure 26. Proportionality test 2.

All of the graphs have an output torque equal to zero for input torques of less than 15 in-lb. This can most likely be attributed to two causes. The first cause is that there is friction in the system that needs to be overcome. The second cause could be that the gauge on the pressure regulator had a negative offset, causing all of the output pressure readings to be low. After the initial phase however, all of the graphs show a constant slope. This demonstrates that the output torque is indeed proportional to the input torque.

3.2.4 Improvements

One problem with the mechanical control system is that after the loppers cut through the toughest part of the piece of wood, there is a great deal of pressure built up in the cylinders and the resistance from the wood drops off dramatically. The high pressure and low resistance causes the loppers snap shut at the end of the cut. This is one area that an electronic controller or snubber could help to improve the performance.

3.3 Air Tank Size

3.3.1 Purpose

The purpose of this section is to determine the size of the air tank which could power an untethered set of pneumatic powered loppers.

3.3.2 Assumptions

In determining the proper tank sizing a few assumptions were made about how the loppers would be used. It was assumed that the average branch that these loppers would be cutting through is equivalent to a ¾" diameter hardwood dowel. It is also assumed that the largest cut they would need to perform will be equivalent to a 1.5" diameter pine branch.

3.3.3 Calculations

Calculations are based on testing performed with the force and angle sensors. For the purposes of these calculations, a "cut" will be the amount of work required to cut through a ¾" hardwood dowel. This has already been calculated to be 14 ft-lbs (see Fig. 13). The amount of work required to cut through the 1.5" diameter pine branch was 57 ft-lbs (see Fig. 13).

The amount of Work (W) to change the pressure in a pressurized vessel can be calculated by [13]

$$W = P * V * \ln\left(\frac{P'}{P}\right)$$

where

V = Volume of the vessel

P= Absolute pressure at initial state

P'= Absolute pressure at final state

Not all the air in a given tank is usable. Once the pressure in the tank drops below the peak pressure needed by the cylinders it is useless. Depending on the pressure in the tank there is a different amount of usable air in the tank. It is ideal to have a low working pressure on the cylinders and a high tank pressure to maximize your usable air. The usable percentage of air in a tank is calculated by

Usable % = 1 – Peak Absolute Cylinder Pressure / Tank Absolute Pressure

Assuming a peak absolute pressure of 60 psi, the results are shown in Table 4.

Tank pressure (psi)	4500	3000	1000	125
Usable percentage of tank	98%	98%	93%	47%

Table 4. Properties at different tank pressures.

Now that the amount of work needed to complete a cut and the usable percentage of tank air at different pressures is known, some comparisons can be made. Table 5 shows the attributes of some different tanks.

Tank Type	Tank Size (in^3)	Weight of tank (lb)	Common max PSI	Energy Stored (ft-lb)
Average Scuba Tank (12L)	732	30.0	3000	982218
Carbon Fiber Scuba Tank	550	11.3	4500	1190635
Large Paintball CO2 Tank	110	4.0	4500	238127
Rhino CO2 Tank (20 oz)	70	4.0	830	18360
Average Paintball CO2 Tank	68	3.0	3000	91244
Pringles Can Size Tank	60	2.0 (estimate)	3000	80510
Rhino CO2 Tank (9 oz)	30	2.0	830	8262
1 Foot Long Tank About the Diameter of Lopper Handle	12	1.0 (estimate)	4500	25977

Table 5. Common tanks and their properties.

The Rhino CO_2 tanks are filled with liquid CO_2, not gaseous CO_2 so the energy stored in those tanks needed to be calculated slightly differently. The vapor pressure of liquid CO_2 at 25ºC is 830psi. Assuming that the change of state from a liquid to a gas happens isothermally, the amount of energy stored in the liquid CO_2 is the same as an equal number of moles of gaseous CO_2 at 830psi. This theoretical gaseous CO_2 container has a larger volume which can be used in the same energy equation that was used for the other tanks. For instance, 9oz (255g) of liquid CO_2 contains 5.80 moles of CO_2. When compressed to 830psi the resulting volume is 137 in^3.

If 50% efficiency for the compressed air system is assumed, the amount of usable work for a given tank size is

$$\text{Usable Work} = \text{Energy in tank} * \text{Usable \% of Tank} * .50$$

Tank Size (in^3)	Cuts per Tank @ 4500 psi	Cuts per Tank @ 3000 psi	Cuts per Tank @ 1000 psi	Cuts per Tank @ 125 psi
732	55461.9	34377.6	8648.7	280.2
550	41672.2	25830.2	6498.3	210.5
110	8334.4	5166.0	1299.7	42.1
70	5303.7	3287.5	827.1	26.8
68	5152.2	3193.5	803.4	26.0
60	4546.1	2817.8	708.9	23.0
30	2273.0	1408.9	354.5	11.5
12	909.2	563.6	141.8	4.6
1	75.8	47.0	11.8	0.4

Table 6. 0.75" diameter cuts per tank for different sizes and pressures.

3.3.4 Prototype Test

The amount of energy needed to make a cut was also tested using the prototype loppers. A six gallon air compressor was pressurized to 100 psi. Then the loppers were used to cut a dowel multiple times until the pressure in the tank was reduced to 75 psi. For this test a 1.0” dowel and a .75” diameter dowel were used. From the previous energy equation we know that it takes 3,250 ft-lb of energy to compress the air in the six gallon compressor from 75 psi to 100 psi. From this we can get the amount of energy per cut for the different dowel sizes.

	# of Cuts	Total Energy Expended (ft-lb)	Energy Required per Cut (ft-lb)
1.0" Dowel	22	3250	147
.75" Dowel	33	3250	98

Table 7. Energy per cut for lopper prototype.

If the amount of energy calculated in the original test done with the load and angle sensors is used, the number of cuts the prototype loppers should be able to make with an six gallon air compressor starting at 100 psi and going down to 75 psi can be predicted. Table 8 shows the predicted number of cuts for different efficiencies as well as the actual number of cuts and actual efficiency.

Material	Total Energy Expended (ft-lb)	Predicted # Cuts (100% efficiency)	Predicted # Cuts (50% efficiency)	Actual # of Cuts	Actual Efficiency
1.0" Dowel	3250	125	63	22	18%
.75" Dowel	3250	232	116	33	14%

Table 8. Predicted vs. actual cut comparison.

It can be seen that the predicted number of cuts assuming 50% efficiency and the actual values are different. There is a 3X difference in work required between the two. This could be caused by the compressed air system being less efficient than 50%. Assuming the compressed air system was 15% efficient would bring the experimental data closer to the prediction.

In the initial tests with force and angle sensors the forces started out low as the loppers started cutting into the wood. As the cut progressed the forces got higher and higher until the force reached a peak and then the force fell off dramatically after that. So there was a small amount of work done for the first third of the cut, a medium amount of work done in the second third of the cut, and a lot of work done in the third part of the cut.

The amount of compressed air needed for the lopper prototype was only based on the peak pressure needed and the volume of the compressed air in the cylinder at that point. It did not matter how hard or how easy it was to cut through the branch up to that point. The cylinder just needed to have a certain pressure in it, corresponding to the peak force needed to cut through the wood. The peak pressure needed to cut through the wood was near the end of the stroke length so most of the cylinder needed to be filled with the highest pressure air. Figure 27 demonstrates how much of the high pressure air that is fed into the pneumatic cylinder is wasted.

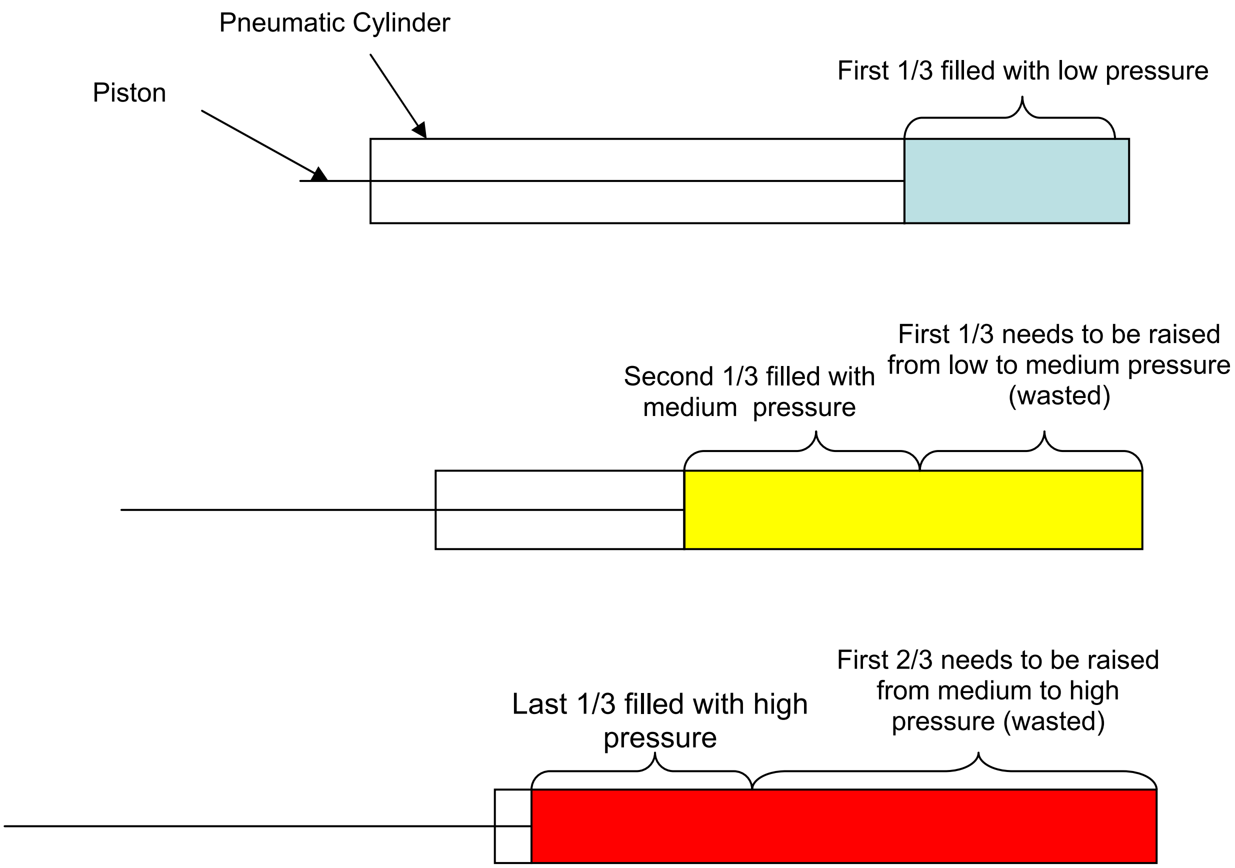

Figure 27. Single stroke pneumatic cylinder inefficiencies.

Figure 28 shows a typical plot for blade angle vs. force from the initial testing involving force and angle sensors. The work done during that cut is equal to the area under the curve.

If the pressure in the air cylinders is slowly increased up until the point of maximum required force, a certain volume of air at a certain pressure is consumed. If the pressure is kept at the maximum for the entire stroke length up until the point of maximum required force, the final state is the same volume of air at the same pressure. This shows that the same amount of air is consumed under both conditions. Figure 29 shows what the corresponding graph for the pneumatic cylinder powered loppers would look like, shown in red, overlaid on the previous graph if we assume the maximum pressure is constant for the entire stroke length up until the point of maximum required force. After the maximum force required point is reached, the loppers have enough pressure left to finish the cut without consuming any more air.

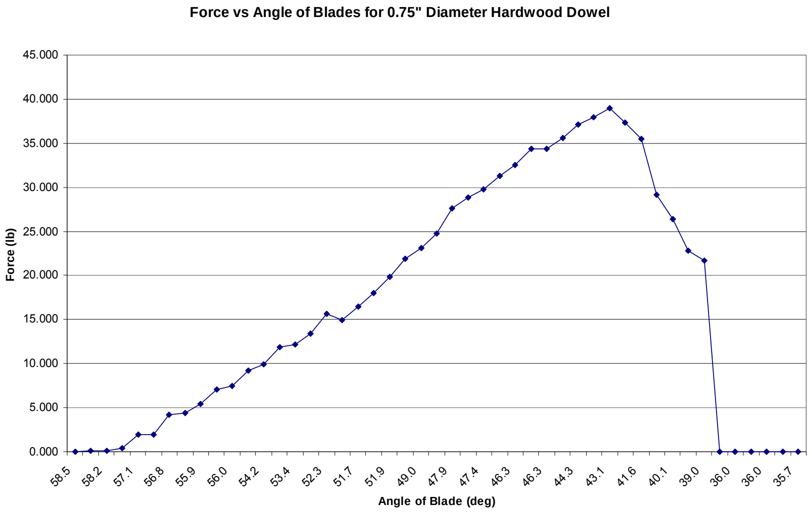

Figure 28. Force vs. blade angle test with sensors.

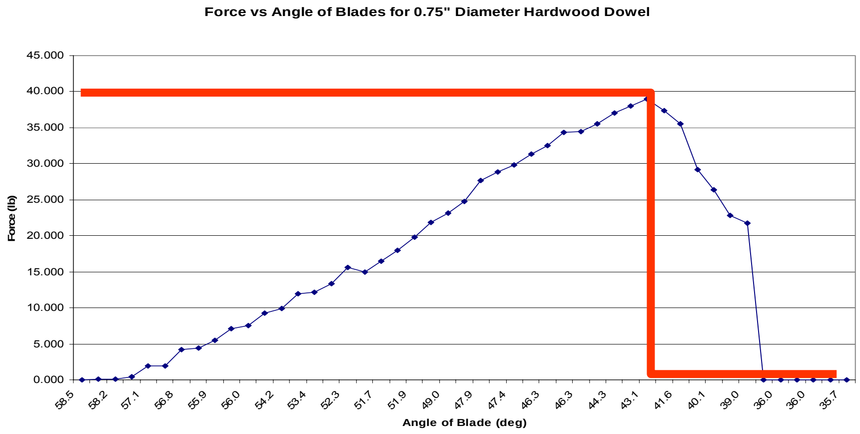

Figure 29. Pneumatic cylinder force vs. blade angle comparison.

The area under the curve for the pneumatic loppers is approximately twice that of the initial test with load and angle sensors. This shows an efficiency for the single stroke pneumatic cylinder of approximately 50%. If this cylinder efficiency is added to the original assumption of a 50% efficient compressed air system, this brings the total efficiency down to 25%. This is closer to the 15% efficiency that was observed in the prototype lopper testing.

3.3.5 Energy Losses

There were two main energy losses associated with the prototype loppers. First of all, once the loppers finished a cut, the pneumatic cylinders were still filled with compressed air. This compressed air contains energy, which is vented to atmosphere when there is no longer an input force on the handle. The second main energy loss is through the pressure regulator which reduces the pressure of the air and thus decreases its stored energy.

The lopper prototype was 14% efficient at cutting through a .75” diameter dowel. Since it takes 14 ft-lb of energy to make the cut, there needs to be 100 ft-lb of energy in the 100 psi air compressor to provide enough energy to make the cut.

The force vs. angle graphs for cutting through the dowel is approximately linear for most of the stroke length so the pressure drop from the tank to the cylinders can be approximated by half of the maximum pressure. The maximum pressure needed in the cylinders for the .75” diameter dowel was 20 psi, thus the average pressure drop was from 100 psig to 10 psig or 115psia to 25psia. The efficiency through an orifice is calculated by

$$Efficiency = \frac{P_U}{P_D}$$

where P_U is the pressure upstream of the orifice and P_D is the pressure downstream of the orifice. This gives an efficiency thought the regulator of 22%. Because of this large pressure drop approximately 78 ft-lb of energy is lost in this step.

When the loppers are fully closed after cutting the .75” diameter dowel, the pressure in the pneumatic cylinders is lower than the peak pressure because the pressurized chamber inside the cylinder expands as the loppers snap shut. If the cylinder pressure is approximately 25 psig when they are fully closed, and the volume of air in the cylinders is 11 in^3, the amount of energy that is vented to atmosphere is approximately 11 ft-lb.

Dowel Diameter (in)	Initial Energy (ft-lb)	Energy lost to Regulator (ft-lb)	Energy vented to Atmosphere (ft-lb)	Remaining Energy for cut (ft-lb)
.75"	100	78	11	11
1.0"	144	92	16	36

Table 9. Energy accounting for .75" diameter dowel.

Dowel Diameter (in)	Initial Energy (ft-lb)	Energy lost to Regulator (% of initial Energy)	Energy vented to Atmosphere (% of initial Energy)
.75"	100	78%	11%
1.0"	144	64%	11%

Table 10. Energy loss as percent of initial energy.

The energy remaining for the cut shown in Table 9 is 11 ft-lb. Since the calculations for these energy losses were approximations, the 11 ft-lb is close to the 14 ft-lb that was actually required to cut thought the .75" diameter dowel. The same calculations were done for the 1.0" diameter dowel as well and can be seen in Table 9. These calculations show that other losses such as friction in the air hoses and non-isothermal effects seem to be very minor compared to the regulator and air venting losses.

This inefficiency in the pressure regulator can be reduced by running the pneumatic cylinders at a higher pressure. Table 10 shows that the percent of energy loss is less for the 1.0" diameter dowel. This is because the pneumatic cylinders needed to operate at a higher pressure to cut through the thicker dowel. This decreases the pressure drop and thus increases the efficiency of the pressure regulator while leaving the losses due to venting to atmosphere almost constant. Another benefit to operating at increased cylinder pressure is that it would also help to reduce the diameter and stroke length of the pneumatic cylinders, making the system lighter and more compact.

4.0 DISCUSSION

4.1 Tank Recommendations

The idea of going with a low pressure tank that can be filled by a home air compressor does not seem viable. Even if the pressure of the actuating piston on the lopper can be held to 50 psi, only half of the air in the tank is usable. This is inefficient. The user would need to wear a separate tank to supply the air. If they needed to make two dozen cuts, assuming the 15% efficiency of the lopper prototype, the user would need to wear a tank approximately the size of a small scuba tank. A composite tank of that size could weigh approximately 10 pounds. This would defeat the purpose of a light weight portable pair of loppers.

A high pressure tank is preferred. This allows the user to use over 95% of the air in the tank even if the lopper pneumatic cylinder is running at 150 psi. The benefit of running a higher cylinder pressure is the fact that the actuator mechanism can be more compact because the pistons can be smaller in diameter and the stoke length can be reduced. Obviously, the higher pressure tank allows the tank to be smaller and lighter as well. An example of safe high pressure tanks used by consumers today are paintball gun tanks which run at pressures from 3000 psi to 4500 psi. These tanks are dropped, hit against trees, and abused but they have still proven safe. Another example is the Rhino tanks which are currently sold at Lowes and come in 20 oz and 9 oz sizes. These are refillable bottles of liquid CO_2 which attach to a regulator that can be clipped to a belt. They only weigh two to three pounds and are 830 psi, corresponding to the vapor pressure of CO_2 at 20°C. Assuming the 15% efficiency of the lopper prototype, the 20 oz and 9oz Rhino tanks could provide 600 and 275 cuts respectively.

4.1.1 Homeowner Recommendation

The homeowner is someone who wants their loppers to be light and easy to use. They do not want to have to strap on a heavy external tank to their back if they want to go trim a few branches. At the most a homeowner would trim only 20-30 branches at a time. This allows the tank on the loppers to be much smaller than a professional landscaper. If the tank was operated at 4500 psi it could have a cross section of just one square inch and be only one foot long and still provide enough air to cut through 135 branches. The paintballs CO_2 tanks from Structural Composites Industries are 45 in^3, run at 4500 psi, and weigh 1.7 lbs, so the 12 in^3 tank could weigh as little as 1 pound and could be integrated into the handle of the loppers. The downside is that the loppers would need to have a docking station which would refill the loppers' tank. This could make it expensive but there could also be other tools developed which would use the same docking station and there could be a whole family of pneumatic tools.

Another possibility is using the Rhino tanks. These tanks would allow a home owner to make hundreds of cuts before having to replace them. A homeowner could possibly go all season without having to change the tank. The tanks cost less than \$20 to refill so the cost is not an issue. However, the homeowner would have to carry around the tank and regulator or clip it to their belt, but this is not a great inconvenience.

My recommendation for the homeowner loppers would be to have a small tank, about 12 cubic inches, built into the handle rated for around 4500 psi. The most feasible solution however would be to use the Rhino tanks since they are already commercially available.

4.1.2 Professional Landscaper Recommendation

The professional landscaper needs to be able to cut many more branches in a given day than a homeowner. They need to cut hundreds of branches a day. Because of this large number of cuts they would most likely need to have an external tank they can wear on their back or on their belt to power the loppers. If the tank is operated at 3000 psi it does not need to be large. It could be the size of a small paintball tank and weigh around four pounds and still have enough air to cut though hundreds of branches. This system would also need some sort of docking station to pressurize the tanks and the beginning of the day. The cost of this docking station is less of an issue with the professional landscaper because they have more money to spend on equipment than the average homeowner.

If the landscaper does not have the money to put into a docking station, another alternative would be the 20 oz Rhino tanks. These would provide enough energy to only be changed out once or twice a day. They would also be fairly convenient to carry around.

The hydraulic loppers that professionals sometimes use are not as convenient as the pneumatic loppers could be. The power source that the hydraulic loppers use usually consists of a small cart with a gasoline powered motor which powers a hydraulic pump. This is not something that the user could wear comfortably on their back.

The recommendation for the professional landscaper would be to have a 100 cubic inch tank, which they wear on their back rated at 3000 psi. This size tank would provide approximately 1000 cuts.

4.2 Design

The mechanical control system worked as expected. It provided proportional feedback under all operating conditions. The harder one pushed on the lopper handles, the harder the lopper cuts. The mechanical control system does have some areas for improvement. Once the lopper has cut though the part of the wood that requires the maximum amount of force, it will snap shut. This would be undesirable in a pair of pneumatic power lopper intended for the general public. If the non-pressurized part of the cylinder had a snubber connected to the outlet it could eliminate this problem by limiting how fast the air could exit the cylinder.

The spring loaded pressure regulating valve used on the prototype also was found to be a simple yet effective way to control the pressure. There was one surprising feature on the pressure relief valve. After the cut was completed it was thought that a valve would need to be opened to relieve the high pressure inside the cylinders. However, the pressure regulating valve relieved the pressure on its own when the handles were pulled apart, as discussed earlier. This reduced the complexity of the system.

The mounting points for the cylinders turned out to work well since the tests were run at around 100 psi. It would be beneficial to run with a higher test pressure so the cylinders could be mounted closer to the cutting head and they would not have to be so long. The cylinders that were used on the prototype are rated up to 250 psi. If a ratcheting head was used, the cylinder could be even smaller since a short stroke length could be used. The number of cylinders could also be reduced to one as opposed to the two that where used in the prototype.

The idea of a ratcheting head also could increase the efficiency of the system. This is something that could be looked into further since it appears that the prototype is using much more energy than it needs to when making a cut.

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Appendix A: Patent Search

These are the most relevant patent search results.

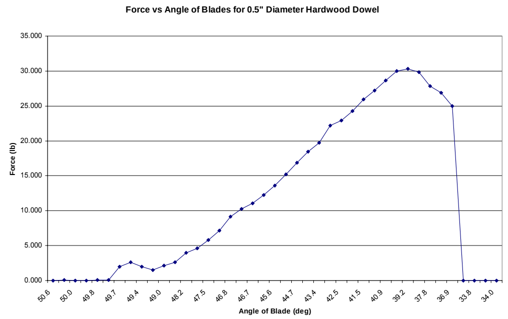
Inventor	Number	Year	Description
J.S. Goodman	RE 21347	1934	Very early patent for a pneumatic powered loppers
E. Landaro	3373490	1966	Pneumatic lopper on an adjustable length pole with two actuators .
Davis	4644652	1987	Basic manually operated loppers
Merwe	4949461	1990	Pneumatic lopper with two switches that both need to be depressed by the operators two hands for the lopper to function.
Michelson	5341572	1994	Basic pole mounted pneumatic lopper
Linden	5570510	1996	Manual powered lopper with a gear driven mechanism at the cutting head to multiply the input force
Linden	5689888	1997	Manual powered loppers with a different gear driven mechanism at the cutting head to multiply the input force
Van Den Hout	5894667	1999	Pneumatically powered pole mounted loppers with a spring return on the jaws.
Huang	6470575	2002	Hand shears with a force multiplying mechanism at the end.
Sun	6901665	2005	Pneumatic pole mounted lopper with an integral hose inside the shank
Collins	7073261	2006	Pair of hand shears which has a mechanism on the side which will grab and hold the piece of branch after it is cut.

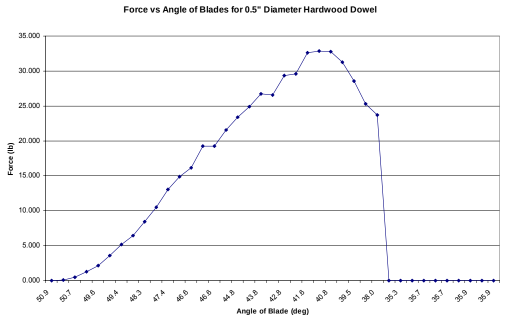
Appendix B: Prototype Bill of Materials

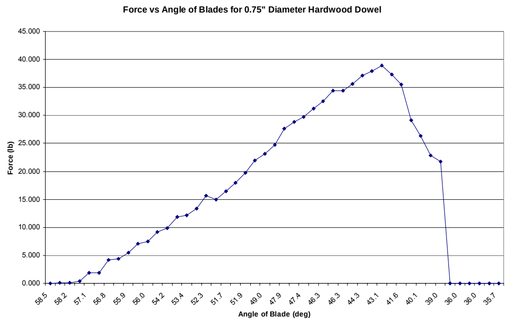
Supplier	P/N	Description	Qty
Home Depot	HDA70503AV	Husky Pressure regulator	1
Home Depot	26" lopper	Corona Bypass 26” lopper	1
McMaster-Carr	6498K458	Stainless Steel Pneumatic cylinder Pivot-Mount, Double Acting, 1-1/4" Bore, 6" Stroke	2
McMaster-Carr	6498K553	Rod Clevis with Pin for 1-1/4" Bore Stainless Steel Pneumatic cylinder	2
McMaster-Carr	6498K563	Pivot Bracket for 1-1/4" Bore Stainless Steel Pneumatic cylinder	2
McMaster-Carr	9041K14	Alloy 6061 Aluminum Strip 1/8" Thick, 6" Width X 24" Length	1
McMaster-Carr	91355K82	Brass Hose Fitting Barb X Barb for 1/4" Hose ID	1
McMaster-Carr	5350K11	Steel Hose Adapter Barbed X Male for 1/4" Hose ID, 1/8" Pipe	1
McMaster-Carr	5350K12	Steel Hose Adapter Barbed X Male for 1/4" Hose ID, 1/4" Pipe	1
McMaster-Carr	54085K11	Choose-A-Color Polyurethane Air Hose 1/4" ID, .375" OD, 250 PSI	4
McMaster-Carr	5076K31	430 SS Smooth-Band Worm Drive Hose Clamp 5/16" to 5/8" Clamp Dia Range, 3/8" Band Width	1
McMaster-Carr	98962A430	18-8 SS Both-Ends Threaded Stud Round Shank, 3/8"-16 Thread, 4" Overall Length	2
McMaster-Carr	98962A230	18-8 SS Both-Ends Threaded Stud Round Shank, 1/4"-20 Thread, 4" Overall Length	2
McMaster-Carr	90034A031	Zinc-Plated Steel Threaded Rod 3/8"-16 Thread, 2' Length	1
McMaster-Carr	90494A031	Grade 2 Plain Steel Hex Thin (Jam) Nut 3/8"-16 Screw Size, 9/16" Width, 7/32" Height	1
McMaster-Carr	91083A031	Plain Steel SAE Flat Washer 3/8" Size, 13/32" ID, 13/16" OD, .051" Thk	1
McMaster-Carr	91101A231	Plain Steel Spring Lock Washer 3/8" Screw Sz, .385" ID, .680" OD, .094" min Thk	1
McMaster-Carr	90490A029	Grade 2 Plain Steel Hex Nut 1/4"-20 Screw Size, 7/16" Width, 7/32" Height	1
McMaster-Carr	91083A029	Plain Steel SAE Flat Washer 1/4" Size, 9/32" ID, 5/8" OD, .051" Thk	1
McMaster-Carr	91102A750	Zinc-Plated Steel Spring Lock Washer 1/4" Screw Size, .260" ID, .487" OD, .062" min Thk	1
McMaster-Carr	90034A007	Zinc-Plated Steel Threaded Rod 6-32 Thread, 2' Length	1
McMaster-Carr	1526A43	Strap Hinge Zinc-Plated Steel, 1-7/8" Leaf Length	2

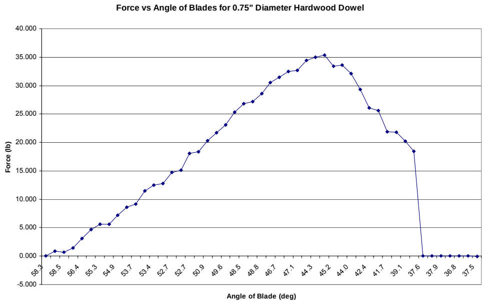
Appendix C: Test Data

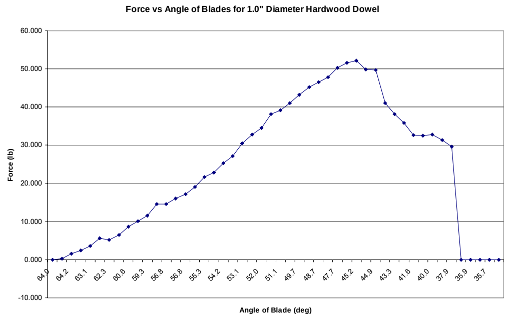
This is testing data from original power and force requirements test.

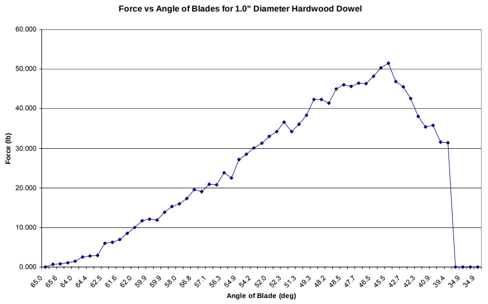


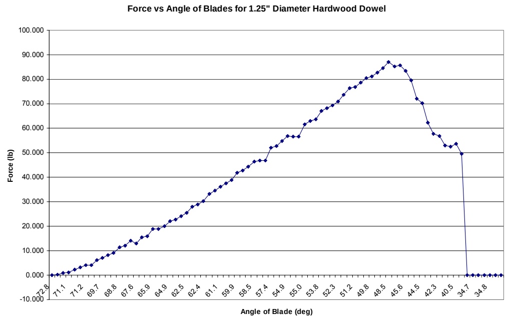


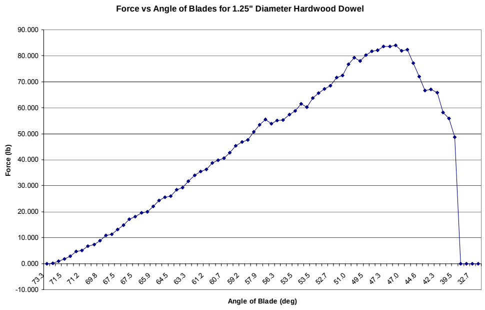


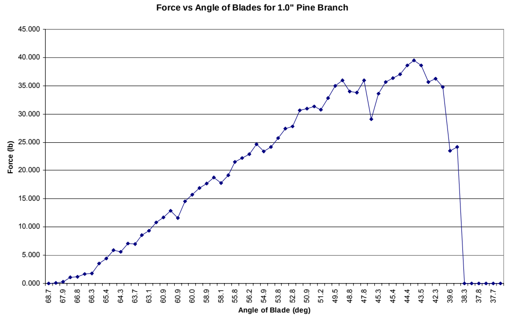


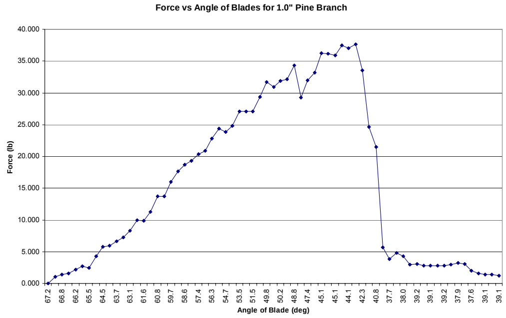


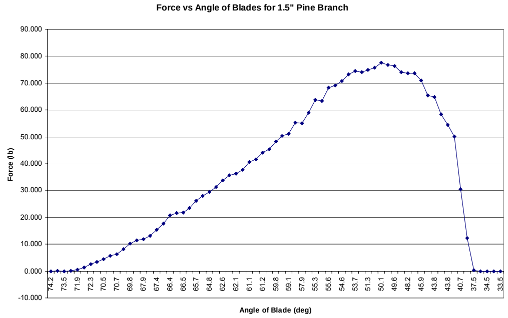


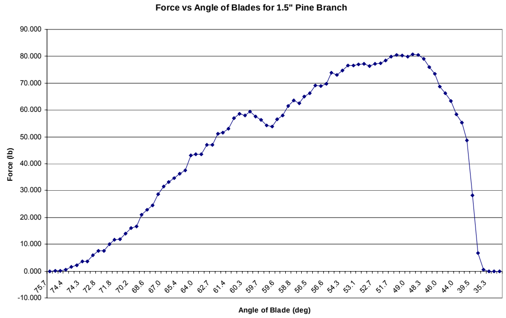

Force vs Angle of Blades for 1.25" Diameter Hardwood Dowel
Force (lb)
100.000
90.000
80.000
70.000
60.000
50.000
40.000
30.000
20.000
10.000
0.000
-10.000
72.8
71.1
71.2
69.7
68.8
67.6
65.9
64.9
62.5
62.4
61.1
59.9
58.5
57.4
54.9
55.0
53.8
52.3
51.2
49.8
48.5
45.6
44.5
42.3
40.5
34.7
34.8
Angle of Blade (deg)

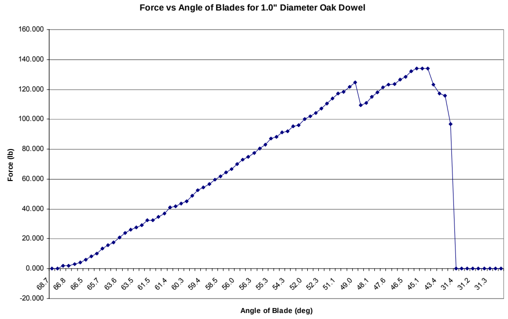

Force vs Angle of Blades for 1.25" Diameter Hardwood Dowel
Force (lb)
90.000
80.000
70.000
60.000
50.000
40.000
30.000
20.000
10.000
0.000
-10.000
73.3
71.5
71.2
69.8
67.5
67.5
65.9
64.5
63.3
61.2
60.7
59.2
57.9
56.3
53.5
53.5
52.7
51.0
49.5
47.3
47.0
44.6
42.3
39.5
32.7
Angle of Blade (deg)


Force vs Angle of Blades for 1.0" Pine Branch
Force (lb)
45.000
40.000
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
68.7
67.9
66.8
66.3
65.4
64.3
63.7
63.1
60.9
60.9
60.0
58.9
58.1
55.8
56.2
54.9
53.8
52.8
50.9
51.2
49.5
48.8
47.8
45.3
45.4
44.4
43.5
42.3
39.6
38.3
37.8
37.7
Angle of Blade (deg)


Force vs Angle of Blades for 1.0" Pine Branch
Force (lb)
40.000
35.000
30.000
25.000
20.000
15.000
10.000
5.000
0.000
67.2
66.8
66.2
65.5
64.5
63.7
63.1
61.6
60.8
59.7
58.6
57.4
56.3
54.7
53.5
51.5
49.8
50.2
48.8
47.4
45.1
45.1
44.1
42.3
40.8
37.7
38.0
39.2
39.1
39.2
37.9
37.6
39.1
39.1
Angle of Blade (deg)

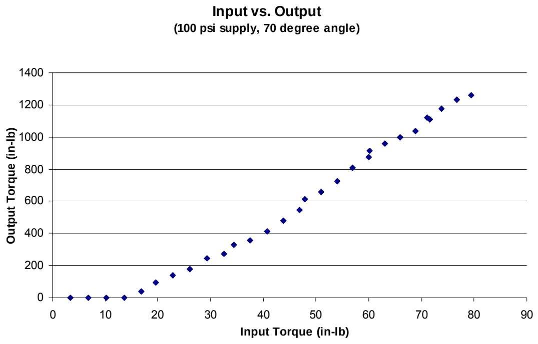

Force vs Angle of Blades for 1.5" Pine Branch
Force (lb)
90.000
80.000
70.000
60.000
50.000
40.000
30.000
20.000
10.000
0.000
-10.000
74.2
73.5
71.9
72.3
70.5
70.7
69.8
67.9
67.4
66.4
66.5
65.7
64.8
62.6
62.1
61.1
61.2
59.8
59.1
57.9
55.3
55.6
54.6
53.7
51.3
50.1
49.6
48.2
45.9
43.8
43.8
40.7
37.5
34.5
33.5
Angle of Blade (deg)

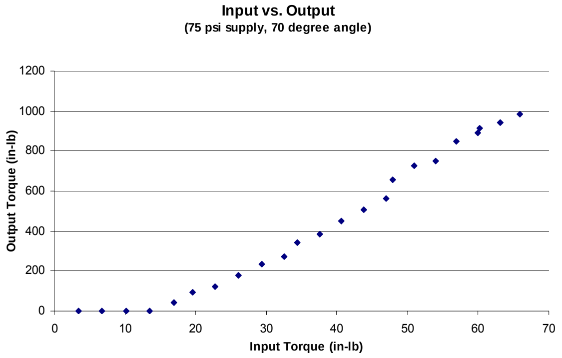

Force vs Angle of Blades for 1.5" Pine Branch
Force (lb)
90.000
80.000
70.000
60.000
50.000
40.000
30.000
20.000
10.000
0.000
-10.000
75.7
74.4
74.3
72.8
71.8
70.2
68.6
67.0
65.4
64.0
62.7
61.4
60.3
59.7
59.6
58.8
56.5
56.6
54.3
53.1
52.7
51.7
49.0
48.3
46.0
44.0
39.5
35.3
Angle of Blade (deg)

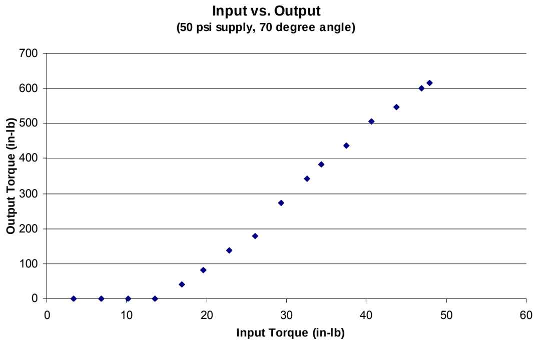

Force vs Angle of Blades for 1.0" Diameter Oak Dowel
Force (lb)
160.000
140.000
120.000
100.000
80.000
60.000
40.000
20.000
0.000
-20.000
68.7
66.8
66.5
65.7
63.6
63.5
61.5
61.4
60.3
59.4
58.5
56.0
56.3
55.3
54.3
52.0
52.3
51.1
49.0
48.1
47.6
46.5
45.1
43.4
31.4
31.2
31.3
Angle of Blade (deg)

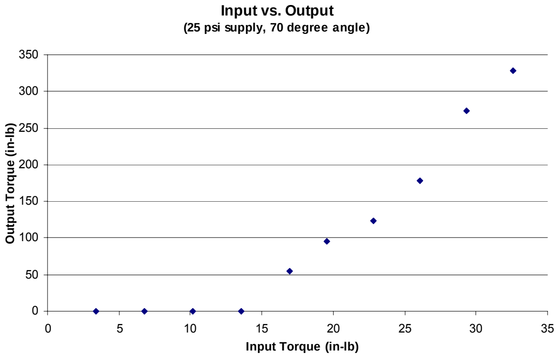
Appendix D: Proportionality Testing

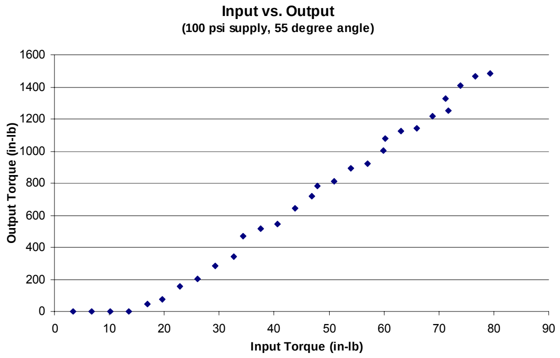
These are the graphs from all of the prototype proportionality tests.

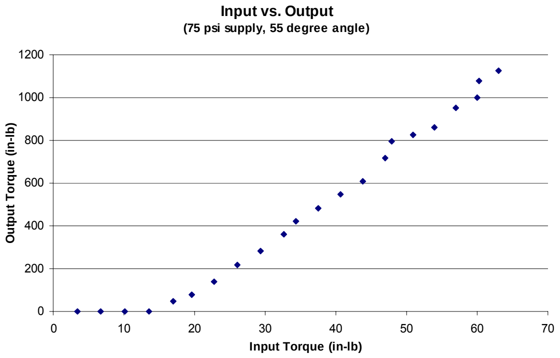


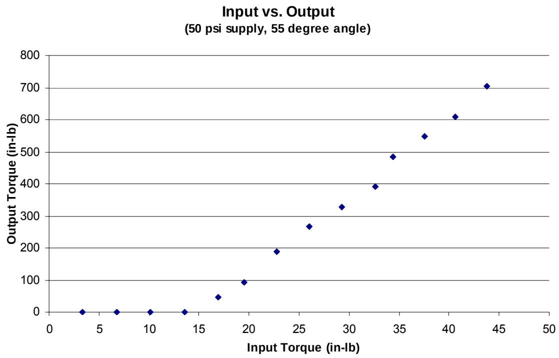




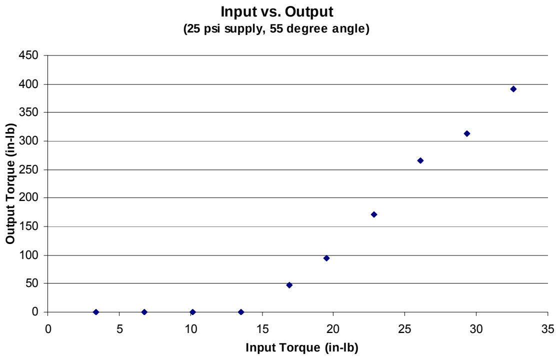




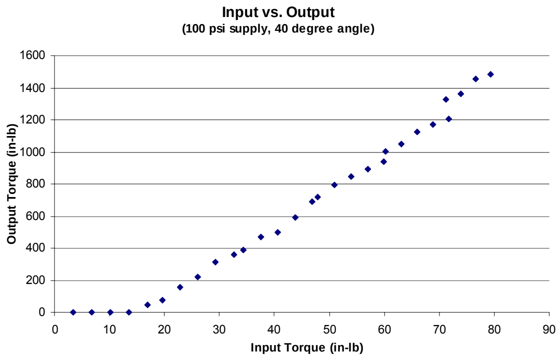




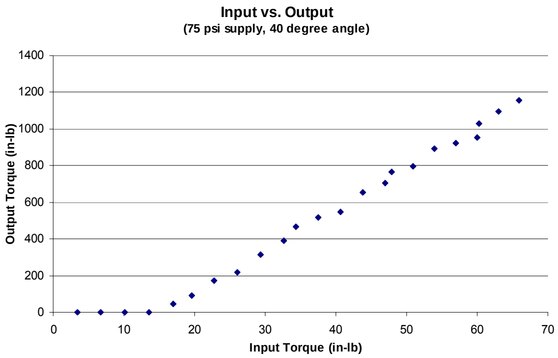
Input vs. Output
(50 psi supply, 55 degree angle)



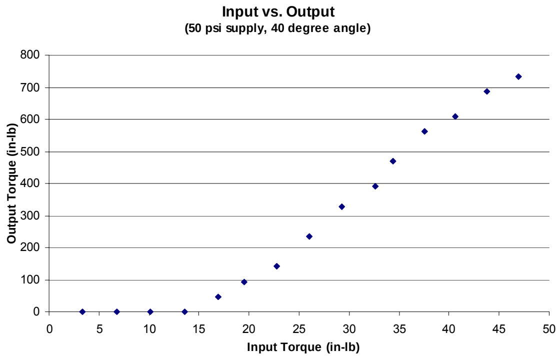
Input vs. Output
(25 psi supply, 55 degree angle)



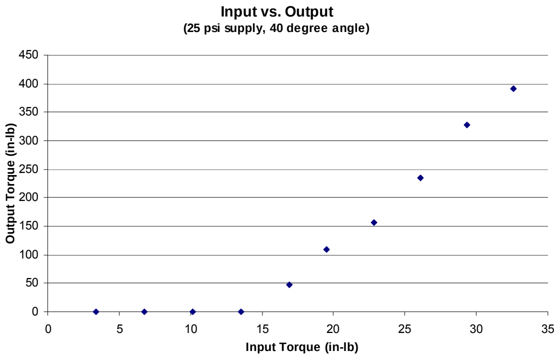
Input vs. Output
(100 psi supply, 40 degree angle)



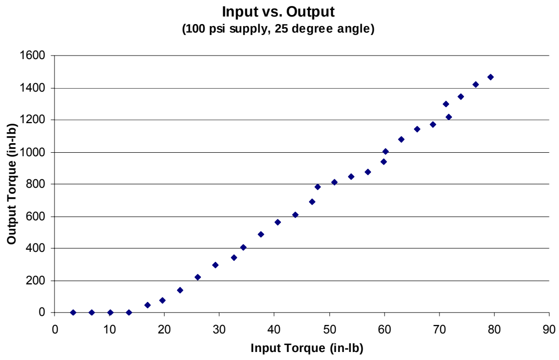
Input vs. Output
(75 psi supply, 40 degree angle)

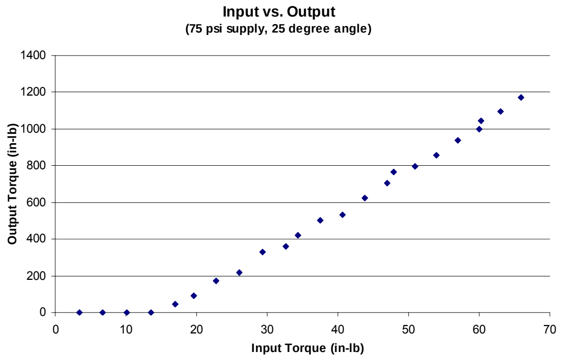


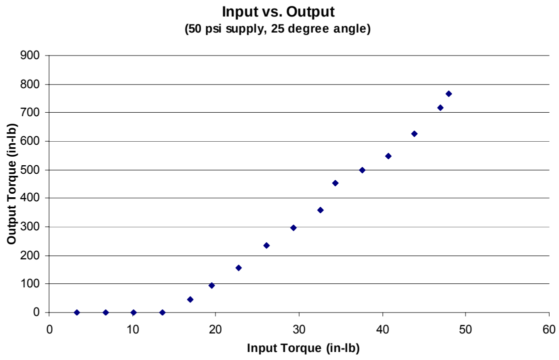
Input vs. Output
(50 psi supply, 40 degree angle)

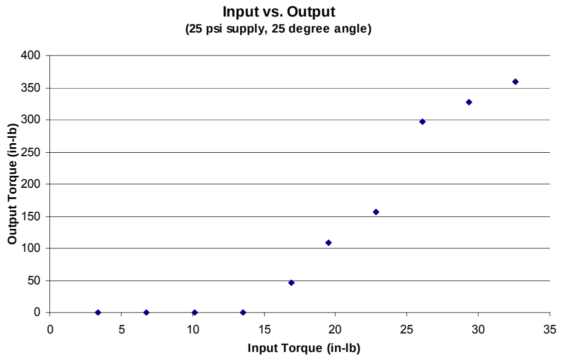


Input vs. Output
(25 psi supply, 40 degree angle)


Input vs. Output
(100 psi supply, 25 degree angle)
Output Torque (in-lb)
0
200
400
600
800
1000
1200
1400
1600
Input Torque (in-lb)
0
10
20
30
40
50
60
70
80
90


Input vs. Output
(75 psi supply, 25 degree angle)
Output Torque (in-lb)
0
200
400
600
800
1000
1200
1400
Input Torque (in-lb)
0
10
20
30
40
50
60
70


Input vs. Output
(50 psi supply, 25 degree angle)
Output Torque (in-lb)
0
100
200
300
400
500
600
700
800
900
Input Torque (in-lb)
0
10
20
30
40
50
60


Input vs. Output
(25 psi supply, 25 degree angle)
Output Torque (in-lb)
0
50
100
150
200
250
300
350
400
Input Torque (in-lb)
0
5
10
15
20
25
30
35