

Legged Robot Using Hydro-Muscles

A Major Qualifying Project Report

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Abstract

Multiple hydraulically actuated muscles (HAM), or hydro-muscles, can be recruited in parallel to exert a greater force than a single muscle is capable of producing. Many of these “muscle groups” can then be used to equip a system for high force output applications. The hopping biped system uses four muscle groups attached to the legs of the biped apparatus to perform a single jumping action when the muscles are contracted. Two muscle groups are attached to the lower section of the apparatus to act similarly to Gastrocnemius muscles, while the other two muscle groups are attached to the upper section of the apparatus to act similarly to Quadriceps muscles. The height reached by the biped system demonstrates the high force output capabilities of HAM. The hopping biped system also represents an excellent test-bed for future studies of legged hopping dynamics.

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Chapter 1: Introduction

The purpose of this project is to demonstrate the high force output applications of hydraulically actuated muscles through constructing a bipedal hopping robot. The bipedal hopping robot is designed to serve as a test-bed for high force output applications of the muscles. Other goals of this project include a high jumping performance, a biologically inspired design, and a modular robotic construction to allow quick alterations of the design. Presented here is the process of design, construction, and experimentation of a bipedal hopping robot equipped with hydro-muscles.

Recent years have brought tremendous technological advancements to the field of robotics. Wheeled robots have long been a standard among mobile robotics researchers for their simplicity, but the emerging field of legged robotics may stand to revolutionize the industry. Legged robots' advantage over wheeled robots regards how they approach mobility; while wheeled robots may be much easier to design and may operate faster than legged robots at this time, wheeled robots are limited to traversing flat floors and ramps. Performing human like actions such as climbing stairs, navigating over obstacles, or traversing rough and uneven terrain is beyond the scope of wheeled robotics, but not legged robotics.

The proceeding report extends the work done last year by the Hydro Artificial Muscle Exo-Musculature project, where hydraulically actuated muscles were first developed and tested [1]. Documented in this report are the efforts undertaken by a team of two senior undergraduate students at Worcester Polytechnic Institute to utilize the technology of hydro-muscles within the applications of legged robotics, and to test their capabilities in producing large forces.

Chapter 2: Background

2.1 Previous MQP

Hydro-muscles were invented by Dr. Marko Popovic at Popovic Labs in 2013 [1]. At this time, hydro-muscles were operated under low pressures (below 80 psi) for proof-of-concept applications to showcase the new technology. During the same year, Dr. Marko Popovic advised a project team that installed three of these hydro-muscles onto a model skeleton arm to exhibit the capabilities of the muscles [1]. A photo of this model can be seen in the following figure:

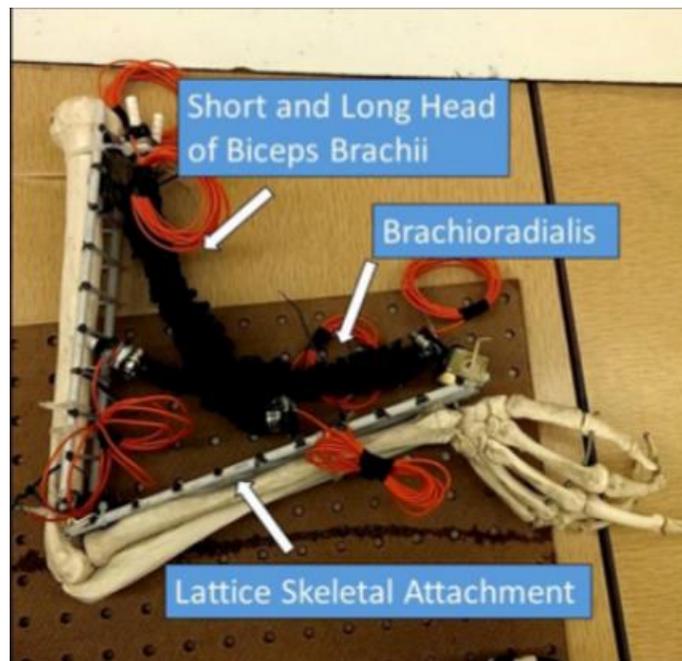


Figure 1: Model skeleton arm equipped with hydro-muscles to exhibit their capabilities.

The robot developed and discussed in this report necessitated further development of hydro-muscle technology. Hydro-muscles that are capable of withstanding significantly larger pressures and producing substantially more power than their predecessors were produced. The advancements made by this team in hydro-muscle technology to meet these requirements are detailed in chapter 4.

2.2 Hydro-Muscles as an Actuator for Legged Robots

Hydro-muscles are a new and developing technology, and may be innovative with many applications in the robotics field. A hydro-muscle is at its simplest, an elastic tube that expands linearly when pressurized with some working fluid. To prevent the elastic tube from expanding radially, the tubing is enclosed within a crumpled fabric sheath that is fixed to both ends of the tubing. Upon pressurization, potential energy is stored in the stretched elastic, which can quickly be transformed into kinetic energy upon releasing the pressure [1].

2.3 Biomimicry and Inspiration from Nature

In order for earthbound animals to move, they must overcome the force of gravity. While moving, animals typically minimize the amount of work they exert to maximize efficiency in their mobility. In order to jump, terrestrial animals must produce enough power to lift their weight into the air. This power is typically generated by muscles in the hips and legs of terrestrial animals [2].

In legged robotics, an iterative approach to design is desirable for improving efficiency and solving complex kinematic problems [2]. In a sense, this approach is similar to evolution's role in biological designs. Legged robots are inherently inspired by biological designs, and are typically modelled after bipeds and quadrupeds. Due to nature's success in solving complex kinematic problems through designing various efficient bipedal creatures, it was decided to base the design of this project using inspiration from natural biological systems.

After performing preliminary research into hopping bipedal animals, the team decided to model the design of the robot after the biology of kangaroos. The team then performed extensive research into the dynamics of kangaroos in order to gain a better idea of how the robot should

operate. A study reported by BBC News provided the majority of the background information that gave inspiration for the final design of the robot [3]. The following images taken from the study provide a visual key to understanding the train of thought that lead to the final design [3].



Figure 2: Stop motion filming of kangaroo. Blue circles mark the joints used in hopping.

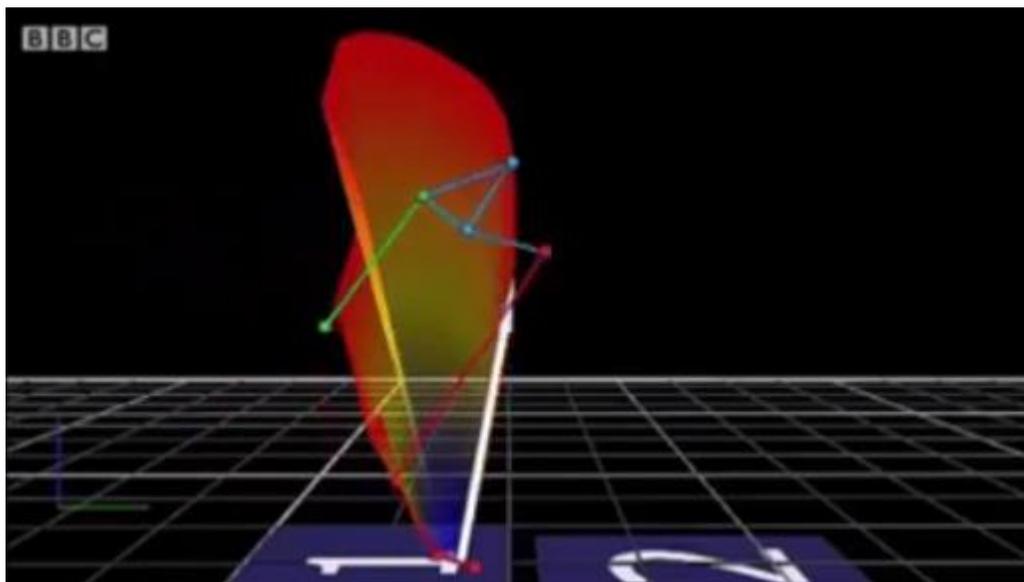


Figure 3: Computer model generated from the stop motion film.

2.4 Existing Bipedal Robots

2.4.1 Festo BionicKangaroo

Before setting out to design and construct a bipedal hopping robot, the team conducted research regarding existing bipedal hopping robots to help better understand current research and designs. The most useful information the team found came from a robotics company called Festo. Festo has created a robot they call “BionicKangaroo,” and a diagram of their design can be seen in the following image [4].

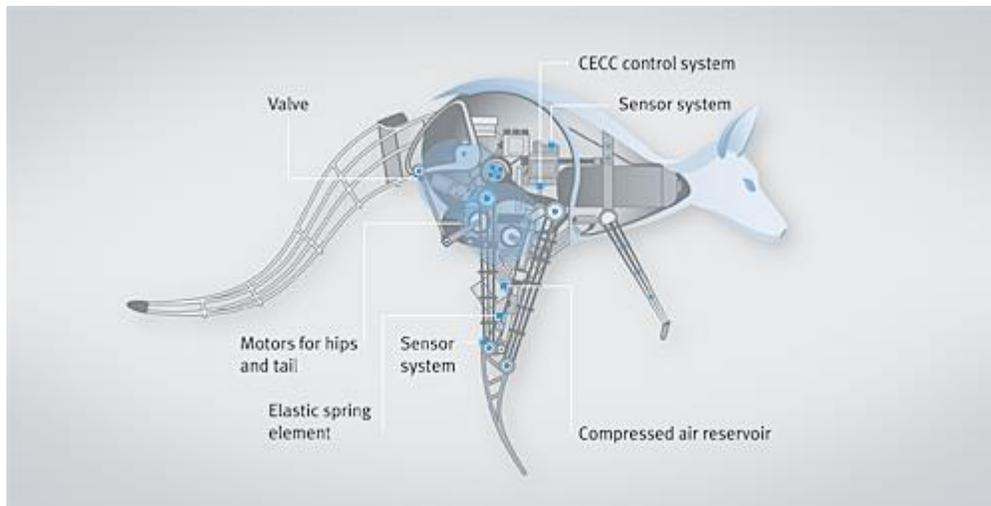


Figure 4: Design of Festo's BionicKangaroo

While Festo’s BionicKangaroo may be the most advanced bipedal hopping robot developed at this time, its design did not relate well to the objective of this project. Although it is a biologically inspired robotic kangaroo, Festo’s design in no way utilizes or is relevant to hydro-muscle technology. Festo’s design was however used as a general reference for imagining the dynamics of the design developed in this project.

2.5 Advantages of Bipedal System for Hydro-Muscles

Bipedal systems carry many advantages in the field of robotics engineering. Bipedal systems are statically stable, giving them the ability to maintain their position passively. They are symmetrical about the sagittal plane, which greatly simplifies design and mathematical modelling [2]. Furthermore, the positioning of bipedal systems before forming a jumping action can be altered to change the trajectory of the jump. These advantages of bipedal systems are extremely useful in accommodating control, design, and modelling of the project.

Performing a jumping action requires overcoming the force of gravity. Equipping a bipedal system with hydro-muscles is an excellent way of demonstrating their high force output capabilities. This is because performing a jumping action requires exerting a force larger than that of gravity, which can be quite large depending on the weight of the object performing the jump.

Chapter 3: Project Objectives

The purpose of this project was to demonstrate the high force output applications of hydraulically actuated muscles through constructing a bipedal hopping robot. The team met with the faculty advisor in the early stages of the project to outline the project objectives that would drive the design. The main objectives that the team established for the design of the robot were:

1. To demonstrate and test the high-force applications of the hydro-muscles on legged robots.
2. To develop a bipedal robot capable of jumping approximately one meter off the ground using only the hydro-muscles for actuation.
3. To construct the robotic apparatus such that it serves as a suitable test bed for future research involving high force output applications of the hydro-muscles.
4. To design the robotic apparatus and its components to be as modular as possible for easy construction, deconstruction, and improvement.
5. To base the design of the robot around inspiration achieved from studying bipedal hopping animals.

3.1 Determination of Design Specifications

Prior to beginning construction of the robot, the team met with the faculty advisor to establish a series of specifications the design was expected to meet. The following sections describe these specifications and explain the reasoning that led to the final design.

3.1.1 Size and Weight

The team desired to construct a robot that could be easily worked on and transported for showcasing and different testing environments. The team decided that the robotic apparatus should be large enough so it can be constructed with standard hardware, piping materials, and tools, but small enough so it can be quickly transported for demonstrations. The robot should also be sturdy enough to survive transportation without damage, and constructed such that anyone, including children, can inspect and touch the apparatus without fear of injury.

Based on these desires, and the objective to have the robot capable of jumping approximately one meter off the ground, the robot was decided to have a size comparable to a red kangaroo with a weight no greater than 10 kilograms.

3.1.2 Cost

Legged robotic projects can quickly become very expensive and therefore inaccessible to those without funding. Due to the low cost of producing the hydro-muscles, the team decided to embrace the idea of being as cost effective as possible to help the technology become more accessible.

The team calculated rough estimates for the cost of materials to construct the robot and found that it should cost no more than \$500 to build.

3.1.3 Actuation

Hydro-muscles are especially useful for their ability to augment power and for their potential in fine position control when utilizing an incompressible fluid [1]. The faculty advisor, and inventor of the hydro-muscles, wanted to further develop and test the technology through

this and other projects. Thus, the team decided to use the hydro-muscles as the only source of actuation in the design of the robotic apparatus.

3.1.4 Locomotion

Performing a jump of approximately one meter in height requires simultaneous actuation of both leg muscles. Each muscle requires two valves for actuation (or one two-way valve), one for pressurizing fluid into the muscle(s) and one for opening the muscle(s) to atmospheric pressure. Allowing for actuation of multiple degrees of freedom per leg would require more valves on board the skeleton apparatus, and would not likely improve the jumping performance of the robot. Furthermore, any additional weight added to the apparatus will result in decreasing the height achieved by the robot in its jump.

Because the robot's legs are required to be actuated simultaneously, the muscles of the robot can be actuated in pairs. The pair of muscles on the bottom part of the skeleton can be controlled with a single two-way valve, as well as the pair of muscles on the top part of the skeleton. Allowing the top and bottom muscle groups to actuate independently allows for fine tuning of the actuation timing for improving the robot's jumping performance. As a result, the team decided to equip the apparatus with a pair of digital two-way valves, one for each muscle group.

3.1.5 Reconfigurability

Finding the ideal geometry for the robot's legs before jumping would allow for an optimized jumping performance. To help find this ideal geometry, the team conducted extensive background research on the skeletal geometries of jumping bipedal organisms, including

kangaroos and humans. The team also researched previous projects involving hopping robots to identify any observable trends in the geometries of their skeletons. Based on the research obtained, no apparent trend exists, with robotic leg geometries varying enormously between robots.

As a result, the team could not decide on any ideal skeleton geometry. In order to maximize the odds of achieving a jump approximately one full meter in height from the ground, the team decided to design a skeleton that is not bound to a permanent specific configuration. This decision allows the user to quickly and easily change the size, placement, and orientation of the robotic legs. Furthermore, the components attached to the legs, such as the hydro-muscles and knee brackets, were decided to be constructed to allow easy interchangeability. These decisions helped improve the modular and reconfigurable nature of the apparatus allowing any user to quickly alter skeletal geometries in order to find the optimal parameters necessary for a high jumping performance.

3.1.6 Future Platform for Hydro-Muscles

Considering the ambitious nature of this project being undertaken by only two students, the team discussed with the faculty advisor the possibility of a future team picking up where this year's team left off. As a result, it was decided that the robot would serve as a test bed on which future projects will build. Therefore, the specifics of the project design were decided to be easily understandable and reproducible. The modular and reconfigurable aspects of the project play a crucial role in this specification as future teams are expected to be able to alter the design and change design components with ease.

3.2 Project Scope and Limitations

The core objective of this project was to design and implement a bipedal hopping robot equipped with hydro-muscles to test the high force output applications of the muscles. Potential future extensions to this project are numerous, but some of the more advanced functionality usually found in robotic systems were determined to be beyond the scope of this project. Some of the limitations on the functionality of the robot include, but are not limited to the following:

- Separate control of each leg
- Active repositioning of legs during aerial phase
- Passive weight distribution for landing
- Fine position control of the hydro-muscles
- Advanced modeling, simulations, and computer optimization
- More degrees of freedom (DoF)
- Directional control of robot trajectory
- Custom manufactured PCB components, valves, and hardware
- Advanced machining and fabrication techniques
- Navigation, mapping, obstacle avoidance

Chapter 4: Design and Construction

4.1 Reconfigurable Construction System

In chapter 3 it was stated that a reconfigurable skeleton is critically important for rapid physical design testing and design alterations. The skeleton of the robot includes not only the primary structural components used to build the main body of the robot, but also provides mounting and attachment points, adjustment features, and the physical characteristics of the robot. Before constructing the final skeleton with full modularity, a prototype was created to test the practicality of using the hydro-muscles to make the skeleton jump. The prototype allowed for easy construction and addition of muscles, but did not allow for quick changes in attachment points.

4.1.1 80/20™

After conducting extensive background research into possible construction systems, the team decided to invest in 80/20™ Modular Framing. The 80/20™ Modular Framing consists of extruded aluminum bars with a square profile featuring T-slots running along the length of every side [5]. A profile of the 80/20™ extrusion can be seen in figure 5. The 80/20™ modular framing is described by its creators as "The Industrial Erector Set"®, and it meets this description with its versatile functionality. Users can quickly detach and reattach components, or loosen an attachment to slide it along the bar and re-tighten them at any point along the 80/20™ bar [5].



Figure 5: 80/20™ aluminum extrusion provides continuous attachment points along the length of the bar.

80/20™ Inc. lists the advantages of T-Slotted framing in the following:

- No welding - no fighting heat stress or warpage
- Lightweight, easy to machine
- Uses standard fractional or metric fasteners
- Less engineering time required
- Easy to fabricate; only simple hand tools required
- T-slot technology is industry accepted
- No expensive fabrication equipment required
- Easily reconfigured for design changes

The advantages listed above to using the 80/20™ aluminum extrusion closely match the requirements of the robot's construction system. 80/20™ is available in a variety of sizes, standards, profiles, and "series" of framing, each with their own accessories. For this project, the 20mm square "20 series" was chosen for constructing the skeleton of the robot as it is the smallest and lightest profile available.

80/20™ is intended for load-bearing structures, so it is more than strong enough to support what the skeleton of the robot requires [5]. However, these advantages result in the 80/20™ construction system being somewhat heavier than other similar aluminum construction systems. Though it may be somewhat heavy in nature, the overwhelming adaptability of the 80/20™ 20-series was deemed to outweigh its weight concerns.

4.2 Skeleton Design

The design of the skeleton of the robot must allow for easy adjustment of the major kinematic geometries while still providing structural stability, simplicity, modularity, and maintaining a light weight.

After the prototype robot skeleton was tested successfully, the final robot skeleton was developed. The final robot skeleton equipped with all of its components can be seen in the figure below.

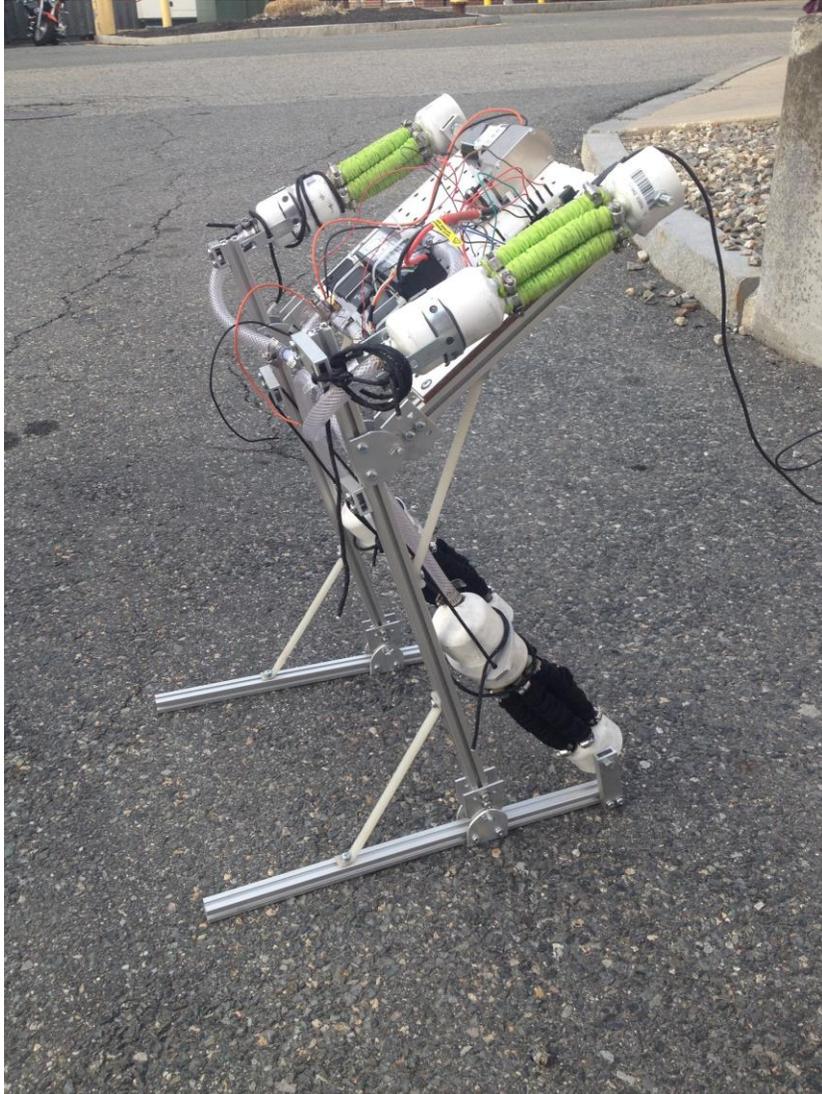


Figure 6: The skeleton of the robot allows easy adjustments of all leg lengths, pivot points, muscle attachment points, and center of mass adjustments.

4.3 Modelling and Simulation

A major advantage to constructing a rapidly reconfigurable test platform is that the robot can be quickly reconfigured to match the configuration of a simulated bipedal model. Optimization of the computer model and the resulting kinematic configuration can be quickly mirrored on the physical robot to test the simulated model. With an accurate simulation and

suitable optimization algorithms, the kinematics of the robot can be optimized even faster than the rapid reconfigurability of the skeleton would allow. Therefore, it was deemed that a computational model and simulation for the robot would be extremely useful.

PTC Creo 3.0, a popular computer automated drafting (CAD) program, was used to create the models of the robotic skeleton, as well as the simulations of the robot's jumping kinematics [6]. It was decided that advanced modeling, simulation, and optimization was outside the scope of this project, and that a basic model and simulation would suffice as a proof of concept that the robot can jump. The basic model running a jumping simulation can be seen in the following figure:

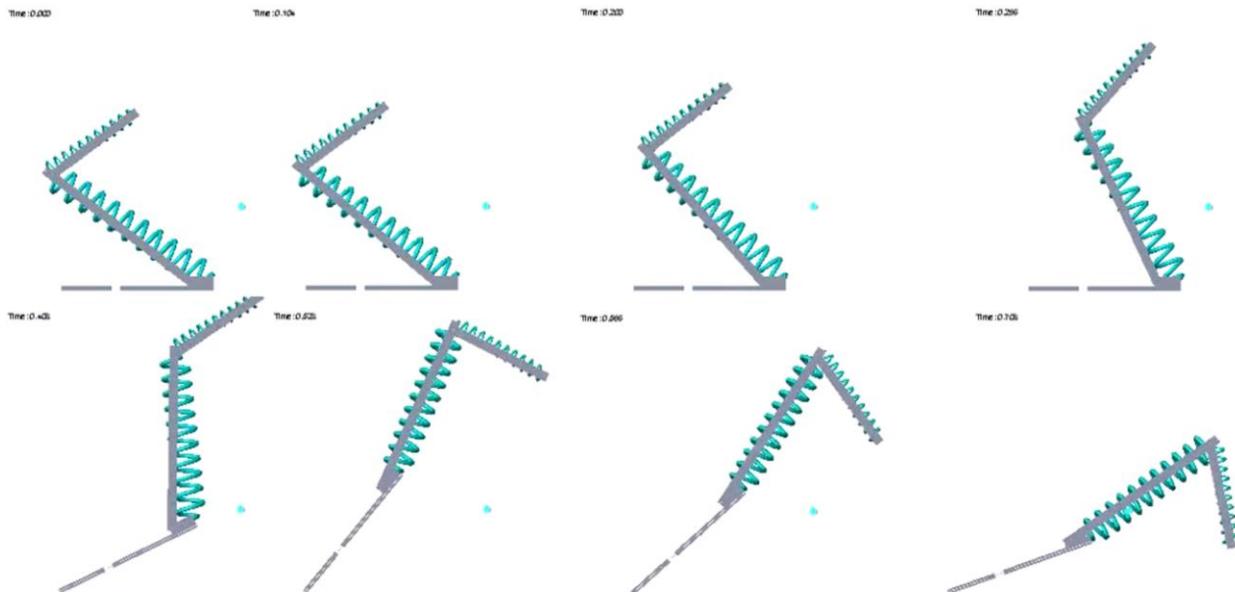


Figure 7: Basic Creo model running a jumping simulation using the Creo software. The first frame shows the robot in a pressurized state, ready for takeoff. The simulation models the hydro-muscles as two sets of springs that actuate at the same time. The simulation was simplified by pinning the toe of the robot to the ground – more advanced simulation was deemed unnecessary.

An analysis of the jump dynamics was obtained from the simulation to determine the conditions governing the moment of takeoff. The analysis can be seen in the following figure, with the moment of takeoff noted.

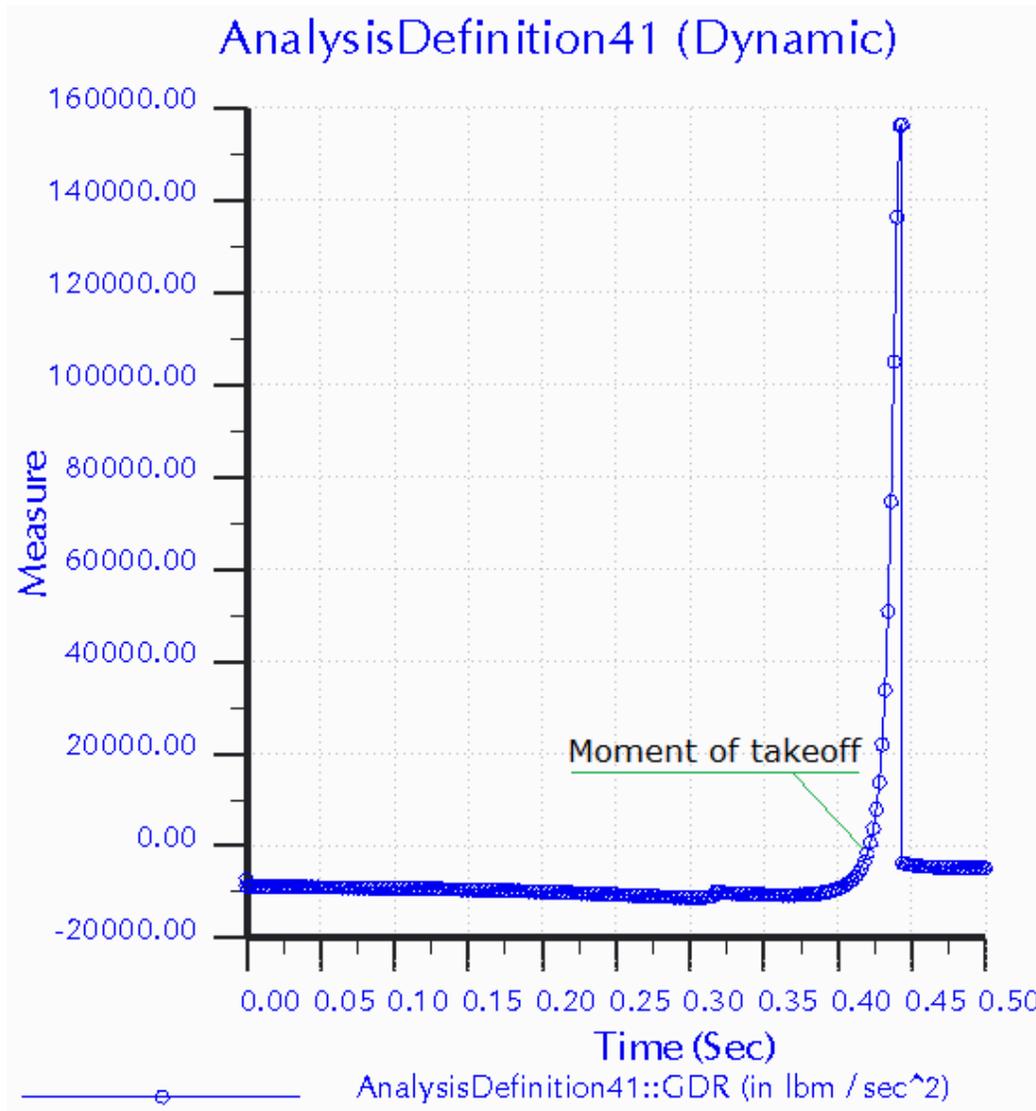


Figure 8: Analysis of jump dynamics simulation showing the moment of takeoff. X-axes represent time after actuation of springs. Y-axes represent the amount of force, in millinewtons, measured on the toe of the robot exerted through actuation. The measurement of 0.0 newtons corresponds to the moment of takeoff, and the moment when the force exerted through actuation upon the toe becomes equal and opposite to the force of gravity.

4.4 Hydro-Muscles as Actuators

The only actuator used to actuate the robot are the hydro-muscles. Connected to the legs of the apparatus, the hydro-muscles provide the drive necessary to produce a jump.

The basic construction of a hydro-muscle consists of an elastomeric tube wrapped tightly with a fabric sheath to prevent radial expansion [1]. As fluid is pumped into the muscle, the fabric sheath constrains radial expansion and forces the hydro-muscle to expand linearly. Usually plugged on both ends with barbed fittings, the barbs have the ability to serve also as mechanical attachment points, allowing a tension force between these points to be generated as the muscle contracts. At least one of the barbs has an opening that interacts with the fluidic system to allow inflation and deflation of the elastomeric tube. The basic structure of the pressure supply system to a hydro-muscle can be seen below.

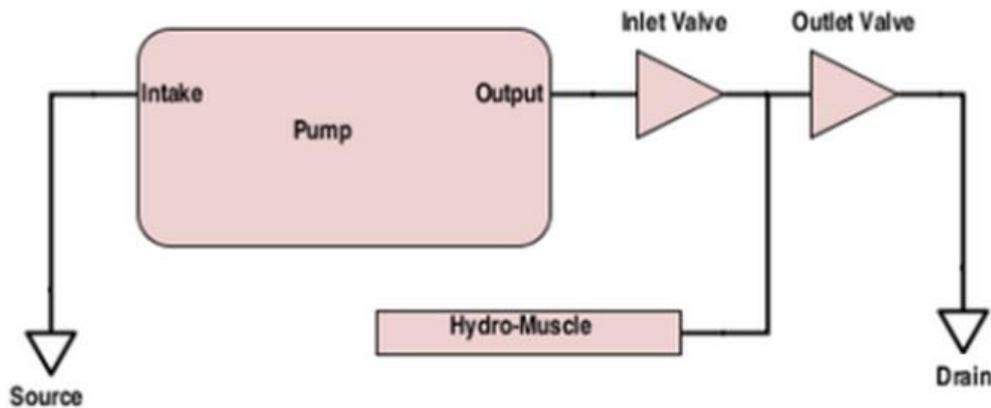


Figure 9: Basic structure of the pressure supply system to a hydro-muscle.

4.4.1 Power Augmentation

Most fluidic actuators contract when pressurized, directly providing the actuation force [8]. This makes hydro-muscles unique among fluidic actuators as their power of actuation is supplied by the power source indirectly [1]. For example, the most common type of fluidic

actuator, the McKibben Muscle, uses contraction as its direct actuation force. When McKibben Muscles are pressurized, they inflate in every direction, necessitating a contraction from their original elongated state. This contraction is used as the actuation force, and can be understood using the following figure [7].



Figure 10: Pressurization of McKibben Muscle.

Though this force has the potential to be quite large, resulting with fairly quick motion, McKibben Muscles rely completely on the fluid pressure and flow available from the pressure source during the actuation process [7]. Hydro-muscles on the other hand only rely on the fluid pressure and flow available from the pressure source when preparing for actuation. Actuation is achieved when pressure is released from the hydro-muscle, causing it to contract, and is independent of the pressure source [1].

Hydro-muscles are constrained from expanding radially by their external sheath. This results in the hydro-muscles being only able to increase their volume in the form of elongation.

The muscle then exhibits behavior as a variable length fluidic cylinder, where changes in the hydro-muscle's length correspond to changes in its internal fluid volume [1]. Figure 11 displays this behavior.

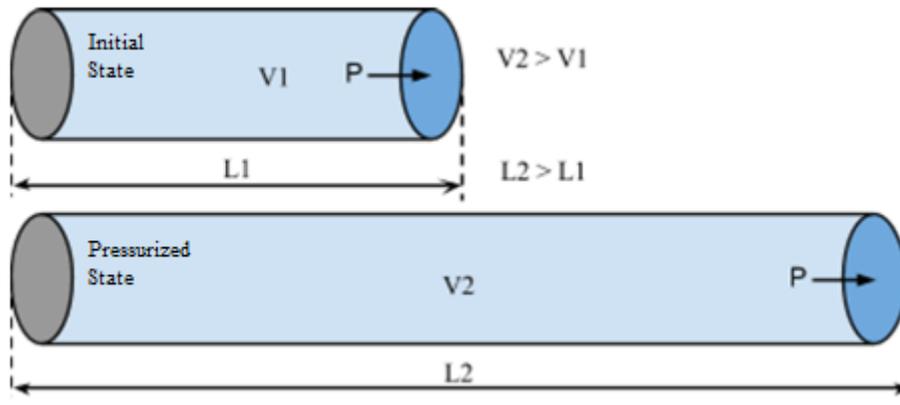


Figure 11: While the walls of the hydro-muscle maintain a constant diameter, the internal pressure causes elongation by pushing outwards on the ends of the muscle.

While the distinctive behavior of the hydro-muscles is their pressurized extension, this is only half of the functionality necessary for their inherent power augmentation. Elasticity is the other necessity. As the muscle extends, the elastic tube elongates. Similar to the nature of springs, when the length of the tube is changed, the tube creates a restoring force to return it to its original state. This force increases with the magnitude of the muscle's extension. The extension force created by the tube extending is opposed by the contracting force provided by the elastic nature of the tube. Assuming there is no change in the fluidic pressure within the hydro-muscle, the extension force will remain constant while the restoring force increases with extension length.

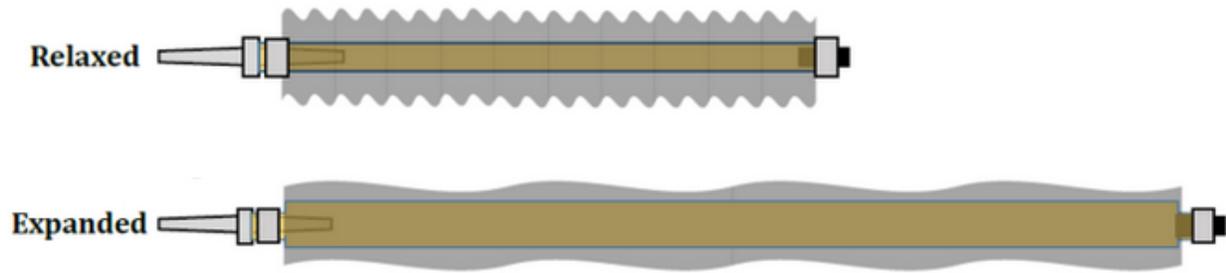


Figure 12: Depiction of the pressurization and extension of a hydro-muscle.

Unlike all other soft fluidic muscles, the elasticity of the elastic tube causes contraction, not the pressure of the fluid within the muscles. Energy is stored as elastic energy in the elastomeric tube as the muscle inflates. The maximum energy stored by the tube is determined by the spring constant of the elastomeric material, its cross sectional area, and the maximum elongation achievable limited by the fabric sheath. After a hydro-muscle is extended, its energy can be stored indefinitely so long as no fluid escapes the muscle. When the fluid is released, the muscle contracts, and actuation is achieved [1].

4.4.2 Compliance of Hydro-Muscles to External Forces

One extremely useful feature of fluidic muscles is their lack of mechanical rigidity. Without the mechanical rigidity of many modern actuators, fluidic muscles carry the advantage of being compliant to external forces, minimizing their risk in causing bodily injury to their operators. The nature of the hydro-muscles' construction provides this compliance, resulting in their advantage of carrying a low risk of causing injury.

4.5 Fabrication of Hydro-Muscles

4.5.1 Elastomeric Tube

The elastomeric tubing serves as the main component of every hydro-muscle. The most important factors that determine the behavior and functionality of the muscle are the choice of material that comprises the tube, and the dimensions of the tube.

The primary function of the elastomeric tubing is to provide the contraction force necessary to actuate the hydro-muscle. There are two factors that contribute to the contraction force: the spring constant of the elastomeric tubing (k), and the displacement length (ΔL) of the muscle upon full extension. The spring constant of the elastomeric tubing is governed by two separate factors, the total cross-sectional area of the material comprising the tube, and the Young's modulus of this material. Increasing either the total cross-sectional area of the tubing or the Young's modulus of the material will result in a larger spring constant, and thus a larger contracting force.

Increasing the maximum extension of the muscle, the total cross-sectional area of the tubing, or the Young's modulus of the tubing material, will proportionally increase the hydro-muscle's force of actuation. Latex tubing was chosen as the elastomeric tubing, as it is widely available in many sizes of both inner and outer wall diameters allowing for construction of hydro-muscles with various spring constants.

4.5.2 Sheathing

The external sheathing of the hydro-muscle's construction serves the following functions:

- Constraining the radial expansion of the elastomeric tubing.

- Allowing for longitudinal extension of the elastomeric tubing.
- Limiting the extension of the elastomeric tubing.

To adequately satisfy these functions, the sheathing must have a relatively high tensile strength to constrain the tubing without ripping. Any failure in the sheathing will result in the elastomeric tubing expanding radially and possibly breaking. Nylon tubular webbing was chosen as the material to sheath the hydro-muscles due to its high tensile strength and because it is available in a variety of sizes. The nylon tubular webbing used to construct the final iteration of the hydro-muscles can be seen in the following figure.



Figure 13: Nylon tubular webbing serves as the sheathing that constrains the elastomeric tubing in the hydro-muscle construction.

4.5.3 Barbed Fittings and Hose Clamps

Attached at both ends of the hydro-muscle are barbed nylon fittings secured with standard hose clamps. The fittings and clamps are very cheap and readily available as standard plumbing supplies. In the construction of a hydro-muscle, the nylon barbed fitting is inserted barbs first into the elastomeric tube and then secured on with a suitably sized hose clamp. While the fittings allow the flow of fluid to and from the hydro-muscles, they can also be used as

attachment points for mounting individual muscles. Barbed nylon fittings were chosen over brass nylon fittings to minimize weight added to the robot.

4.6 Parallel Operation

The power capable of being exerted by the hydro-muscles is limited by the size of their constituent components. Latex tubing with the largest total cross-sectional area was used to maximize the power attainable from the hydro-muscles. However, it was quickly realized that a single hydro-muscle constructed to be as powerful as possible would come nowhere close to being capable of lifting a 10 kilogram robot off of the ground. Thus, the team decided to utilize many hydro-muscles in parallel through creating a system of muscle groups, or “muscle fibers”. Utilizing many hydro-muscles in parallel allows for the restoring force of each extended muscle to be added together to form the restoring force of the entire muscle fiber, similarly to how springs operate in parallel. Both the prototype and final muscle fiber constructions can be seen in the figures below.



Figure 14: Prototype muscle fiber. After testing the prototype muscle fibers, it was decided to use larger tubing to increase the total force output.



Figure 15: Final hydro-muscle construction. Both the prototype and final muscle fiber designs were utilized in the final robotic construction.

The construction of the muscle fibers is not very different from the construction of an individual hydro-muscle. Six individual hydro-muscles are used in parallel to form each muscle fiber. Each muscle is constructed separately in regular fashion but then attached at either end to specially constructed PVC piping. At the top of each muscle fiber are two PVC end caps. The end caps are sealed together, with one hole drilled at the top and six holes drilled at the bottom to allow the flow of fluid. At the bottom of each muscle fiber is one PVC end cap with six holes drilled to hold the nylon fittings that are then sealed to prevent the flow of fluid. The PVC end caps also allow for a greater range of attachment points to the robotic apparatus. The result is a single component capable of producing much greater actuation power than any individual hydro-muscle.

4.7 Flow

The actuation of hydro-muscles is dependent upon their contraction. Thus, the speed at which the hydro-muscles contract is the governing factor of their actuation power. This means the force of actuation is limited by the speed at which pressure flows out of the system.

Therefore, it is desirable to design a system that minimizes the time it takes for the system to depressurize.

Water was used at first as a working fluid due to its nature as an incompressible fluid. After initial testing, it was found that using water added far too much weight to the robot to make any sort of jump feasible. Air was then tested as a replacement fluid, and was found to work effectively in actuating the same hydro-muscles. Air added a negligible amount of weight to the robot and was found to be released faster when depressurizing the system as compared to water. The rate of flow out of the hydro-muscles can be optimized to increase the force of actuation.

4.8 Electrical System and Control Circuitry

4.8.1 Power Supply (Batteries)

Lithium Polymer (LiPo) batteries were chosen to serve as the on-board power supply. LiPo batteries are a favorite among robotics hobbyists for their high energy density and their capabilities in both high current output with a high capacity. For these reasons, as well as the wide availability of LiPo batteries, the robot was equipped with two 5-cell (14.8V) 5000mAh LiPo batteries (Turnigy 5000mAh 4S 20C LiPo Packs). The product configuration table for the batteries can be found in the following figure [8].

Capacity(mAh)	5000
Config (s)	4
Discharge (c)	20
Weight (g)	536
Max Charge Rate (C)	2
Length-A(mm)	148
Height-B(mm)	49
Width-C(mm)	33

Figure 16: Product configuration table for the batteries used in this project.

4.8.2 Control Circuit

Each pair of hydro-muscles on the robot are controlled by a single two-way solenoid valve. Each solenoid valve is controlled by a signal sent from the microcontroller to either open or close the valves. A SunFounder 2 Channel 5V relay shield module and a breadboard make up the control circuit, and can be seen in figure 17 [9].

4.8.3 Microcontroller

When choosing the microprocessor, three main considerations led to the selection: processing power, available digital inputs, and available digital outputs. For a simple jumping motion controlled manually or by a timer, processing speed on the order of one kilohertz is acceptable. Thankfully, the requirements of this project fall within the realm of capabilities of most modern common microprocessors.

Based on these requirements, an Arduino Uno was chosen as the microcontroller to control the robot. The Arduino Uno operates at 16MHz, has 14 digital inputs and outputs, and is one of the most well supported microcontrollers currently available [9]. The Arduino Uno microcontroller can be seen equipped to the robot in figure 17.

4.8.4 Software System

Control of the robot is made possible by the software system. The software operates on the Arduino Uno sending a signal to the fluidic solenoid valves, opening or closing the valves. The software receives manual input and outputs a digital signal, causing actuation of the robot, and a jump to occur.

The process by which the robot jumps occurs in the following sequence. First, a signal is sent to the Arduino Uno, causing both valves to open one way, allowing flow of fluid into the

hydro-muscles. Once the hydro-muscles are fully extended, the fluidic pump is powered off to stop the flow of fluid. From this point on, no energy is required to keep the robot in this state – energy is only required to send the next signal to the valves to actuate the robot. When the next signal is sent, the valves open in the other direction, allowing the fluid to be released from the hydro-muscles.

Because this robot only needs to perform a high jumping action, no position control of the muscles is necessary. Thus, the software is simplified to provide manual operation of the valves. An example of the coding used to operate the robot can be found in the appendix.

A delay can be set in the software to allow the top and bottom valves to open one after the other, allowing actuation of the top and bottom muscle groups separately. This delay can be altered to control the trajectory of the jump more precisely. In this project, the top valves were programmed to open slightly before the bottom valves, giving the robot a forward push before the more powerful bottom muscles lift it upward.

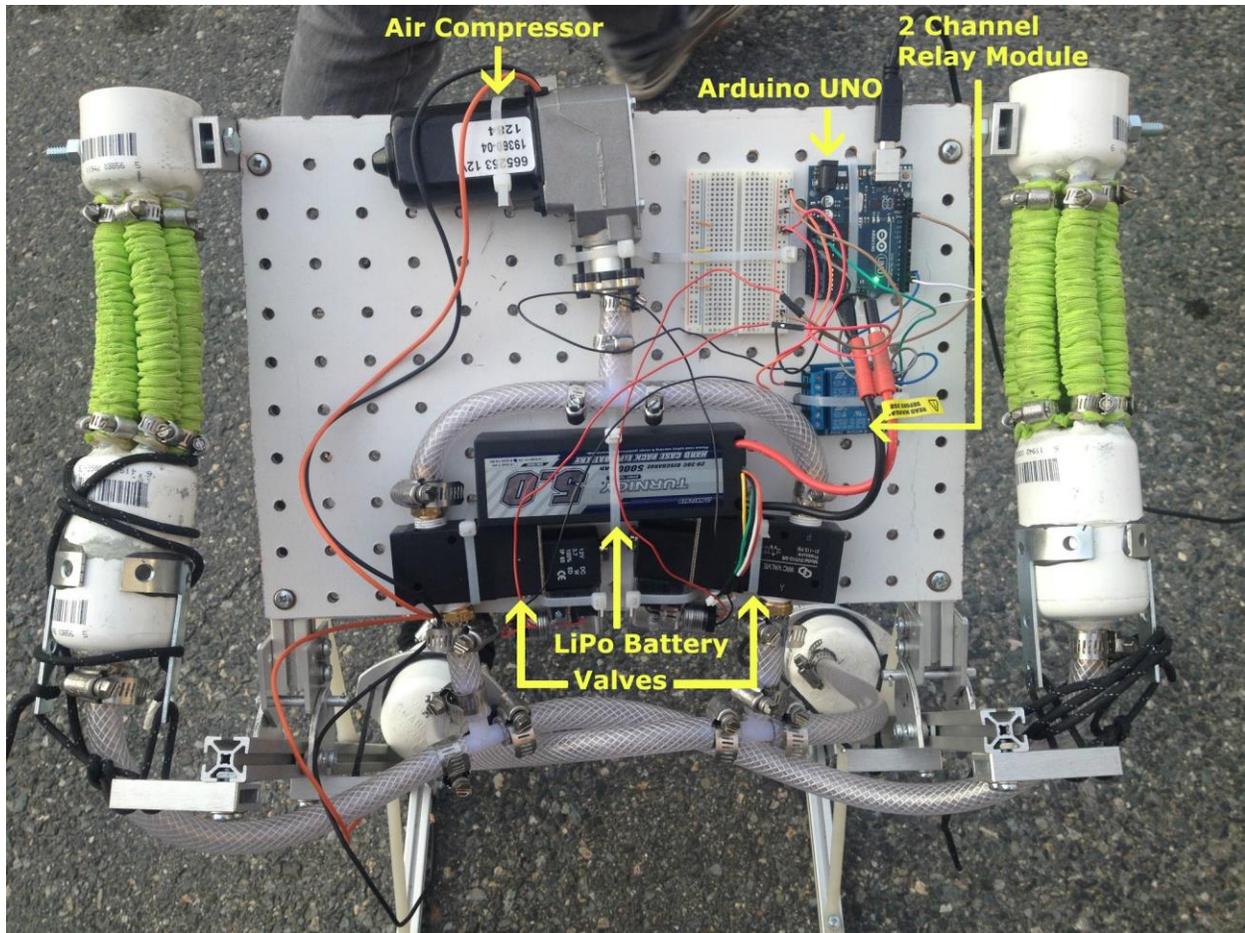


Figure 17: Top view of final construction showing electronic components attached to particleboard.

4.9 Final Construction

The design choices and materials discussed previously were used to fabricate every hydro-muscle and muscle fiber used in this project. All of the latex tubing used had a 1/4" inner diameter. However, the prototype muscle fiber and final muscle fiber used latex tubing of different outer diameters. The prototype used latex tubing with a wall diameter of 1/8" while the final muscle fiber design used latex tubing with a wall diameter of 3/16" to increase the restoring

force generated by pressurizing the muscles. Both the prototype and final muscle fibers used 6 hydro-muscles in parallel.

The final design of the hopping biped system used four muscle groups attached to the legs of the biped apparatus to actuate the robot and perform a jumping action. Two muscle fibers are attached to the lower section of the apparatus to act similarly to Gastrocnemius muscles, while the other two muscle fibers are attached to the upper section of the apparatus to act similarly to Quadriceps muscles. All of the muscle fibers were secured to the frame of the robot using parachute cord. The final design can be seen in the following figure.



Figure 18: Iteration of the final construction with the prototype muscles used on top and the more powerful muscles used beneath.

Chapter 5: Iterative Testing and Results

Methodology for Experimentation

5.1 First Test

5.1.1 Setup

Once the team developed the muscle fiber prototype, experimentation using water as the working fluid began immediately. The prototype muscle fiber extended to approximately twice its original length with no issue. At this point, the team developed a prototype skeleton for the robotic frame out of wood. A Creo computer model of the wooden prototype skeleton design can be seen in the following figure [6].



Figure 19: Creo computer model of the wooden prototype skeleton design.

5.1.2 Response

While the prototype muscle fibers actuated the legs of the robot, they did not come close enough to producing enough power to lift the robot from the ground. At this point, it was decided that water added far too much weight to the robot to make any sort of jump feasible, especially if the final skeleton design was to be robust and therefore heavier. Air was then tested as a replacement fluid using a pneumatic pump, and was found to work effectively in actuating the same hydro-muscles. The team then began design and construction of the final robotic skeleton and created the more powerful muscle fibers.

5.2 Second Test

5.2.1 Setup

Once the team completed construction of the final robotic skeleton and the improved muscle fibers, the team brought the completed robot outside to begin testing. The team was hesitant to test the robot indoors due to the relatively large pressures being stored within the muscle fibers. An exploding hydro-muscle could send components such as the hose clamps flying as projectiles. From extensive prior testing of the muscle fibers, the team realized there is very little risk of the hydro-muscles exploding under the testing conditions. However, the team decided it was best to minimize every risk of possible injury. Thankfully, the robot operated without any issue.

In this test, the stronger muscle fibers were attached to the bottom of the robotic skeleton while the prototype muscle fibers were attached to the top. In the following image, the robot can be seen with its muscle fibers fully pressurized, ready for takeoff.

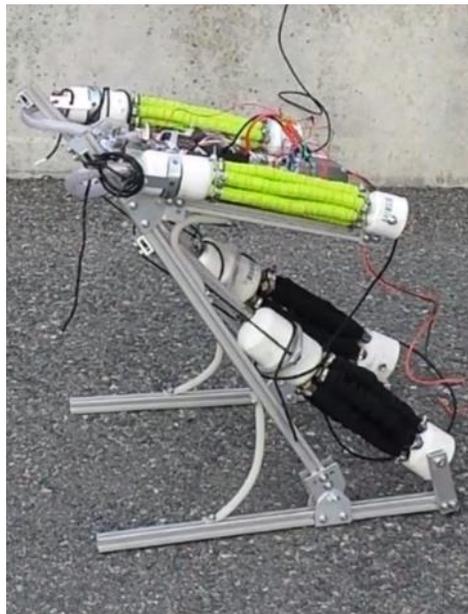


Figure 20: Iteration of final design in pressurized state, ready to perform a jump.

5.2.2 Response

The muscle fibers actuated the legs of the robot with great success. While the force of actuation was not large enough to lift the robot to the goal of approximately one meter off of the ground, the team was satisfied with the performance achieved considering this was the first real test of the final robotic design. One major factor in the robot's lackluster jumping performance was its placement on an unlevelled surface. The robot was tested directly outside of the lab where the ground had a slight downhill slope. The robot was placed with its front facing the top of the slope, such that when the legs of the robot were actuated, the robot pushed itself backwards and down the slope. A photo of this performance can be seen in the following figure, showing the robot land on its heels after jumping slightly backwards.

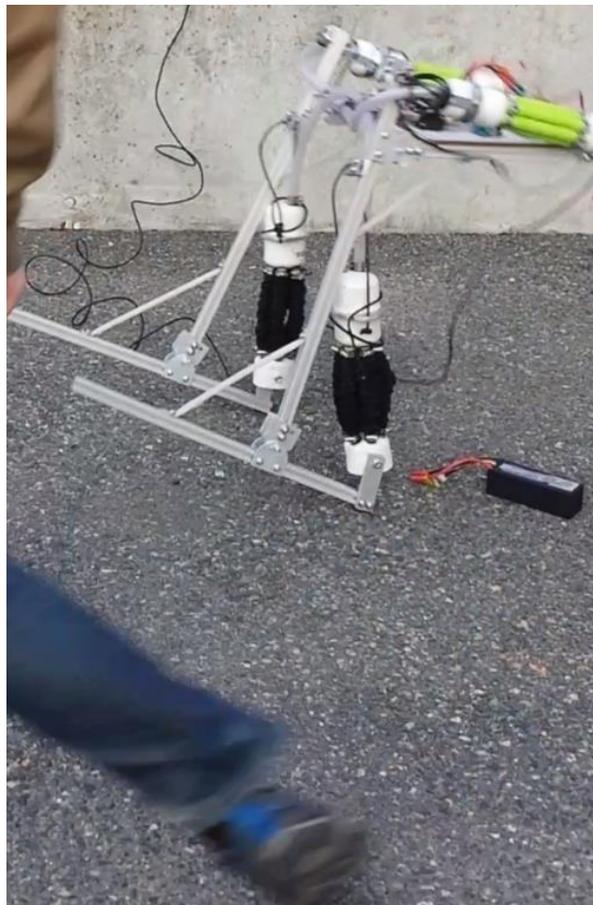


Figure 21: Iteration of final design landing on its heels after jumping backwards.

5.3 Third Test

5.3.1 Setup

Once the team successfully tested the final robotic design outdoors, the team moved indoors to continue testing and improve the robots performance. The best results achieved by the robot are described in the following.

The first improvement the team made to the design was to switch the top and bottom muscle fibers. The team noticed that the bottom muscle fibers would have to extend much further than the previous design iteration allowed during testing in order to perform a successful forward jump. Although this meant placing the more powerful muscle fibers on the top of the robot, the team found that this setup performed better than the previous iteration in giving the robot a slight push forward before taking off into the air.

The following figure displays the robot with its muscle fibers fully pressurized, ready for takeoff. In this image, a large rectangular block of aluminum can be seen under the heels of the robot. This piece of aluminum was added to raise the back of the robot slightly, giving its legs a better kinematic geometry for jumping.



Figure 22: Iteration of final design in pressurized state, ready to perform a jump.

5.3.2 Response

The muscle fibers in this test actuated the legs of the robot with even better success. While the force of actuation was still not large enough to lift the robot to the goal of approximately one meter off of the ground, the team decided that this jumping performance was satisfactory to display the high force applications of hydro-muscle technology.

After iterative testing and precisely altering the geometry of the muscle fiber's attachment points to achieve the best jumping performance, the robot reached a maximum height of approximately six inches off the ground. This performance can be seen in the following figure, where the robot is shown jumping forward.



Figure 23: Iteration of final design reaching approximately six inches in height from the ground.

5.4 Cambridge Science Festival

The Cambridge Science Festival is an annual event that showcases a number of science and technology related exhibits and activities for children and families. The bipedal hopping robot developed in this project was featured in the “Robot Zoo” section of the festival alongside many other projects developed at Popovic Labs. The robot performed dozens of live demonstrations in front of the public without a single failure and was among the most popular robots at the event.

Chapter 6: Conclusions

Hydraulically actuated muscles can be used for many high force applications. There are a number of novel ways to increase the pulling force generated by muscle contractions to meet many demands. The hopping bipedal robotic apparatus developed in this project serves as a suitable test bed for demonstrating the hydro-muscles high force capabilities. Future research will improve upon the robotic apparatus design and develop even more ways of increasing the hydro-muscle's pulling force.

6.1 Actuation and Locomotion

Following extensive testing of the many iterations of design, the robot successfully performed a hop reaching approximately six inches off of the ground using only the hydro-muscles as a source of actuation. Although the force of actuation from the muscle fibers was not nearly large enough to lift the robot to the goal of approximately one meter off of the ground, the team decided that this jumping performance was acceptable in displaying the high force capabilities of hydro-muscle technology. Thus, the goal of demonstrating the high force output applications of hydraulically actuated muscles through constructing a bipedal hopping robot was deemed successful.

6.2 Reconfigurable Test Platform

The use of 80/20™ 20-series modular T-slotted aluminum extrusion exceeded expectations and was crucial to meeting the goal of the project to design the robotic apparatus to be as modular as possible for easy construction, deconstruction, and improvements. Besides

providing modularity, the 80/20™ extrusions helped make the robot structurally robust and continuously adjustable such that the design met the goal of serving as a suitable test bed for future research involving high force output applications of the hydro-muscles.

6.3 Future Work and Recommendations

Future projects regarding the high force output applications of the hydro-muscles or working on the bipedal hopping robot test bed should focus on the following recommendations:

The kinematics of the apparatus and muscle placement can be fine-tuned to improve the jumping performance of the robot. To further improve the actuation power of the hydro-muscles, thicker latex tubing can be used to construct even stronger muscles. Furthermore, more hydro-muscles can be integrated into each muscle fiber and the design of the muscle fibers can be optimized to contain more hydro-muscles. The speed at which the muscle fibers contract can be improved by using larger valves, tubing, and fittings to increase the flow of air, increasing the actuation power of the hydro-muscles. Lastly, development of length control for the hydro-muscles will allow for greater control of the robot during the pressurization phase.

Chapter 7: References

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Appendix

Example of code:

```
int bottommuscles = 2;
int topmuscles = 3;
int state = 0;

//state of system, 0: resting with valves closed (on), 1: valves open (off, jump!)

long lastUpdateTime = 0;
void setup() {

// Declare valve control pins as outputs

  pinMode(bottommuscles, OUTPUT);
  pinMode(topmuscles, OUTPUT);

  digitalWrite(bottommuscles, HIGH);
  digitalWrite(topmuscles, HIGH);
  Serial.begin(9600);
}

void loop() {
  int a;
  if (a = Serial.available()) {
    for (int i=0; i<a; i++) {
      Serial.read();
    }

    if (millis() - lastUpdateTime > 750) {
      state++;
      state %=2;
    }

    lastUpdateTime = millis();
  }

  if(state == 0){
    digitalWrite(topmuscles, HIGH);
    delay(50);
    digitalWrite(bottommuscles, HIGH);

  else {
    digitalWrite(bottommuscles, LOW);
    digitalWrite(topmuscles, LOW);
```

}

}