Final Report

High Five

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Abstract

This document presents the development of High Five, a system which augments the jump height of its user by 5 inches. Its primary design considerations were high impulse power delivery and user safety, which has implications for exoskeletal designs. Exoskeletons suffer from a battery technology that cannot meet their power demand. One inefficiency is that exoskeletal actuators operate on a high duty cycle. Using a high impulse power delivery method would improve the efficiency of an exoskeleton by reducing power consumption when the system is idle. High Five is a test bed for this high impulse power delivery. The design was based on jump phase characteristics obtained by experimentation. Data analysis yielded criterion for system activation. To meet performance specifications, High Five had to supply 1100 pounds of force within a window of 100 milliseconds. Power is provided by a set of air springs which were selected for their high, modulatable force output and quick response rate. System activation conditions are handled with a high speed electronic control unit connected to a gyroscopic sensor. High Five successfully enhanced a vertical jump by 5 inches within a 5% error margin, proving that high impulse power delivery is viable and safe for applications that act upon a human user.

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1.0 Introduction and Background

A wearable robot is considered a technology that aids humans by extending, complementing, and enhancing their capabilities and functions, or by empowering limbs [1]. Among the types of wearable robots are exoskeletons: robots designed with biological models to mimic the anatomy of limbs and assist human limitations of strength and endurance. The close physical interaction between human and exoskeleton allows for efficient power transfer from robot to human by means of external force systems. The power transferred is useful for limb rehabilitation, disability assistance or performance augmentation.

Exoskeletons have as a priority to not hinder human motion and avoid unnatural or arbitrary movements that could lead to hyperextension or hyperflexion of joints. To achieve this, the human biology is taken as an overall system together with robot mechatronics. The analogy of biomechatronics is used to correlate a robot's mechanism, control, sensors, and actuators to its human equivalents (joints, brain, nervous system and limbs, respectively) in human-robot interactions. Actuators in constant performance might not be necessary for exoskeletons if the tasks were being performed quickly rather than slowly. The concept of supplying high power for brief amounts of time would yield lighter and more efficient exoskeletons due to them requiring smaller actuators. This concept has not been considered for exoskeletons, and could be the solution to the limitations being faced in exoskeleton designs.

Lower limb exoskeletons aid ligaments, muscles, soft tissues, bones and tendons responsible for knee extension, hip extension and ankle plantarflexion. During hip extension, the muscles involved are the gluteus maximus and the hamstrings as shown in Figure 1.

Knee extension occurs almost simultaneously with hip extension, and involves the muscles known as the quadriceps femoris (includes vastus medialis, lateralis and intermedius, and the rectus femoris), presented in Figure 2.

The muscles responsible for ankle plantar flexion are gastrocnemius and soleus plantar flex, displayed by Figure 3. Two jointed muscles are flexors at one joint and flexors or extensors at another joint [2]. Three two jointed muscles are present in lower extremities of a human: semitendinosus, semimembranosus, and biceps femoris (long head), rectus femoris (one of the quadriceps), and gastrocnemius (calf).

2.0 Purpose

The purpose of this project is to design, analyze, build and test a jump apparatus that improves the standing vertical jump capability of one person by an extra height of 5 inches as a proof of concept for an alternative delivery method for exoskeletons.

3.0 Objectives

A jump apparatus will be designed, analyzed, built and tested to augment the stationary vertical jump height of an individual by no less than 5 inches using a high impulse energy delivery method. The jump apparatus shall be fabricated to meet specifications. Alamo Engineering is to stay within project funding budget. Alamo Engineering is to report the final results of the project.

4.0 Key Performance Specifications

4.1 User Safety

The system must be safe to the user, causing no harm of any kind. The most important areas of concern in regards to potential damage to the human body are bone fracture or failure and tendon rupture. The design will have as a priority to perform with no injury to the user.

4.2 System Performance

This system was designed to increase a user's stationary vertical jump by a minimum of 5 inches A percent error range of $\pm$ 5% is given to allow for various deviations that occur.

4.3 Energy Requirement

According to analysis detailed in subsequent sections, the system must deliver 135 lb*ft to augment a jump by 5 inches.

4.4 System Activation Time

The system must be capable of being fully activated within 300ms. It has been designed to fully activate within 100ms.

5.0 Concept Design

The design of High Five took into consideration biological constraints and system specifications. All prototype systems were designed to work in tandem with natural jumping mechanics while providing high impulse power delivery. User safety was also considered a priority design consideration.

5.1 Airbag Mount

The 3D model, concept schematic, exploded view for this design is presented in Figures 4, 5, and 6, respectively. Each design iteration can be seen in Figures 7 and 8. This system consists of pneumatic air springs capable of exerting the required force to propel an individual to the benchmark height. It is a detachable footwear launching system fabricated from two hinged plates. The system would be connected to pneumatic lines for flow delivery from a compressed gas system to produce the required pressure and volume to the air springs. The air delivery system shall be electronically controlled with a gyroscope and myRIO. This design will increase the jump height of an individual by deploying an air spring located under the user's foot. A hinge between the plates the foot is mounted on will allow the system to articulate and mimic the natural motion of the foot during launch. The air spring itself shall be adjustable along the length of the plate it is mounted to. This will allow for system tuning, and will ensure minimal to no moment generation. This design focuses on adding external energy to a jump after the muscles in the hip, thigh, and ankle have completed their extension. The air spring shall be fed by an external gas supply. The fluid will be supplied at a sufficient pressure to deploy the spring with 135 lbf*ft of energy. The system attached to the user shall not exceed 35 lbf. The system is designed to accept users with US men's shoe sizes from 10 to 13 and weighs up to 220 lbf. The system is designed to be resistant to impact.

5.1.1 Advantages and Disadvantages

This system's strengths start with the ability to regulate the compressed gas and therefore controlling the amount of force produced by the springs. This system is the most reliable because of the total force the air springs can produce. It also offers improved stability due to the designed adjustability in the air spring location. The air spring system does suffer from some drawbacks. This system has demanding timing requirements on deployment. The total time for system deployment is approximately a third of a second. It requires a controller capable of reading sensor data and writing outputs very quickly. This system is a tethered system, and its gas supply will deplete and require replacement. This system has several specialized parts that will have to be produced for the project, with all associated machining costs.

5.2 Knee Brace

This system is based on a spring attached to two medical braces, one attached on each of the user's legs. The concept schematic and exploded view for this design is presented in Figures 9 and 10 of the Appendix, respectively. This design focuses on the redistribution of the mechanical energy generated by one-joint muscles. It has been found that when a two-jointed muscle attempts to perform two functions at the same time, its potential decreases significantly. Having a two-jointed muscle focus on one function at a time maximizes its potential. This system will make use of this effect by supplying energy to the leg as it extends. The system shall be controlled by an ECU and a gyroscope. When certain angle and acceleration conditions are met the system will deploy. The deployment shall occur at the transition between the preparatory and takeoff phase of a jump. The spring would be winded by a DC motor to store energy. It would require an appropriate spring constant based off the deflection between an individual's crouching position, compressing the spring, and their standing position, where the spring would be uncompressed.

5.2.1 Advantages and Disadvantages

One strength of this system is its versatility due to its placement around the knee instead of the foot. It is a single unit assembly, and thus the easiest concept to fabricate. It requires no increased exertion from the user. However, this solution is the most likely to cause muscle injury unless a stop mechanism is designed. It is the most expensive concept because medical braces are costly. This system is also non-adjustable. It mimics exoskeletons without performing as well as one.

5.3 Spring Mount

This design consists of two plates, a top plate upon which the foot rests, and a lower plate which makes contact with the ground as shown in Figures 11 and 12. Between the two plates rest a series of coil springs on guides. The springs are wound using electronic actuators. The foot is held is place with a series of straps and an ankle support.

5.3.1 Advantages and Disadvantages

This system has the advantage of being the least expensive of all systems considered. The coil springs that were being considered are cheap and readily available. The system would have been able to deliver the required energy to augment a jump by 5 inches. The systems main disadvantage was that it lacked adjustability. Any tuning that would have been required would have required partial system disassembly.

6.0 Final Design

The final Air Spring Mount Design is presented in Figures 4 and 5. This design consists of air springs put together with two hinged plates. It is a detachable footwear that places the air springs under the user's feet, in line with their center of gravity. Pneumatic lines will deliver flow from a compressed gas system to produce the necessary pressure and volume for the air springs.

The system will operate as designated by the Control System shown in Figure 13, which consists of the Electrical Configuration presented in Figure 14, and the Pneumatic Configuration (Figure 15). Each configuration is to work in unison to achieve the desired performance. MyRIO will take readings from an accelerometer and a goniometer. When specific values are read, if the emergency cutoff is not engaged, it will send a signal to open the solenoid valve that is to supply the fluid flow to the air spring. This valve will remain open for a designated amount of time based on tuning. Once that time has passed, flow will be cut, and the second solenoid valve will open to allow flow to exit from the air spring.

6.1 Analytical Methods

The Applied Biomechanics Research Laboratory was utilized to determine jump kinematics. A male individual of 176.2 lbs, shoe size 12, and a height of 6’5” was equipped with sensors on his sternum, shoulders, elbows, hands, hips, knees, ankles, toes, and heels. The individual performed three jumps at maximum potential. Plates recorded force exertion while high speed cameras recorded joint trajectory during each jump. Figure 16 presents the force exerted in each jump phase. According to the data analysis, total deployment time for the system is approximately one third of a second. The control system for the selected design must work within that time frame. Force exertion reaches maximum values during the landing phase. The final design must withstand such force values.

6.2 Mechanical Analysis

The performance of the jump apparatus relies on the biomechatronic relationship between human and robot. The system will be designed for enhancing human lower limb capabilities as defined by a stationary vertical jump. Therefore, the human body must be analyzed as a mechanical system to which the jump apparatus, another mechanical system, will adapt. Both systems can be taken as a whole mechanical system when both structures work simultaneously to achieve the objectives according to specifications.

The human body can be modeled as a set of rigid segments linked by joints to be analyzed as stated by continuum mechanics. With this, external forces (R) and moments (M) can be defined as shown in Figure 17.

The redundancy problem states that the biological motor system has too many degrees of freedom and redundancy in the amount of sensors and actuators. This fact makes the specific determination of forces in each muscle impossible. However, the human body serves as an efficient system that does not require such detail.

Figure 18 presents the Free Body Diagram of the Airbag Mount system where F_s is the spring force, W is the weight of the system and F_N is the normal force produced.

Vertical jump kinetics can be defined by Newton’s 2nd Law of Motion, which states that the acceleration of an object as produced by a net force is directly proportional to the magnitude of the net force, in the same direction as the net force, and inversely proportional to the mass of the object. [3] The following equation presents Newton's 2nd Law of Motion,

$$\sum F = m_b a_{cg} \tag{11.3.1}$$

where $\sum F$ is the summation of all forces acting on a body, m_b is the mass of the body, and a_{cg} represents the acceleration of the body's center of gravity (Figure 19). The individual's center of gravity is relevant to the system design because it designates where the airbag placement to minimize the production of undesired moments about the ankle.

When Newton's 2nd Law of Motion is applied to vertical jump kinetics, it becomes

$$F_N - W = (m_b)(a_{cg})$$

where F_N is the vertical component of the ground reaction force, W is the person's body weight, m_b is the person's body mass, a_{cg} is the vertical acceleration of the CG. A jump is achieved when the acceleration is positive and F_N is greater than W, thus, creating a net positive force acting on the body. The forces that must be taken into consideration for the system performance are those as shown by Figure 18.

The minimum energy required by the system is defined as the difference in energy produced by an unassisted jump and an augmented jump. The unassisted jump mass is defined as m_1 and achieves a height of h_1 at a standard gravity of 32.2ft/s^2. The augmented jump is set at the same conditions with the exception that the mass, now m_2, is increased due to the added mass of the system but will generate a higher jump height, denoted as h_2. The energy difference is based off the following terms and shown as

$$E=F_{w2}h_2 - F_{w1}h_1$$

where F_{w1} is defined as the total weight that of the user jumping with or without the jump apparatus. From the specifications, the maximum weight of the user and system are determined together with the augmented jump height. These values are 220 lbf, 35 lbf, and 5 inches, respectively. Assuming that an unassisted jump height is 10 inches with all other known variables, it is determined that the minimum energy that must be submitted into the jump is 1625 lbf*in or 135 lbf*ft.

From analysis of Table 1, a design height of 3 inches was selected. This gives a total deflection of 1.2 inches for the actuator. From this deflection the force required for the actuator to output can be determined by using the formula

$$E=\int F dx \tag{11.3.2}$$

This gives a per shoe required force of 677 lbf to achieve the required augmented jump height. Using this force and Table 1 gives a required pressure of approximately 68 psi. The force derived from the analysis was then used in the method shown in Figure 13 and determined to be safe for application upon the user.

6.3 Design refinements

The air spring system underwent three major iterations. The first iteration, Figure 7, had several deficiencies. First, the placement of the air spring was located behind the foot. It was found that this placement would induce an undesired moment about the ankle that would lead to potential user injuries. The second major deficiency of this design was that the housing of the system attached to the user was made of steel and was ultimately deemed too heavy to be comfortable for the user to wear.

The second iteration, Figure 8, addressed these problems by relocating the air spring under the ball of the user's foot. It was determined that this position was more desirable as it put the load applied by the air spring in line with the user's center of mass. Due to the fact that the exact center of mass of a human is variable, a method of adjusting the location of the air spring was implemented. This allows the air spring to be tuned to the center of mass of an individual user. Additionally, the material of the housing was changed from steel to carbon fiber.

The third iteration, Figure 5, saw a major redesign to the carbon fiber housing. The design in the second iteration had fairly complicated geometry that would have required a form and autoclave to cure. This process was cost prohibitive. The geometry was simplified in such a way that a prefabricated carbon fiber plate could be used. A sole was added to the design to provide grip and a midsole to dampen impact loading from the jump and landing as well.

During this time, changes were also made to the pneumatic system. The operating fluid was originally to be compressed carbon dioxide. It was found that the phase change of the liquid carbon dioxide to gaseous carbon dioxide would cause the gas to be at an extremely low temperature. The sourced solenoids and tubing could handle the low temperature, but they were cost prohibitive. The operating fluid was switched to nitrogen, which was determined to be acceptable for use in the system without major modification. Ultimately, nitrogen was determined to be too expensive to use, and compressed air was selected as a replacement working fluid.

6.4 Key Drawings

Key drawings for the system relate to the adaptability that was designed into the air spring system. The air spring, air manifold, and mechanical assembly are the critical components of the air spring system and are shown in Figures 20, 21 and 22, respectively.

7.0 Prototype Fabrication

7.1 Fabrication Methods

A full scale mechanical prototype was fabricated to reveal the engineering design conflicts on cost effective materials as shown in Figure 23. The upper and lower plates were fabricated from 0.25” acrylic plastic. The plates were cut and trimmed to the dimensions specified in their respective drawings to allow for the installation of the system’s hinge and air bag. An aluminum hinge was installed with removable fasteners for ease of installation and removal of the components. A series of 1/8” acrylic plastics were bonded together to achieve the design height of the air manifold assembly. It too, was drilled to accept the installation hardware for the installation of the air bag. The soles were manufactured with bonded Ethylene-vinyl acetate foam which were used for the final design of the system.

The fabrication methods were based on standard shop practices and aviation industry standards. The air manifold was the sole component requiring machining on a vertical mill. The manifold was machined to accept installation hardware for the upper aft plate and the air bag. A 2” step was also machined to allow for the installation of the hook and loop straps. Four slots were also machined for the adjustability of the manifold on the mechanical system. The machining process maintained a Ra of 32 μ”. The manifolds were also tapped to accept a 3/8” NPT air fitting, as shown in Figure 24.

The carbon fiber laminates were cut and trimmed to drawing dimension utilizing a cutting wheel and a grinder while maintaining a minimum Ra of 63 μ”, as shown in Figure 25.

The soles were bonded to the shoe assembly using commercially available adhesive. Mechanical pressure was applied to the sole assemblies during the curing process of the adhesive, refer to Figure 26. This process created a laminate sole much like the carbon fiber plates are manufactured.

Sheets of 0.4” thick sheets were bonded as a laminate to achieve the design height. The radii of the soles were achieved with the use of a barrel sander after the curing process, as shown in Figure 27.

The carbon fiber plates were drilled and countersunk using aviation guidelines. The fastener holes were drilled maintaining a 2D edge distance, or two times the diameter of the rivet to the edge of the part. The distance between the row of rivets, or pitch, was drill to maintain a 4D to 6D spacing, as shown in Figure 28.

The aluminum hinge was trimmed and position to be drilled with the common holes from the foot plates. The hinge and the plates were riveted together using 100 degree countersunk aluminum rivets. The rivets were installed using a pneumatic rivet squeezer, rivet gun and bucking bar, as shown in Figure 29 and 30.

The hook and loop straps were slide through the soles and manifold prior to their installation. A coat of clear acrylic enamel was used to coat all metallic materials that come in direct contact with the carbon fiber laminate plate. The coating provides a barrier at the mating surface which prevents the forming of galvanic corrosion. Standard shop practices were used to assemble the remaining components to finalize the system, as shown in Figure 31.

7.2 Drawings

The layout and assembly drawings of the system can be viewed in Figures 5,6, and 22 in the Appendix.

7.3 Bill of Materials

The materials chosen were selected for their strength to weight ratio and their economic value.

The mechanical assembly was designed to be as light as possible without compromising the safety of the user. The material was also acquired based on the price to provide an economical solution to the customer. The mechanical system consisted of 20 parts as shown in Table 1. The carbon fiber laminated plate was the most expensive part, yet it was the most critical. Although the material cost $243.18, it was the best strength to weight ratio material available. The air bags were relatively inexpensive and it met and exceeded the specifications required by the system. The bags are the heart of the system, yet the pair were allocated at a price of $41.81. The use of the high density polyethylene for the air manifold assembly was also a result to the weight reduction goal. It proved to be less expensive than aluminum. The total cost of $76 included the material and the machining labor. An aluminum hinge was procured in lieu of a stainless steel hinge. It was also chosen for its lightweight properties and price. The hinge was procured locally for less than $6. The remaining miscellaneous fittings and hardware were also purchased with weight saving characteristics in mind.

The components for the pneumatic system were chosen with efficiency in mind. The compressed gas is supplied with a 13 gallon compressor. It supplied 5.1 scfm at 90 psi. The use of the electric compressor provided the system with unlimited jumps. It was provided by one of the team members of Alamo Engineering. It replace the use of a previous design which used a nitrogen tank and expensive regulator. The $ 62 electronic solenoid chosen for the system allowed for the use of ½" tubing. This allowed the system to be provided with a large volumetric flow. The fast action of the solenoid also played a large role in the procurement of this particular solenoid. The solenoid has a reaction time of less than 20 milliseconds. The Department of Transportation (DOT) approved air lines were purchased for $39.99. The lines were chosen for safety reason for they were SAE J844 certified. The remaining fittings and connections were allocated locally with quality and price in mind. The electrical system was chosen with the reaction time and ease of programming in mind. The Electronic Control Unit (ECU) had to receive and delivery information in less than 0.6 seconds. The NI myRIO-1900 proved to have the capabilities to perform such tasks. It is commercially available for $250 however, it was provided by the customer. A $3 pendant switch was purchased to provide the user with a safety switch in the event that a malfunction occurs. The bill of materials are integrated into the parts lists for the mechanical, pneumatic, and electrical system which can be found in Tables 2, 3, and 4, respectively.

8.0 Prototype Tests

A preliminary test was carried out during the development of High Five. The test involved the general system performance of augmenting a person's jump height. In this altered version of the system performance test, the electronic control unit was not integrated into the system. Instead, a pendant switch was hooked up to the battery powered solenoid valve and compressed gas tank. This involves increased operator interaction with the system, requiring the operator to prompt the solenoid to release the gas into the tubes to the air springs. This brings about a greater source of error in the timing of the air spring inflation in the jump process. Despite this, it was determined that an increased jump height can be obtained by jumping with High Five equipped. Comparable results were obtained at an operating pressure of 80 psig and can be viewed in Table 5.

8.1 Test Plan Summary

The written test plan for High Five consists of seven tests, five major ones and two minor ones. The full detailed test plan can be found in the appendices of this document. The tests range from the subassemblies to the complete system. They are intended to ensure that the assembly and all of its components work together upon full system activation.

8.2 Test Setup or Apparatus

Test setup is custom made for each test. Each will be briefly covered, with specifics mentioned in the Test Plan in the Appendices. Preliminary values were obtained for early testing which will be updated upon completion of testing.

8.2.1 Pressure

The pressure test involves the following components: the compressed gas tank, the tubing, tube fittings, solenoid valve, and pressure gauge. The intention behind this test is to acquire the pressure of the working fluid that enters the air spring. By knowing the inlet pressure, the force exerted by the air spring can be found. This test involves the tubing to be connected from the air spring to the compressed gas tank with the involved air fittings. The pressure gauge will also be equipped near the entrance of air spring while connecting the tubes. The solenoid valve is to be actuated through a pendant switch which is to be wired to the solenoid prior to testing. The test is performed by turning on the compressed gas tank and actuating the solenoid. The pressure is to be read off the pressure gauge and reported in the test package. Pressure values are recorded in Table 3 and compared to the calculated pressure to ensure analysis accuracy.

8.2.2 Control System

This test comprises the main electronic control unit's ability to control the subsystems of the apparatus. The subsystems used in the complete jump apparatus will be tested with the electronic control unit to ensure that communication occurs effectively for the purposes of the jump apparatus. This test will ensure that the electronic control unit is compatible with the subsystems as well as verifying that the script guiding the system performs as desired. The start of the test begins when the myRIO receives the signal from the gyroscope. The end of the test is when the signal reaches the solenoid valve and the system is allowed to actuate. The measured value for this test is variable t, which is the time for the control system to complete the program. The electronics subassembly is tested following the control system diagram in Figure 13. As defined by the Software and Electronics Package, the time it takes for full system activation is 38.5 milliseconds. The tolerance range for this test on time is ±2.5% and the results recorded are listed in Table 4.

8.2.3 Straps

Testing the straps for the system is related the straps fixed to the housing that are used to adhere the operator to the jump apparatus. The testing involves a pull test which will be performed using a ten pound weight while hanging the housing subassembly upside down. The straps on the housing will be exposed to five seconds of holding the ten pound weight upside down. Results of the test will be entered into Table 8.

8.2.4 NDIs

Nondestructive inspections, or NDIs, are used in maintenance inspections of equipment to determine component health. The inspection is done using one or multiple human senses such as sight, touch, smell, or hearing in conjunction with various tools. One tool that will be used will be the tap hammer which is further discussed in Section 5.3. The tap test will follow Aviation

Maintenance Technician Handbook-Airframe, Volume 1, Chapter 7. A variant of a NDI is the detailed visual inspection which includes the use of the human senses but without the use of tools and will be employed when the tester decides no tools are required for the inspection. The inspection is considered complete if the complete assembly is evaluated to have not experienced any of the failure conditions listed in Table 9. The results of the NDIs are listed in Table 9.

8.2.5 System Performance

The completed jump apparatus will be submitted through performance testing to satisfy the design specifications within ±5% of the added 5 inches added to the user's jump natural height, h_n. For the purposes of this test, the augmented jump is defined as a jump performed with the jump apparatus with delivery of compressed gas. The unaugmented is defined as jumping with the jump apparatus with no delivery of compressed gas. The performance testing will be done by analyzing videos taken of both augmented and unaugmented jumps. Videos taken of the jump are analyzed to visually verify the physical height that the user reaches in both an unaugmented jump and a jump apparatus assisted jump, h_a, as performed by the user. Specifically, the frames of the video are to be analyzed using a video camera with a frames per second of 30. In cases where the jump height peak occurs between frames a fractional frame value will be utilized. The fractional frame value will be the drop that occurred between frames. Before performing either set of jumps, the user must perform the warm up described in Table 10. The warm up is to ensure that the user obtains their maximum physical height from a jump and for injury prevention. The results between the two sets of jumps will be compared to verify that the jump height did in fact increase by 5 inches with the tolerance of ±5%. The results of the test are to be recorded in Table 5.

8.2.6 Weight

The completed jump apparatus must be weighed to ensure that it meets the designated physical specifications. The test to verify this will be done by placing the assembled housing on a scale to determine the weight of the system. The results of the test are to be recorded in Table 11.

8.2.7 Operator

An evaluation of the operator will be held to determine if he or she is capable of utilizing the jump apparatus in the desired manner. The operator's weight, shoe size, height, and previous injury history will be measured and provided. The operator's weight, W_O, will be measured with a scale, the shoe size, S, will be measured by a Brannock device, and the health history will be disclosed verbally by the operator and recorded. The conditions set by this test are specified in Table 12.

8.3 Test Results

The test results are displayed in Tables 5 through 12. Based off the results, Alamo Engineering was able to determine that subassemblies and the complete jump apparatus High Five were able to increase the operator's jump height by 5 inches. The jump height was obtained within specifications set down by Alamo Engineering and does not require further modifications. For further explanation of the test setup and results, refer to the Test Plan and Test Report Documents.

9.0 Project Management

9.1 Personnel

9.1.1 Team Mentors

Dr. Pranav Bhounsule, Mr. Jack Simonis, and Mr. James Johnson were crucial in guiding Alamo Engineering to make the best decisions in a timely manner.

9.1.2 Ivelisse Negroni

Ms. Negroni was the team lead of Alamo Engineering. She handled all Project Manager tasks.

9.1.3 Michael Turasz

Mr. Turasz was the Test Engineer of Alamo Engineering.

9.1.4 Noah Trent

Mr. Trent was the main Analysis and Design Engineer of Alamo Engineering.

9.1.5 Cesar Sifuentes

Mr. Sifuentes was the Manufacturing Engineer of Alamo Engineering.

9.2 Overall Schedule

Figure 30 presents the current schedule for Alamo Engineering's tasks.

9.3 Financial Performance (including ME 4812 and ME 4813)

Based off the hours work and the loaded labor rates from the industry a baseline project budget was conceived. The total budget cost for High Five was determined to be $462,867.61.
Figure 31 presents the Hourly Labor Rates used to approximate the project's labor and material costs. The project's BCWS (Budgeted Cost of Work Scheduled), BCWP (Budgeted Cost of Work Performed) and ACWP (Actual Cost of Work Performed) for Senior Design 2 are presented in Table 11. BCWS represents the amount of work schedule to be performed by the team over a specific amount of time. BCWP is the planned cost for the amount of work scheduled, listed at $463,536.43. ACWP is the cost of the actual work performed by the team members, listed at $478,622.61. The Schedule Performance Index is 1 and the Cost Performance Index is 0.97 as calculated using the previously mentioned budget costs. These values indicate that the project is currently over budget and on schedule. This is due to delays in fabrication, extended labor hours in the electrical system, and additional research leading to the submission of multiple engineering change orders. The Budget Projections are presented by Figure 32. The schedule of tasks and deliverables are presented in Figure 33.

10.0 Conclusions

Analysis showed the air spring footwear system was to meet functional requirements and specifications as required. The jump apparatus weighs less than 35 lbs, and does not cause any harm to the user because of its stability. The jump apparatus enhanced the user's jump height by 5 inches within the acceptable tolerance. High Five proves that supplying high amounts of power for short periods of time is a feasible concept for exoskeleton limitations.

11. Appendices

11.1 List of Figures

Figure 1. Hip Extension Muscles [4]

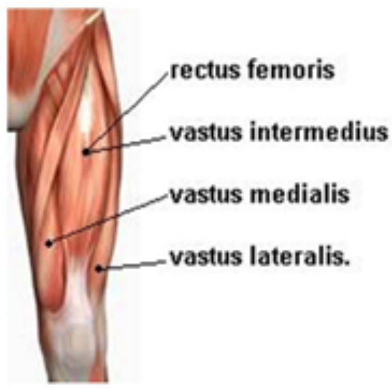


Figure 2. Knee Extension Muscles

Figure 3. Plantar flexion Muscles

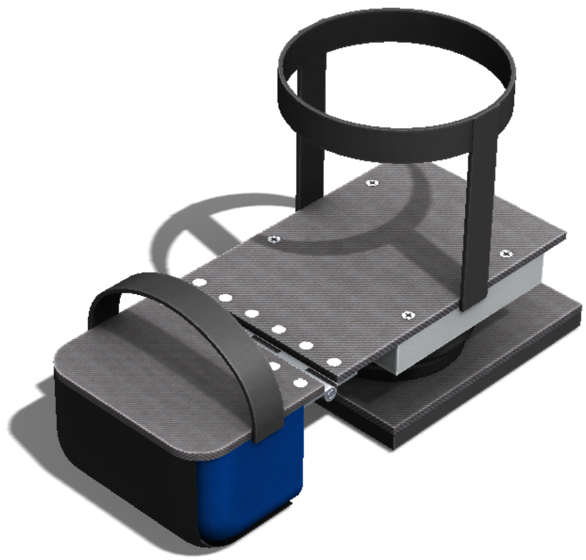


Figure 4. Final Air Spring 3D Model

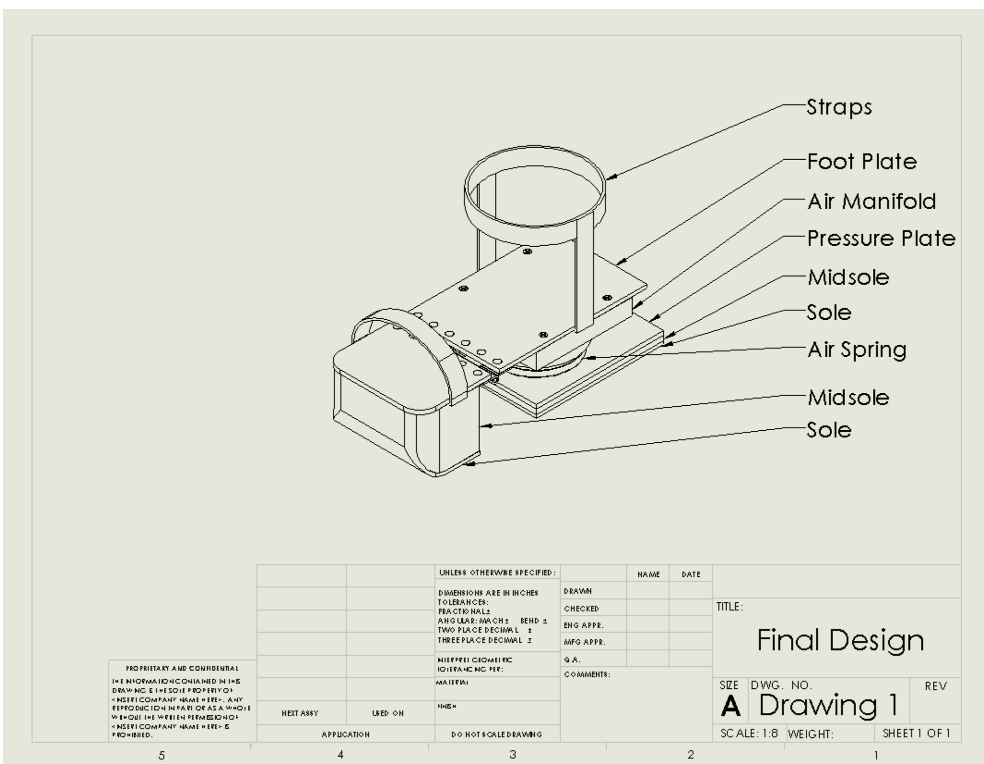


Figure 5. Final Air Spring Concept Design

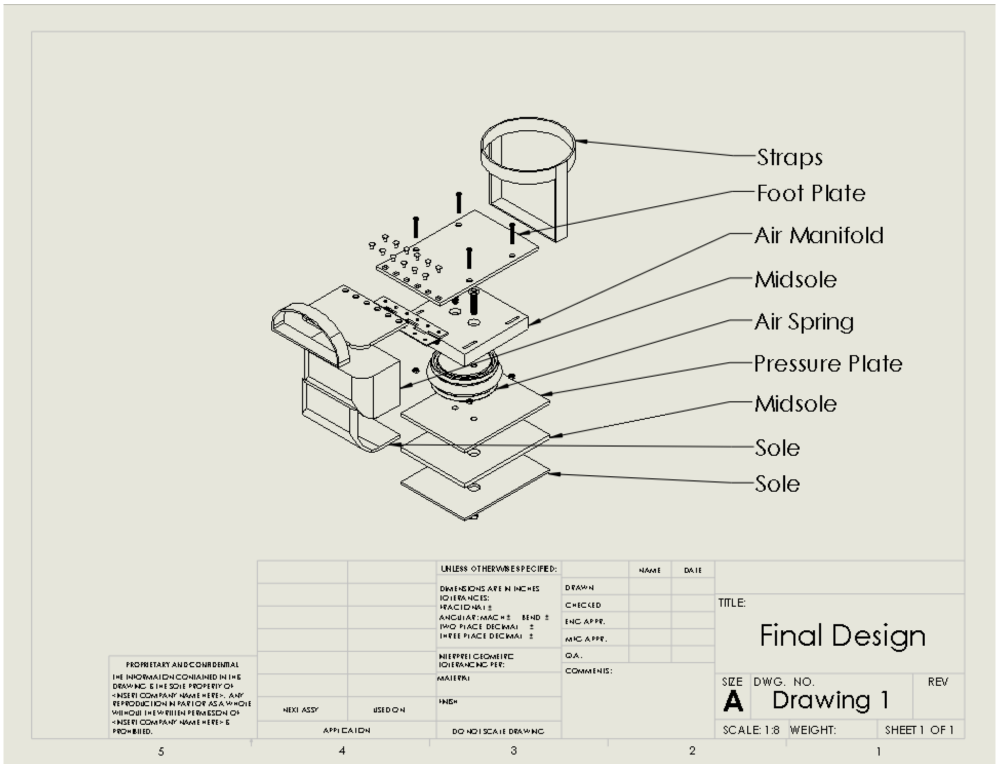


Figure 6. Final Air Spring Exploded Design

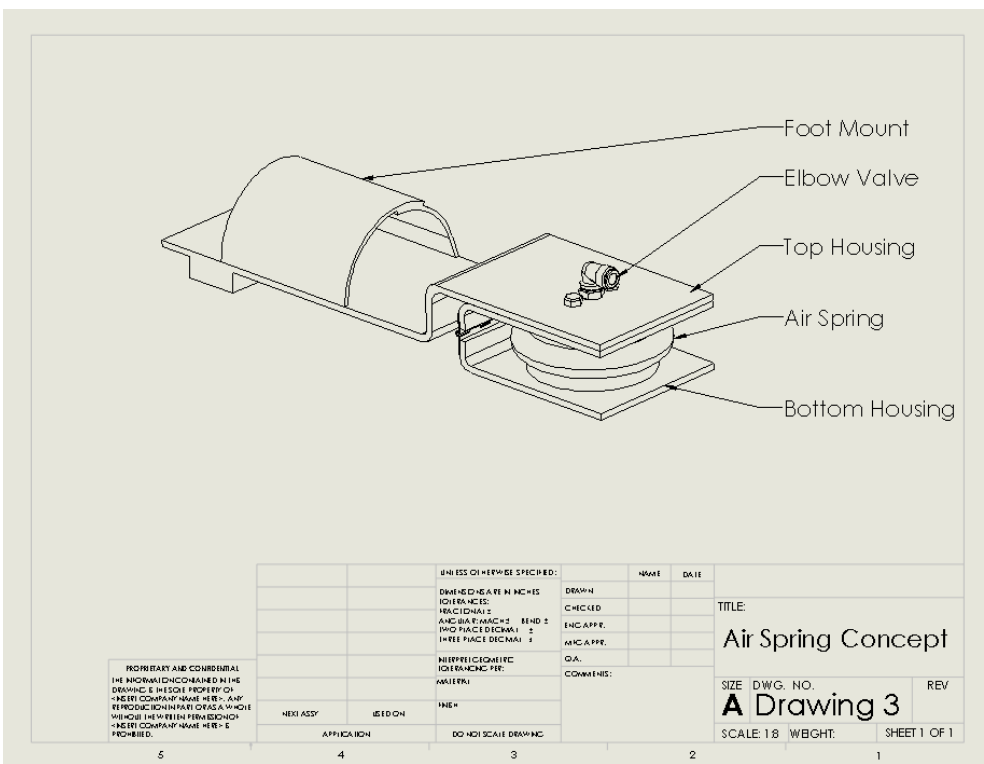


Figure 7. Air Spring Concept First Design

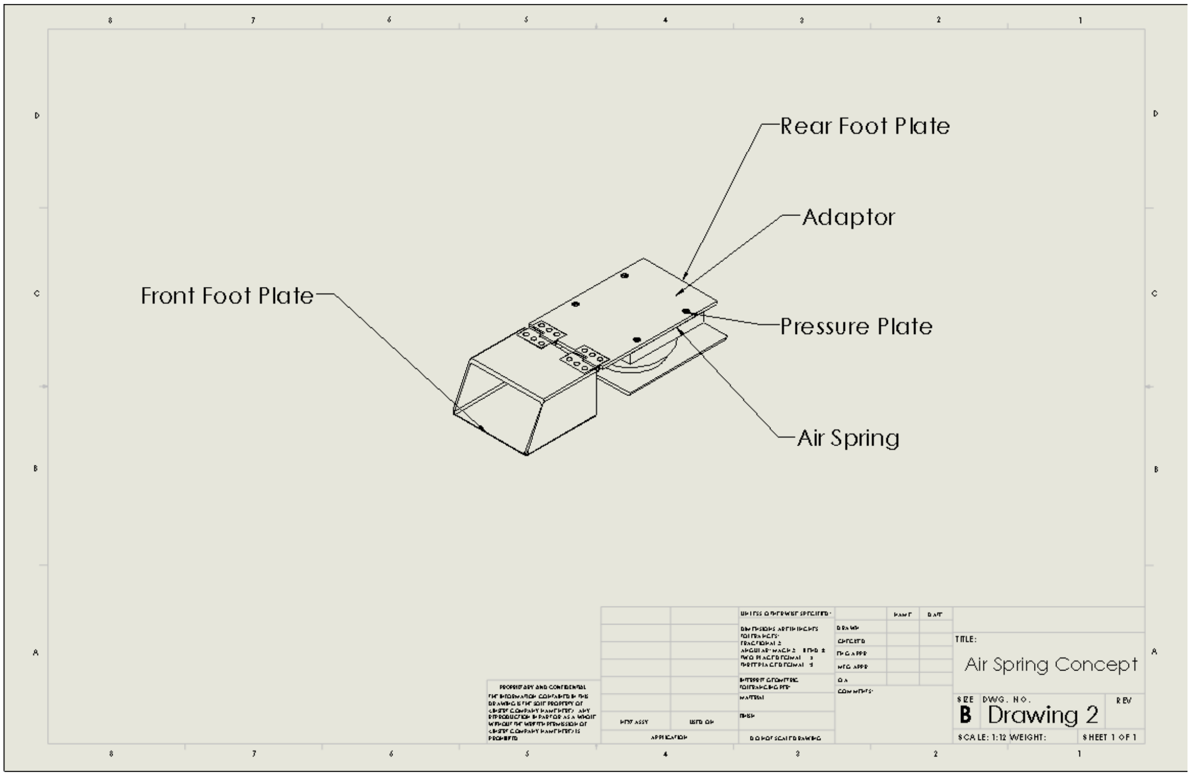


Figure 8. Air Spring Concept Second Design

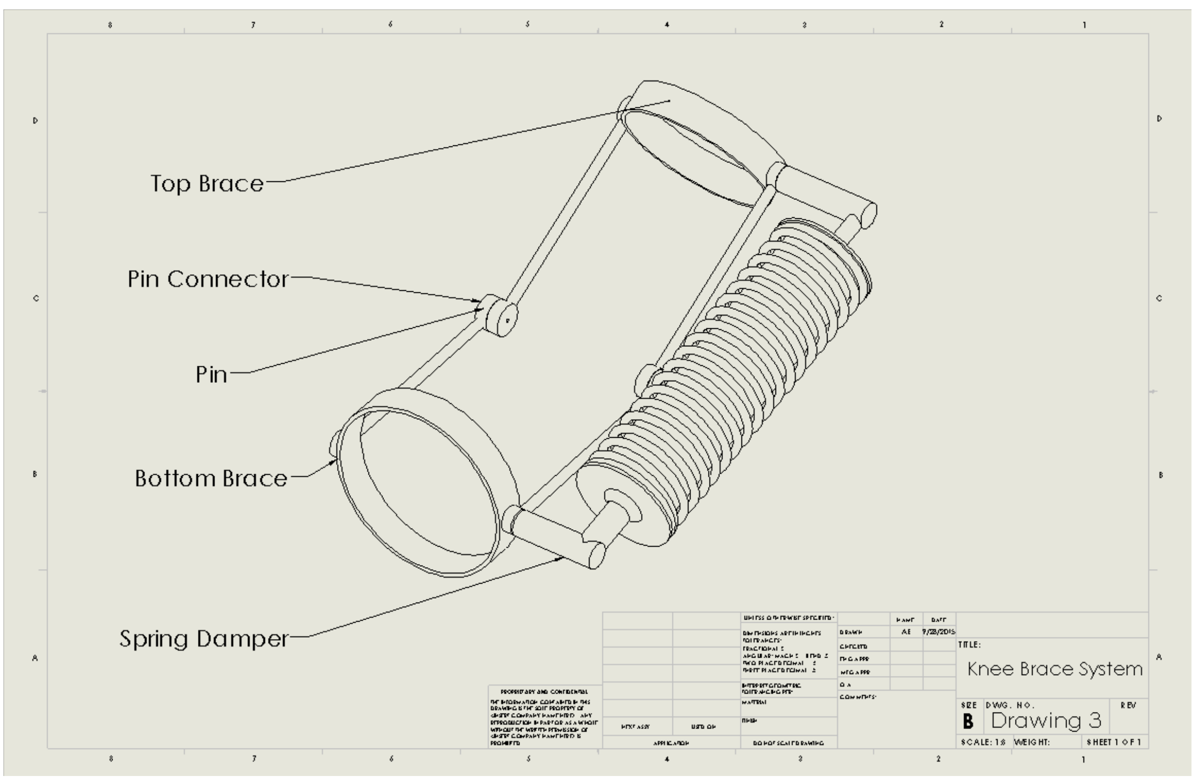


Figure 9. Knee Brace System

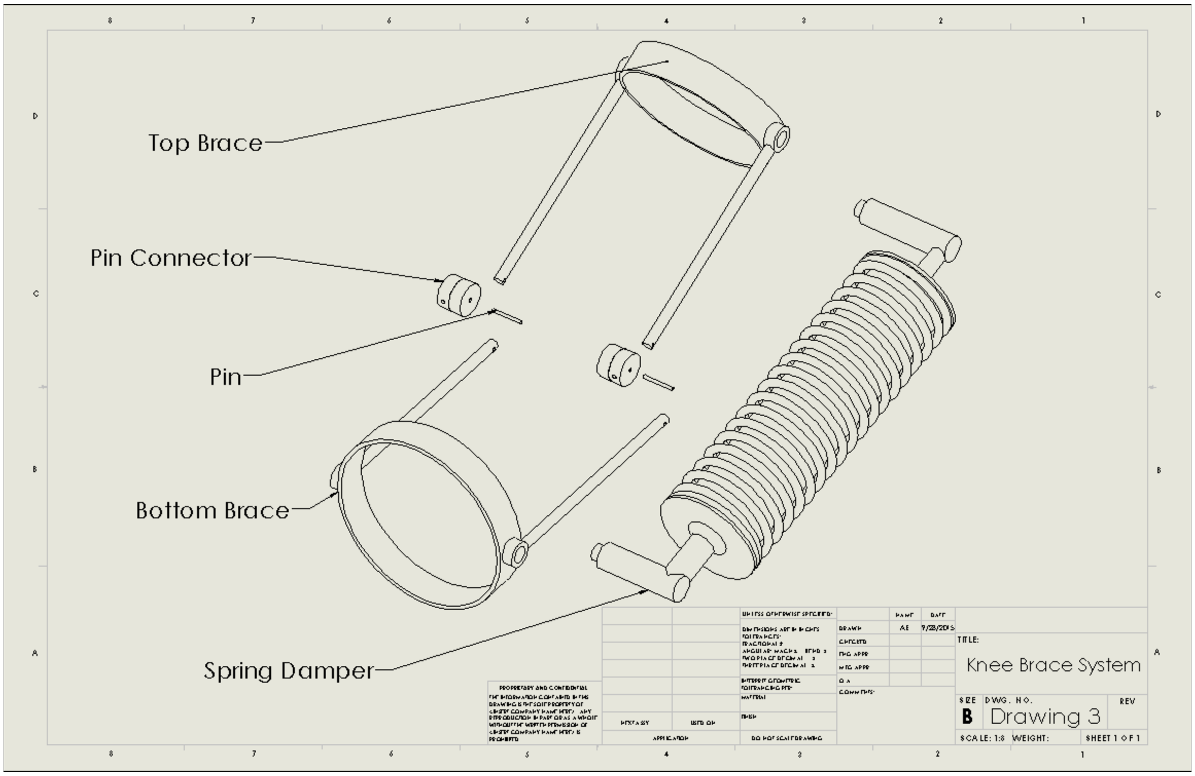


Figure 10. Exploded Knee Brace Design

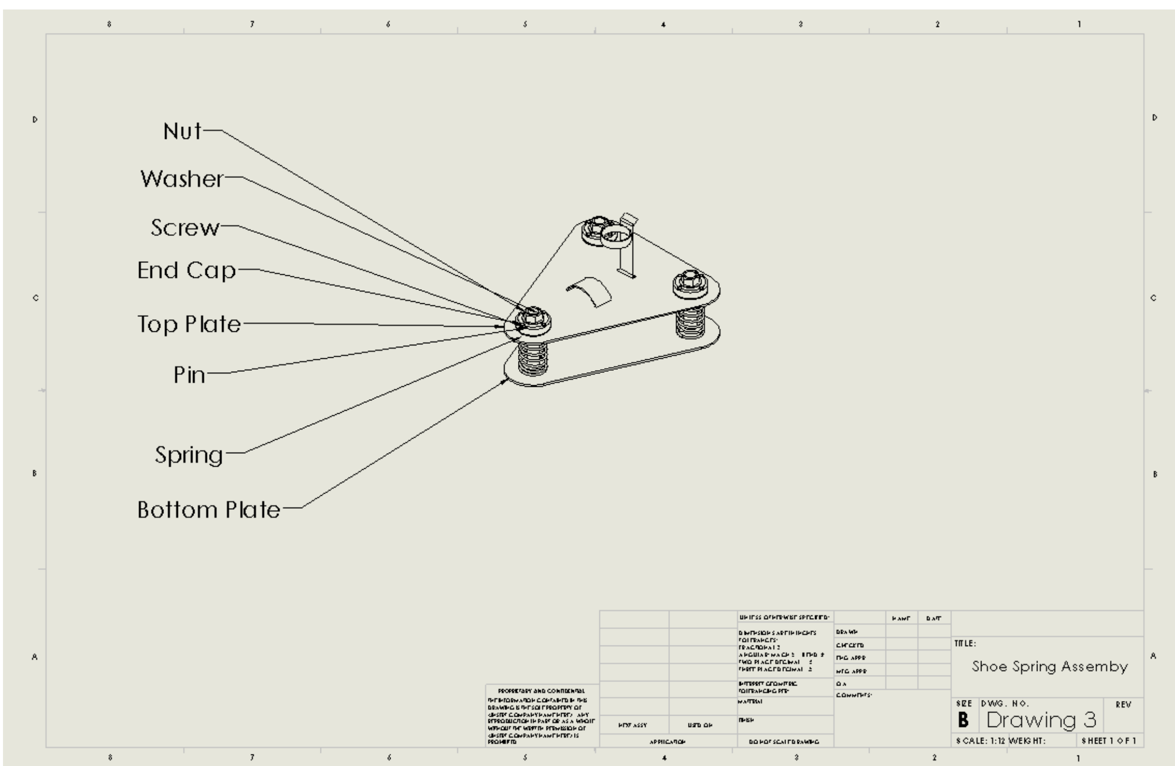


Figure 11. Shoe Mount Assembly Design

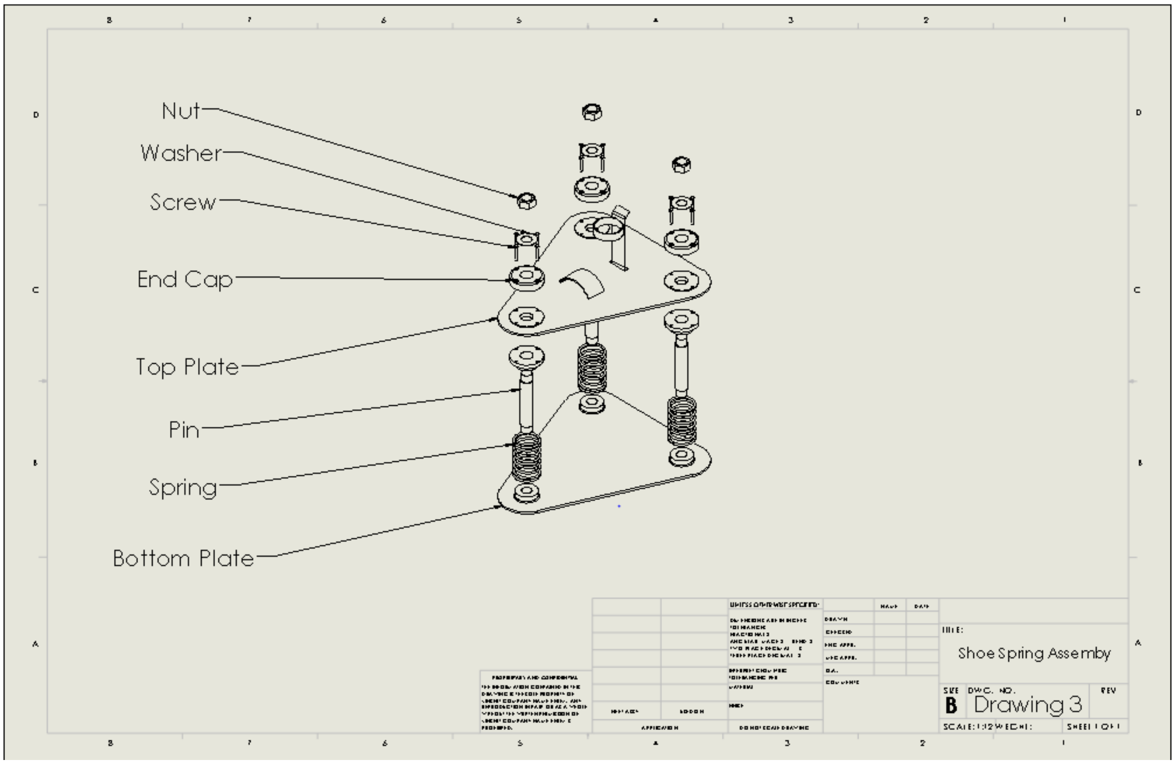


Figure 12. Exploded Spring Mount Assembly

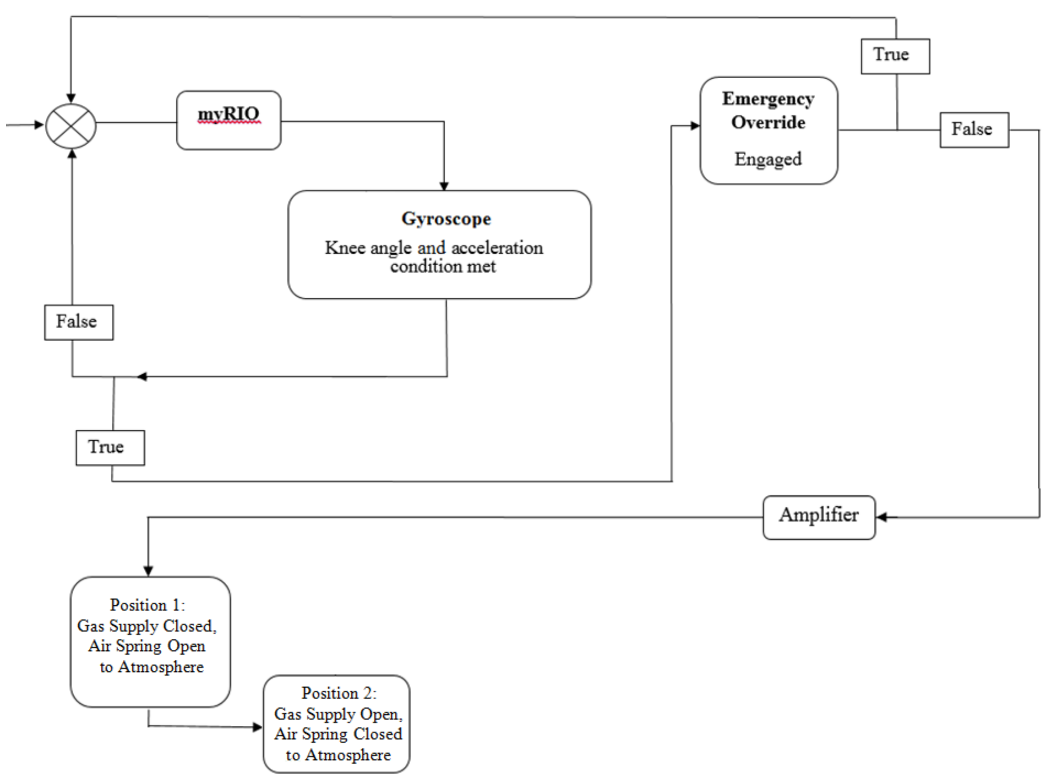


Figure 13. Control System

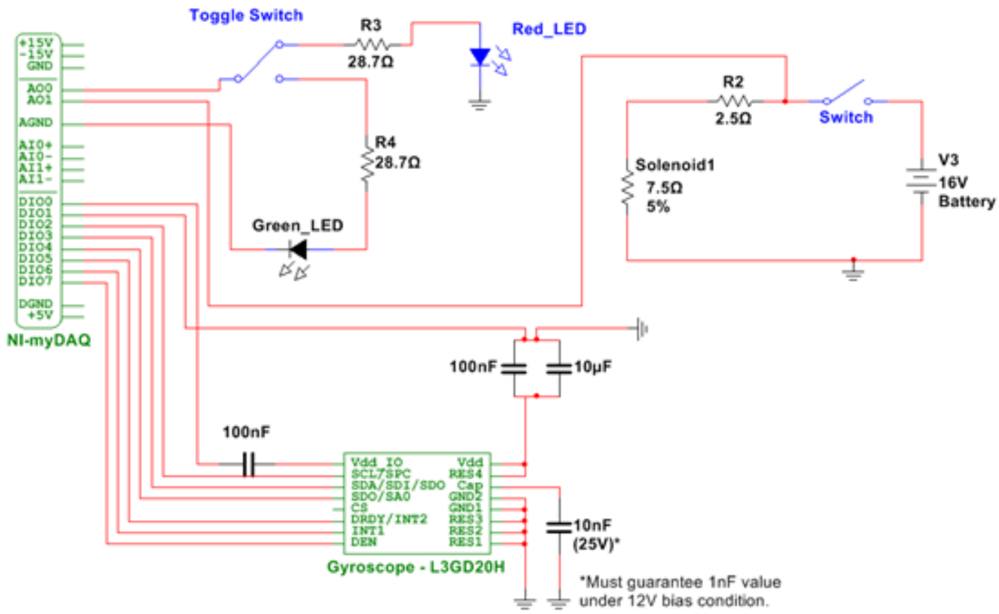


Figure 14. Electrical Schematic

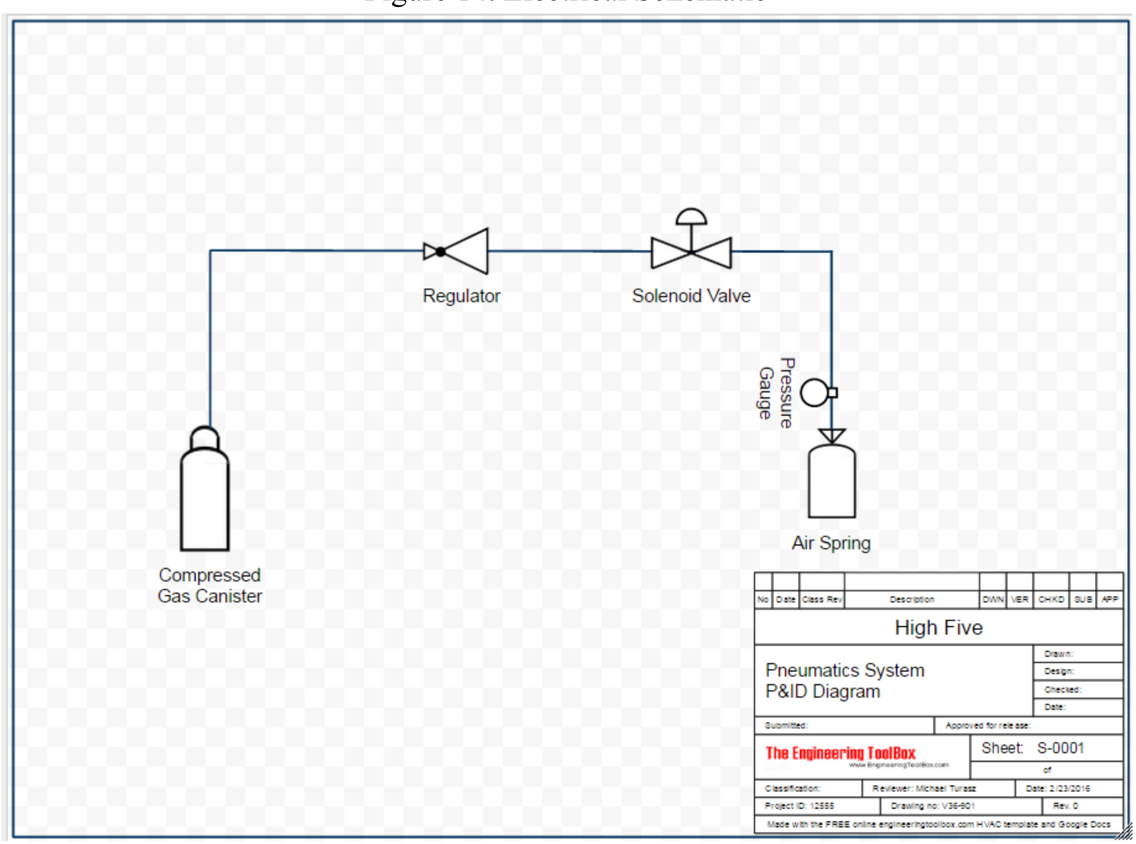


Figure 15. Pneumatics Configuration

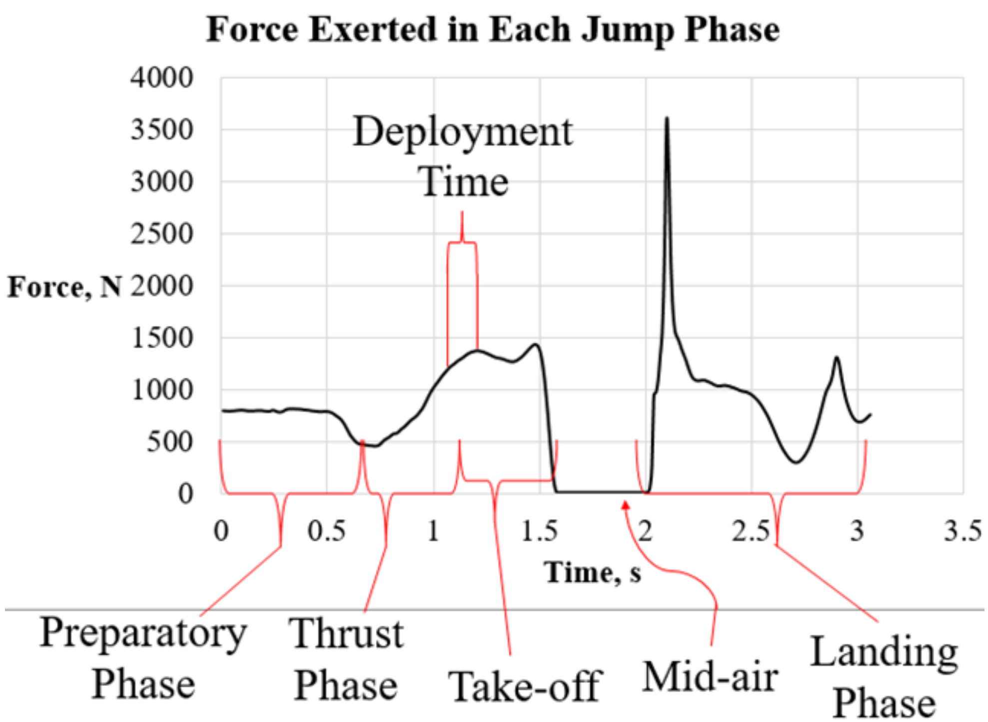


Figure 16. Force Exertion at Each Jump Phase

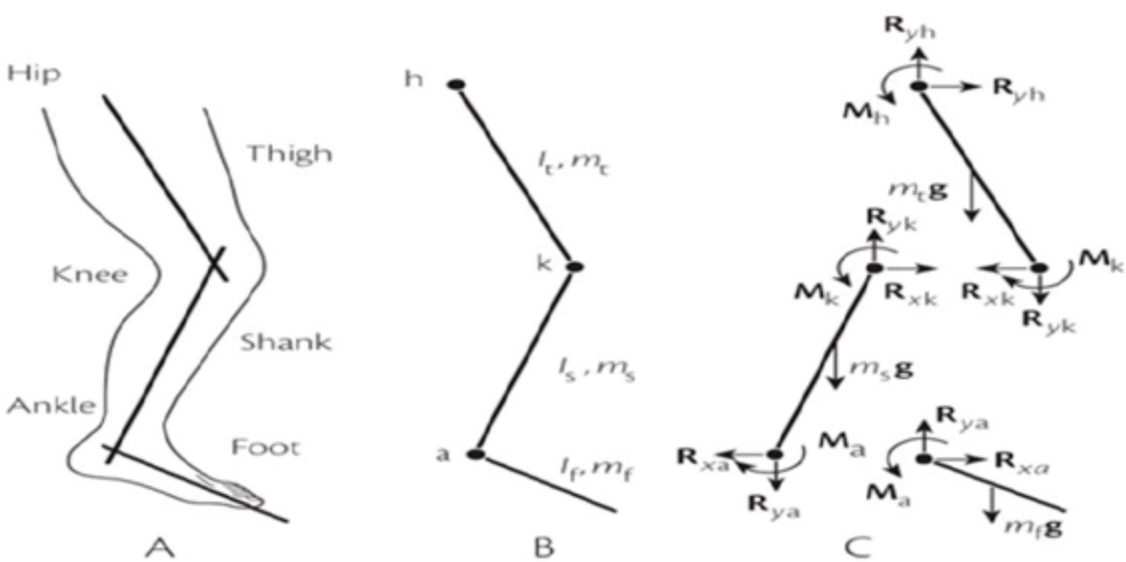


Figure 17. Free Body Diagram (C) of the lower limb based on anatomical model (A) of lower limb. [1]

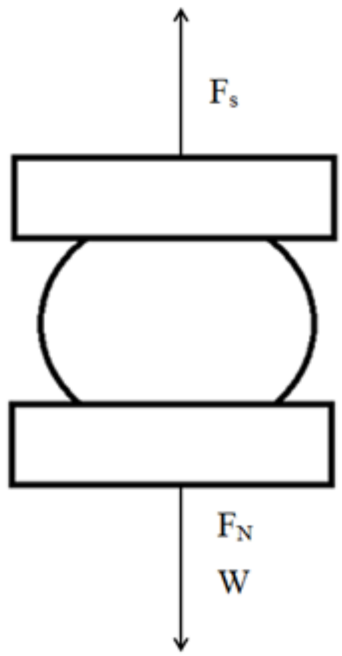


Figure 18. Free Body Diagram of Airbag System

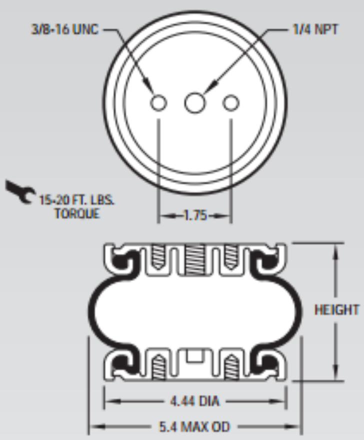

Figure 19. CG of human body [5]

AIRSTROKE ACTUATORS **AIRMOUNT** ISOLATORS **Firestone** **16-ST**

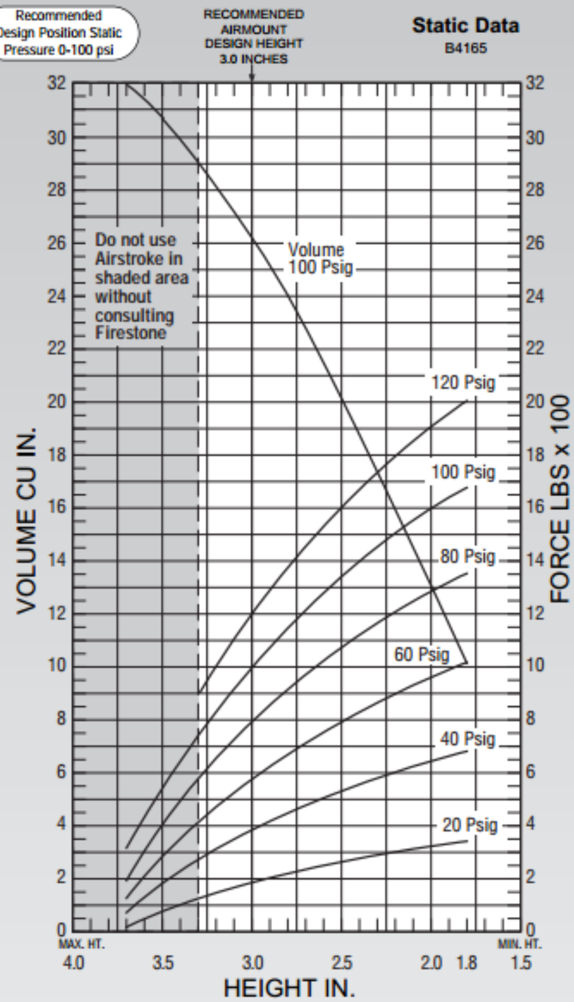
Description		Assembly Order No.
Style 16-ST Two Ply Bellows	Blind nuts, 1/4 NPT	WO2-358-5000
	Stainless steel plates	WO2-358-5002

Assembly weight .... 1.25 lbs.

Force to collapse to minimum height (@ 0 PSIG)..... 8.0 lbs.



NOTE: The bellows extends beyond the bead plates at minimum height.



See page 12 for instructions on how to use chart.

Dynamic Characteristics at 3.0 in. Design Height (Required for Airmount isolator design only)

Volume @ 100 PSIG = 26.2 in³			Natural Frequency	
Gage Pressure (PSIG)	Load (lbs.)	Spring Rate (lbs./in.)	CPM	HZ
40	400	704	249	4.2
60	600	1,003	243	4.1
80	800	1,303	240	4.0
100	1,000	1,602	238	4.0

Force Table (Use for Airstroke™ actuator design)

Assembly Height (in.)	Volume @ 100 PSIG (in³)	Pounds Force @20 PSIG	@40 PSIG	@60 PSIG	@80 PSIG	@100 PSIG
3.3	29.0	130	270	410	590	780
3.0	26.2	200	400	600	800	1,000
2.5	20.0	270	530	800	1,070	1,330
2.0	12.5	320	640	960	1,280	1,600
1.8	10.0	340	670	1,010	1,350	1,680

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Figure 20. Air Spring

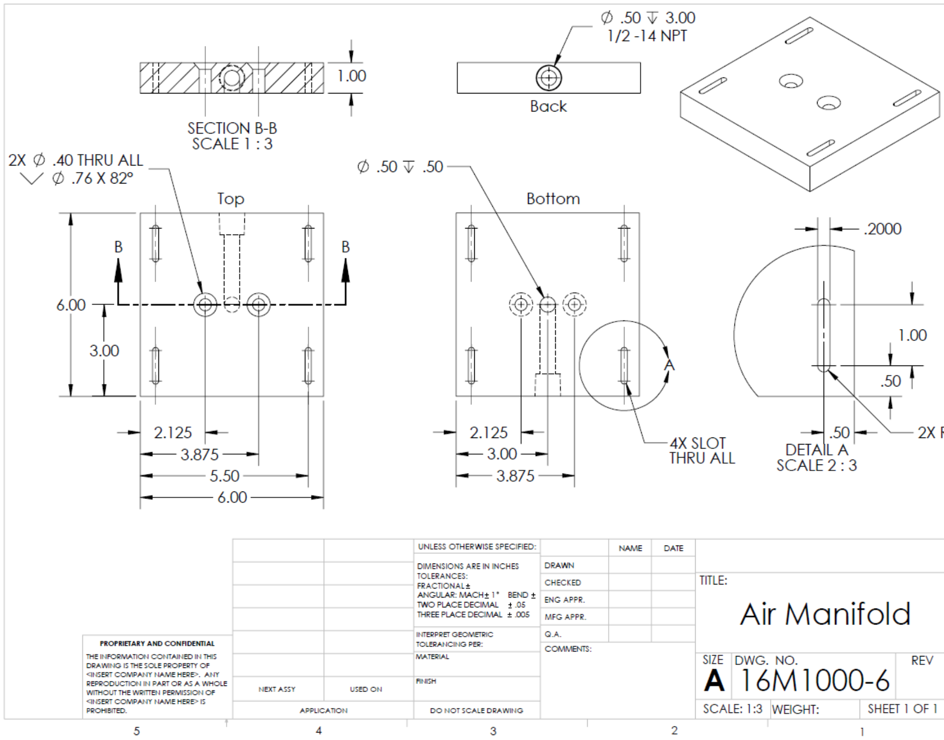

Figure 21. Air Manifold

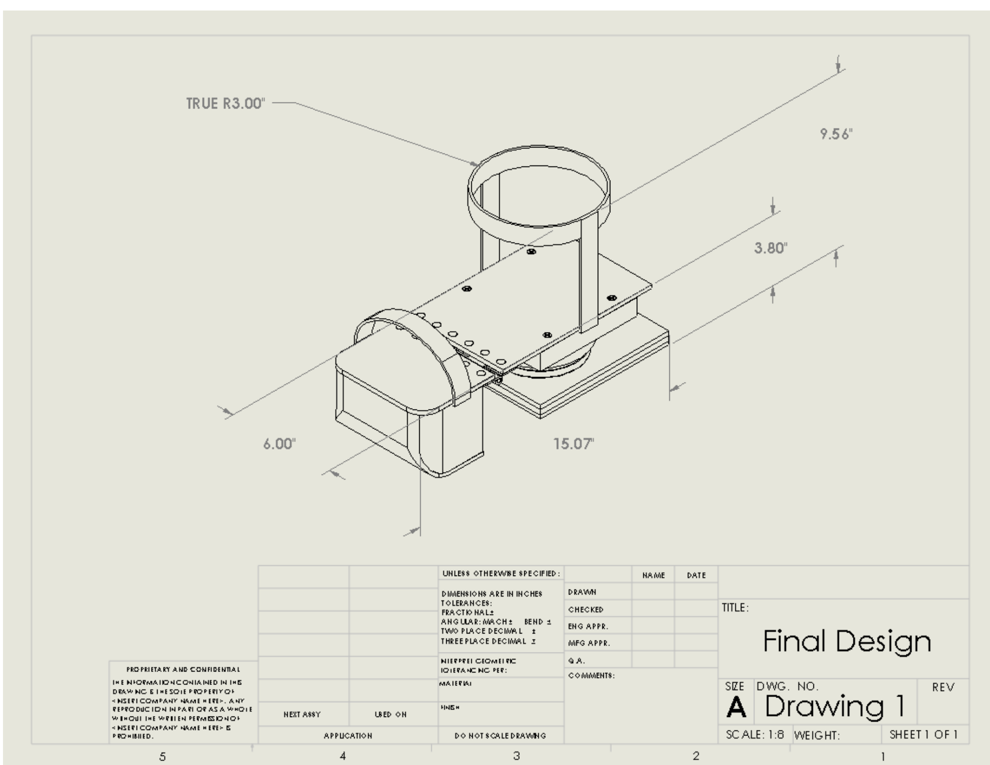

Figure 22. Mechanical Assembly

Figure 23. Mechanical Prototype

Figure 24. Air Manifolds

Figure 25. Cutting Process

Figure 26. Bonding Process

Figure 27. Sanding Process

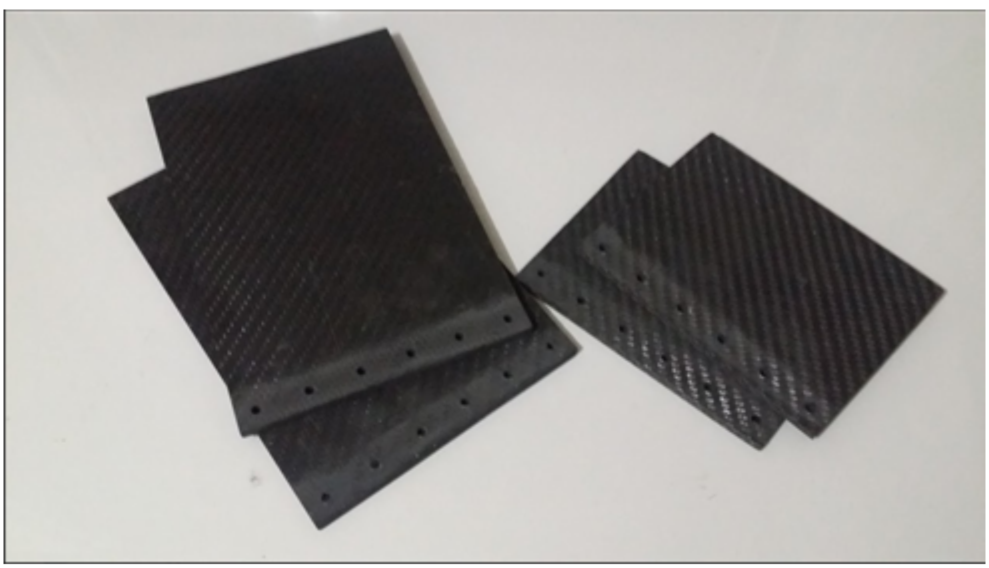

Figure 28. Upper Plates

Figure 29. Riveting Assembly

Figure 30. Riveted Assembly

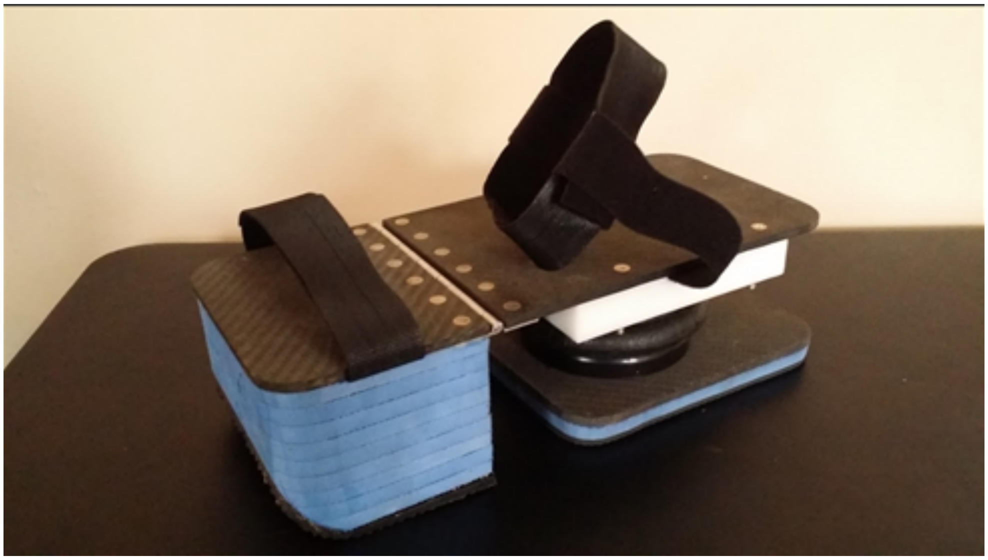

Figure 30. Final System Build

Hourly Labor Rates

Labor Category	Hourly Rate	Comment
Senior Project Manager	$375	Your instructor
Senior Engineer	$300	Project faculty advisor including customer advisor
Engineer	$200	Individual students
Technician	$150	Your labor charge when assembling and making parts for your project
Machine Shop	$100	Paul's cost or outside fabricator cost or your labor cost for making parts
Secretary	$90	Labor cost when typing and preparing reports
Laborer	$75	General utility chasing parts and clean-up

Material Burden Fee

Parts Category	Burden	Comment
Any purchased item	10% of estimated cost	Labor selecting item bill separately

Figure 31. Hourly Labor Rates

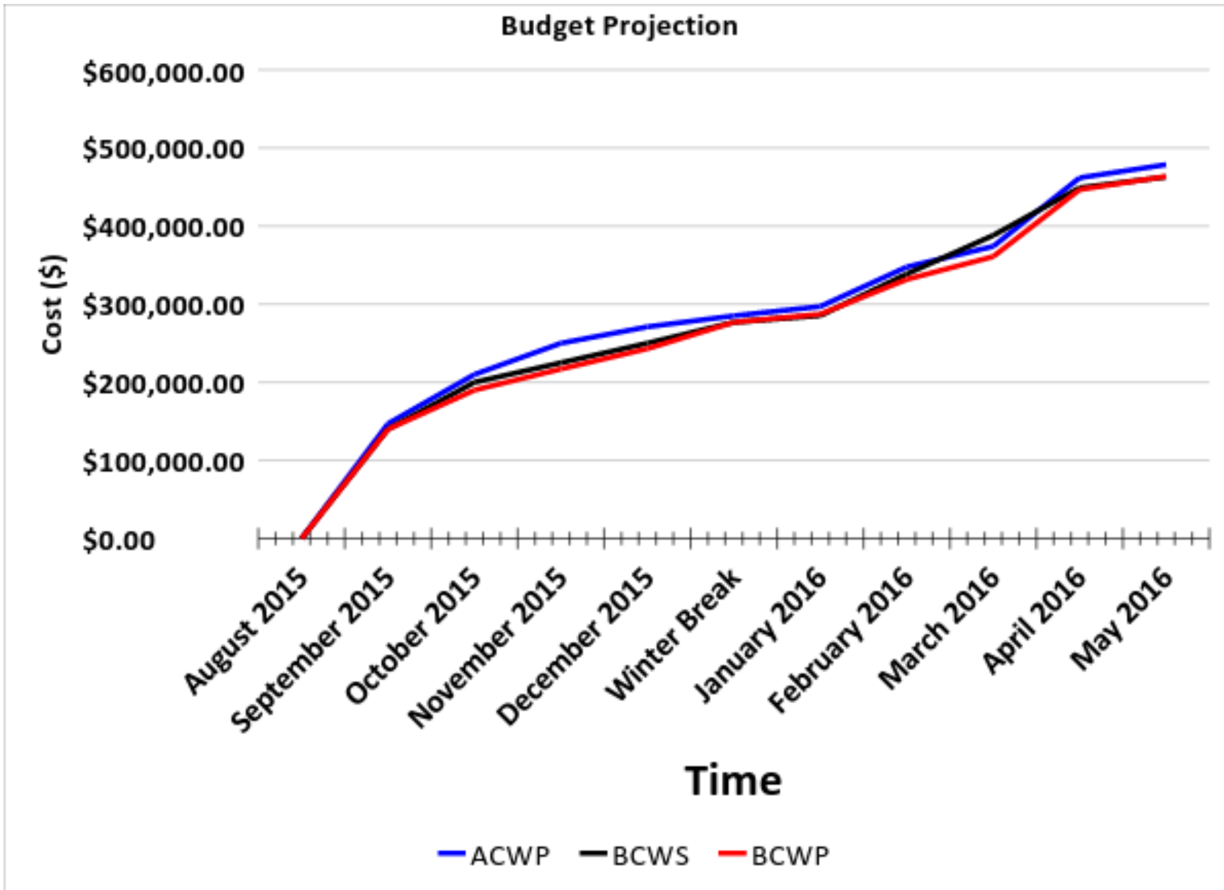

Figure 32. Budget Projection

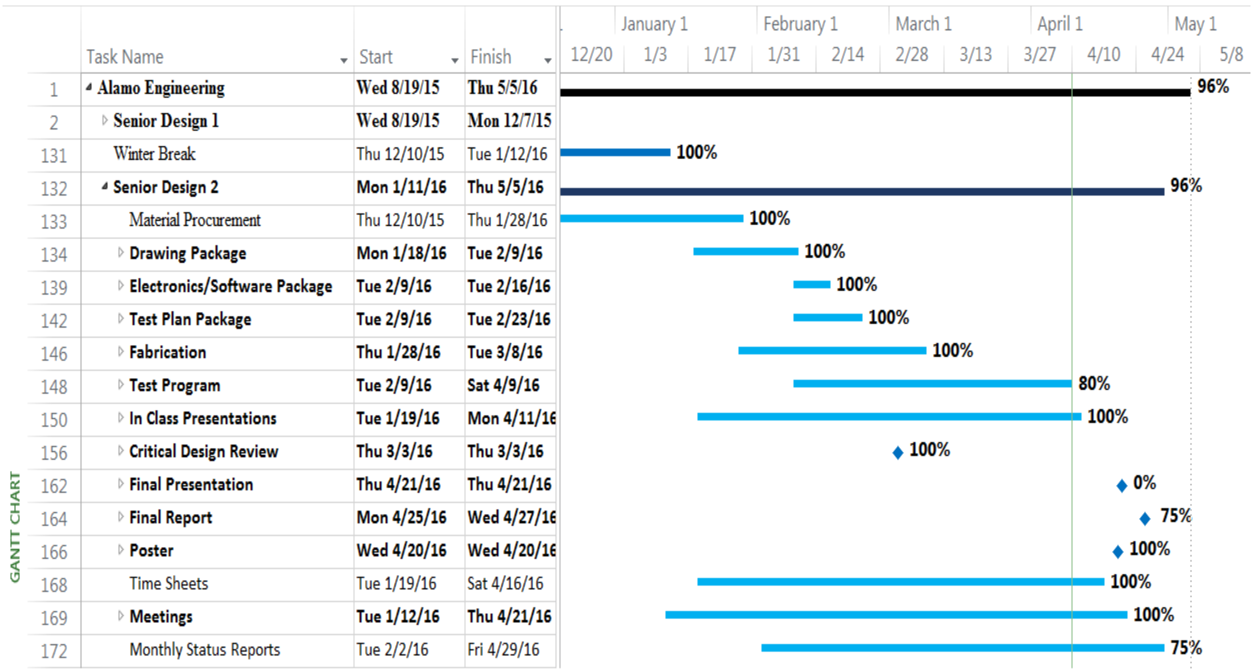

Figure 33. Schedule

11.2 List of Tables

Table 1. Force Table from Firestone Airstroke Actuator Data Sheet

Assembly Height (in.)	Volume @100 PSIG (in^3)	Pounds Force				
		@20 PSIG	@40 PSIG	@60 PSIG	@80 PSIG	@100 PSIG
3.3	29	130	270	410	590	780
3	26.2	200	400	600	800	1,000
2.5	20	270	530	800	1,070	1,330
2	12.5	320	640	960	1,280	1,600
1.8	10	340	670	1,010	1,350	1,680

Table 2. Mechanical Parts List

16M1000-100											
	Quantity			Part Numbe	Nomenclature	Material Description	Material Specification/ Part Number	Manufacturer/Supplier	U/M	Drawing Sheet	Notes
1				-1	Foot Plate, Fwd	Laminate, Carbon Fiber	409-624	Rockwest Composite	6in x 4.5in x.24i	4	
1				-2	Foot Plate, Aft	Laminate, Carbon Fiber	409-624	Rockwest Composite	9.25in x 6in x .24	5	
1				-3	Base Plate, Aft	Laminate, Carbon Fiber	409-624	Rockwest Composite	6in x 8in x .24in	6	
1				-4	Hinge	304 Stainless Piano	1582A73	McMaster Carr	12 in	7	
1				-5	Bag, Pneumatic		W02-358-5000	Firestone Industrial Produ	1 ea	8	
1				-6	Manifold, Air	High Density Polyethylene			6in x 6in x 1in	9	
1				-7	Midsole, Fwd	Ethylene-vinyl Acetate	2lbs/cu ft		6in x 4.5in x 3.6i	10	
1				-8	Midsole, Aft	Ethylene-vinyl Acetate	2lbs/cu ft		6in x 4.5in x .3in	11	
1				-9	Sole, Fwd	Rubber	9709	Soletech	6in x 5.75in x .19	12	
1				-10	Sole, Aft	Rubber			6in x 4.5in x .19i	13	
1				-11	Seal, Air	Rubber, Neoprene	50A Durometer		6x6	14	
12				-12	Rivet	MS20426AD-6-x			12 ea	15	
4				-13	Screw	NAS517-3-x			4 ea	16	
4				-14	Nut	MS21043-3			4 ea	17	
2				-15	Bolt	Medium-Strength Steel	92865A624	McMaster-Carr	2 ea	18	
2				-16	Screw	Machine Screw	91771A630		2 ea	19	
1				-17	Fitting, Air	Push-to-Connect, 1/2 NF	5779K122	McMaster-Carr	1 ea	20	
1				-18	Strap, Fwd	Hook and Loop	91100	Velcro	18 in	21	
1				-19	Strap, Aft	Hook and Loop	91100	Velcro	18 in	22	
1				-20	Strap, Support	Hook and Loop	91100	Velcro	18 in	23	

Table 3. Pneumatic Parts List

16P2000-100											
	Quantity			Part Numbe	Nomenclature	Material Description	Material Specification/ Part Number	Manufacturer/Supplier	U/M	Drawing Sheet	Notes
1				-1	Compressor	13 gallon, ASME tank		Campbell Hausfeld	1 ea	26	
1				-2	Regulator	Inert Gas, Cylinder	CGA-580	Victor	1 ea	27	
1				-3	Fitting 1, Regulat	3/8 NPTF, Brass	50635K439	McMaster-Carr	1 ea	28	
1				-4	Fitting 2, Regulat	3/8 NPT	5779K121	McMaster-Carr	1 ea	29	
1				-5	Tubing	DOT 1/2 inch		SMC	4 ft	30	
1				-6	Holder	8 AA Cell Battery	140-978	Parts Express	1 EA	31	
2				-7	Fitting	3/8 NPT	5779K121	McMaster-Carr	2 ea	32	
1				-8	Solenoid	1/2 inch, 3 way	3V410	WIC Valve	1 ea	33	
3				-9	Tubing	DOT 1/2 inch		SMC	5 ft	34	
1				-10	Fitting, Wye	Glass Filled Nylon	5779K46	McMaster-Carr	1 ea	35	
2				-11	Screw	Self tapping		McMaster-Carr	2 ea	36	

Table 4. Electrical Parts List

16E3000-100											
	Quantity			Part Numbe	Nomenclature	Material Description	Material Specification/ Part	Manufacturer/Supplier	U/M	Sheet	Notes
1				-1	Switch, Pendant		6944K62	McMaster-Carr	1 ea	39	
1				-2	Wire, 14 Gauge	Strand Wire	8054T17	McMaster-Carr	25 ft	40	
1				-3	ECU, myRio		NI myRIO-1900	National Instruments	1 ea	43	
1				-4	Wire, Activation	Stand Wire, 14 Gauge	8054T17	McMaster-Carr	25 ft	41	
1				-5	Gyroscope	Three axis	L3GD20H	ST Life	1 ea	42	

Table 5. System Performance Test

Trials	Natural Jump Height (in)	Expected Augmented Jump Height (in)	Actual Augmented Jump Height (in)	Percent Error (%)
1	6.5	11.5	11.2	2.6
2	6.8	11.8	10.5	11.0
3	5.9	10.9	11.6	6.4
4	6.2	11.2	12.9	15.2
5	5.8	10.8	10.9	0.9
Average	6.24	11.24	11.42	1.6

Table 6. Pressure Test

Trial	Expected Pressure (psig)	Actual Pressure (psig)	Percent Error
1	53	52.0	1.9
2	53	52.2	1.5
3	53	52.1	1.7

Table 7. Control System Test

Trials	Expected Time (ms)	Actual Time (ms)
1	38.5	33.3
2	38.5	34.5
3	38.5	33.4
4	38.5	33.3
5	38.5	34.7

Table 8. Straps Test

Test Area	Pass/Fail
Straps	Pass

Table 9. NDI Failure Conditions

Failure Conditions	Pass/Fail
Physical Deformations (e.g. Cracks, Rust, Chipping, etc.)	Pass
Improper Assembly (e.g. Loose Fittings)	Pass
Foreign Objects (e.g. Debris in Tubing)	Pass
Hollow Sounds from Delaminated Carbon Fiber	Pass

Table 10. Warm Up Routine

Exercise	Sets and Repetitions*
Leg Swings	3x10
Butt-kicks	3x10 (10 for each leg)
Pike Stretch	20 seconds on each side
Hacky-sack stretch	3x10
Toy soldier stretch	3x10
Walking lunges	3x10

*Sets times Repetitions e.g. 3x10 is three sets of ten repetitions.

Table 11. System Weight

Target Weight	Actual Weight
35 lbs	5.4 lbs

Table 12. Operator Conditions Test

Condition	Met	Failed to Meet
Shoe Size: 10-13	✓	
Weight: 175-220 lbs	✓	
Health Conditions*	✓	

Table 13. Financial Values

BCWS	BCWP	ACWP	Total	SPI	CPI
$462,867.61	$463,536.43	$478,622.61	$462,867.61	1.00	0.97

11.3 List of Equations

11.3.1 Newton's 2nd Law of Motion

- = Sum of forces
- = mass
- = acceleration

11.3.2 Energy

- = Energy
- = Force
-

11.4 Functional Requirements

11.4.1 Safety

The system must be safe to the user, causing no harm of any kind. The most important areas of concern in regards to potential damage to the human body are bone fracture or failure and tendon rupture. The design will have as a priority to perform with no injury to the user.

11.4.2 Jump Height

This system is designed to increase a user's stationary vertical jump by a minimum of 5 inches. This will be accomplished by augmenting the muscle energy that a user invests into a jump.

11.4.3 Weight Restriction

The user allowed to operate the system must fall within a weight range of 175 lbs to 220 lbs. The system will be designed to be capable of lifting within that range: any person with a lower weight runs the risk of being overshot while anyone of higher weight will not experience the minimum jump height increase.

11.4.4 Shoe Size Restriction

The system will be designed to accommodate men's shoe size 10 to 13. The user must have shoe sizes within this restriction in order to use this system.

11.4.5 Propulsion Surface

The apparatus must be used on a flat and even surface to ensure that there is minimal energy loss and that the energy given by the system will be effectively utilized in the vertical jump.

11.4.6 Required Warmup

Before using the system, the user must undergo a series of exercises (Table 1) that comprises a warmup routine to avoid injuries. The warmup is also required to guarantee that the user will be performing at the highest physical potential.

11.4.7 Start off Position

The operator of the system will be standing in an upright, squat-like position before propelling upwards. The swinging of the arms during the act of jumping shall be mandatory.

11.5 Engineering Specifications

11.5.1 Materials and Workmanship

11.5.1.1 Workmanship

11.5.1.1.1 Metals

The metallic materials used in the system shall be of non-corrosive material. Corrosive metallic material shall be protected with an exterior finish for corrosion control purposes. Protective exterior finish shall be applied at the faying surfaces of two metals.

11.5.1.1.2 Non-metals

Non-metallic materials which may cause dissimilar metal corrosion shall be treated with an exterior finish at the faying surfaces.

11.5.1.1.3 Corrosion Control Performance

Exposed metallic materials shall be protected with an exterior protective finish if the material has been allocated without a protective finish.

11.5.2 Design and Operating Requirements

11.5.2.1 Electrical System

An Electronic Control Unit will be required. This control unit will be used to control some of the subsystems of the project, particularly where precise timing is required.

11.5.2.2 Measurements and Instrumentation

Commercially available rulers and measuring devices are acceptable for the measuring process. No calibration is required for the measurement devices measuring the vertical heights. The sensors shall be capable of measuring within the limits of the jump cycles.

11.5.2.3 Local User Interface

The User Interface shall allow effective operation and control of the system. The user interface shall be able to communicate with the sensors gathering data from the user.

11.5.2.4 Communication

Communication shall be transmitted via electrical wiring and Universal Serial Bus (USB) connectors.

11.5.2.5 Weight

The weight of the system will be accounted for by two components: tethered weight and untethered weight. The system weight that is considered detrimental to the process of jumping is the weight of equipment attached to the user and is categorized as untethered weight. This attached equipment shall not exceed 35 lbs.

11.5.3 Transportability

The system shall be capable of being transported in a van. The system is to be securely restrained to prevent heavy vibrations. The system is to be transported between 32° F to 135° F. The unit shall be capable of being transported by a single individual with no aid of machinery.

11.5.4 Ownership and Support Requirements

11.5.4.1 Safety

The selected solution shall have as a priority the safety of the user. Weight, shoe size and overall health requirements must be met for a person to qualify as a user as explained by subsequent sections of this document (See Section 11.5.4.5.1). The user will undergo warm up procedures that will prepare muscles and tendons for jumps to diminish the risk of injury.

11.5.4.2 Human Factor Engineering (HFE)

Scopes of Human Factor Engineering are addressed throughout this document. The characteristics, capabilities, expectations and limitations of the people who will operate the unit are addressed by weight and shoe size restrictions, warm up exercises and health requirements (See Section 11.5.4.5.1). The equipment and technology used, and the elements that the user needs to interact with are addressed in other sections.

11.5.4.3 Reliability

The system shall remain serviceable and perform as required to complete the testing phase.

11.5.4.4 Maintainability

The system will not require major repairs from the manufacturers of the components.

11.5.4.5 Servicing, Operation, Maintenance

The compressed gas container shall be serviced by an authorized service station when required. The batteries are to be replaced by the users as required. The system is to be operated with a minimum of two people.

11.5.4.5.1 Operator

11.5.4.5.1.1 Weight

The user allowed to operate the system must fall within a weight range of 175 lbs to 220 lbs. The system will be designed to be capable of lifting within that range: any person with a lower weight runs the risk of being overshot while anyone of higher weight will not experience the minimum jump height increase.

11.5.4.5.1.2 Shoe Size

The system is to be designed to accommodate men's US shoe size 10 to 13. The user must have shoe sizes within this range in order to use the system.

11.5.4.5.1.3 Overall Health

The user shall not have a history of strokes, broken bones, muscle problems, joint replacements, or high blood pressure.

11.5.4.5.2 Operator Test

User must meet the requirements specified in Section 11.5.4.5.1. The operator must show proficiency in the usage of the system.

11.5.4.5.3 Test Points

Test points will be at maximum muscle performance, which will be ensured by the warm up exercises explained further in Section 11.5.7.2. The user will be weighed. The user must answer a questionnaire on their health history. The operator shall also be proficient in the operation and emergency operations of the system in case of a system malfunction.

11.5.5 Environmental Requirements

11.5.5.1 Operational Temperature

The equipment shall be operational in indoor controlled temperatures ranging from 55° F to 100° F.

11.5.5.2 Temperature Shock

The test shall perform in a constant temperature condition. The change in temperature could affect the overall performance of the system.

11.5.5.3 Humidity

The system shall not be operated in an environment exceeding 90% humidity.

11.5.5.4 Rain

The system shall not be operated in rain.

11.5.5.5 Altitude

Performance altitude shall range from 900 ft to 1100 ft above sea level.

11.5.5.6 Propulsion Surface

The system will be operational on a level, dry surface.

11.5.5.6 Electromagnetic Interference

The operations shall not be performed near large power lines to prevent interference with the ECU.

11.5.6 Identification, Marking and Information

Hazardous identification markings shall comply with the Occupational Safety and Health

Administration and local regulatory agencies.

11.5.7 Manuals and Special Instructions

11.5.7.1 Manual

A manual will be composed to instruct users on restrictions, risks, operating instructions, and overall maintenance of the unit.

11.5.7.2 Warm up

Table 7 presents the warm up a user must perform before utilizing the apparatus. The warm up preparation will minimize injury risks while improving jumping performance.

11.5.7.3 Starting Position

The operator of the system will be standing in an upright, squat-like position before propelling upwards.

References

[1] Pons, José L. *Wearable Robots: Biomechatronic Exoskeletons*. Hoboken, NJ: Wiley, 2008. Print.

[2] Kelso, Tom. "Two-Jointed Muscles of the Lower Body." *Breaking Muscle*. N.p., 2015. Web. 07 Sept. 2015.

[3] "Newton's Second Law." *The Physics Classroom*. N.p., 2015. Web. 27 Oct. 2015.

[4] "Runner Unleashed." *WordPress.com*. N.p., 29 July 2014. Web. 19 Sept. 2015.

[5] "Woodhull, A.M., K. Maltrud, and B.L. Mello. "Alignment of the Human Body in Standing." *Springer Link*. Pringer International Publishing AG, May 1985. Web. 27 Oct. 2015.