ME 450 W15 FINAL REPORT

Passive Dynamic Walker

Section 4 Team 15

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1. EXECUTIVE SUMMARY

Our team has been tasked with designing, testing and building a passive dynamic walker, which will be used in outreach activities. In an outreach event, the demonstration of our walker mechanism would engage audiences in dynamics and mechanical design, inspiring students to pursue STEM careers. It has been stipulated that our design has to be suitable for low cost, do-it-yourself production so as to facilitate the ease of replicability in the context of an educational institute or a user's home.

The project has thus been concluded. As such, we have been able to evaluate our design's ability to meet our user requirements. First, we have successfully created a passive dynamic walker capable of locomoting down a smooth incline. It has, with great reliability, traversed down a slope 48 inches in length. Secondly, the passive dynamic walker can be manufactured with rudimentary DIY methods. Thirdly, we note that the cost of procuring the parts (per unit walker) is approximately $75. Lastly, we observe that our final design is indeed suitable for outreach. This is because most members of the public were largely able to successfully operate the walker during the Design Expo within their first attempt.

The most crucial strength of our design is the large basin of attraction that our walker possesses. This means that the walker is not overly sensitive to the initial conditions provided by the human user, thereby enabling ease of operation. In addition, our walker is able to traverse over a range of slope sizes, from an 8% gradient to a 12% gradient. We have also designed our walker to have detachable feet, to allow the user to adapt the walker to best perform on any available slope.

Cognizant of the weaknesses of our design, we note that our walker costs approximately 87.5% more than the intended cost. We are able to attribute this to the proportionately high cost of the roller bearings. We are also aware of the manufacturing challenges a DIY manufacturer will face during the assembly of the inner leg where any failure to align the inner leg structure would result in the constriction in motion of the valve and a severe degradation in the walker's performance.

To aid in the ease of manufacturability of the inner leg, we recommend the addition of snap fit joints onto the inner leg. This can be achieved by making minor modifications to our current CAD designs. More importantly, a considerable effort is required to identify the necessary dimensions required for a snap fit to be feasible. This is challenging, given the variance in the laser cut part dimensions due to inaccuracies in the manufacturing process.

Another manufacturability improvement is the integration of ballast into walker design. This would thus negate the need for additional ballast masses, which are current adhered by means of duct tape.

To further reduce the cost of our prototype**,** we recommend that further efforts be undertaken to piece together a low cost, yet fully functional roller bearing assembly. In addition, we also recommend the exploration of the use of a thinner sheet of acrylic, or even the use of less expensive materials. It is likely that a thinner sheet of acrylic would still be sufficiently structurally robust to support passive dynamic walker.

2. PROBLEM DESCRIPTION

Passive dynamic walkers are clever mechanisms that can traverse down a shallow incline, driven only by gravity and the dynamics of their mechanical structure. In this project, we will attempt to design a walker that can walk on smooth surface at a shallow incline without the use of elevated tiles. Our design should be purely mechanical, without motors or sensors.

The chief goal of the project is to design a walker that is suitable for STEM (Science, Technology, Engineering, and Math) outreach purposes. This device must show the fundamentals of Newton's laws and exhibit a considerable degree of anthropomorphism to keep audiences engaged. Another aim of this project is to develop a design to allow the general public to build and assemble their own passive dynamic walkers. This requires a low-cost design that enables the construction of a replica walker with low barriers to entry in terms of cost and user assembly.

3. BACKGROUND

The concept of a legged mechanism that walks down an incline using only gravity has been in existence for some time- the earliest patents date back to the late 1800s and early 1900s for simple toys that could traverse down a shallow incline. In recent times, there is growing interest in developing highly-mobile robotic system for use in high-risk scenarios. This involves the implementation of legged locomotion. However, early legged systems are characteristically energy inefficient, slow and are largely susceptible to external perturbations. As such, through the study of passive dynamic walking, roboticists hope to harness the natural walking gait observed in legged organisms.

McMahon [3] ,while studying the bipedal locomotion of human beings, theorized that the swinging leg exhibited a dynamic motion that resembled that of a jointed pendulum. In doing so he developed several walking models, including one which sufficiently displayed the human walking motion despite not being actuated by muscle torques.

McGeer [2] demonstrated how the double pendulum mechanism with correct limitations produces the necessary conditions for each subsequent step. He constricted the movements to two dimensions and cast the anthropomorphic walking motion as a multi-phase trajectory problem that requires the implementation of Newton's method to establish a suitable periodic initial condition. In addition, he implemented a knee joint onto his walker device; using a set of appropriate initial conditions, he was able to demonstrate movement that appeared more 'natural' and had numerous advantages over straight-legged walkers, including being more efficient, reliable and recovering more rapidly from perturbations [4]. Ruina and his team [5] have expanded on McGeer's work, creating several 2D kneed walking simulations and many different functional passive walkers that are able to traverse down a smooth incline. Ruina also created a motorized walker that walks on flat ground but relies on the passive walker dynamics for its gaits.

The field of passive dynamic walking is one that has been extensively studied. In exploring the walking gaits of inanimate devices, much work has been taken to improve the stability and efficiency of the passive dynamic walkers.

3.1 Benchmarking

Throughout the extensive history of passive dynamic walking devices, large changes in the aesthetics and efficiencies of these devices have developed through research. Beginning with toys from the 19th and 20th centuries, passive dynamic walkers took on numerous crude shapes. Many resemble animals or humans and rely on a rocking motion to allow for stiff, jointless swinging legs to be able to complete their motion. Both rocking applications heavily rely on weight distribution to allow for the rocking motion to be completed.

Specifically, the example from Kraus and Villemejane's patents, while not completely passive applications of the rocking motion, are representative of the type of motion seen in passive walkers. Kraus' patent proposed the design of a wind-up toy soldier in 1932 [8]. The soldier can walk across the ground, but relies on the shifting of an internal mass to create a lateral rocking motion of his body to allow for the swing leg to complete its motion [8]. Villemejane's design [9] adapted the moveable mass within the toy to shift from front-to-back, causing the toy to rock back and forth. This motion allows for this toy's swing leg to complete its motion and permits the toy to crudely walk forward.

As research interest in the subject of passive dynamic walkers began to increase, advancements in the efficiency and stability of these devices could also be seen. Single-joint walkers conventionally rely on a rocking motion to prevent toe-scuffing (i.e. 'tipping' of the mechanism). double-joint walkers utilize the retraction of a knee joint to generate ground clearance. In addition, by designing the walker's foot such that the foot's center of curvature is placed well in front of the knee, the stance leg will remain locked. Kneed walkers have been extensively studied, as they exhibit a more natural gait that was appealing for further research in biological kinematics. Such research has been conducted at numerous institutions such as Cornell University by field-renown Andy Ruina [5] and University of Manitoba by Dr. Christine Wu [7].

Additionally, as the field of passive dynamic walking has expanded to rehabilitation applications in the medical field, the popularity and scope of research on kneed walkers has seen an increase in focus. This can clearly be seen in new patents that have been proposed in recent years, such as that of Akihito and Katsuya's patent for a walking machine. This patent proposes a kneed walker which is powered by the application of a force by a single person [10]. The device serves as a conventional walker in the sense that it is a mobility aid [10]. The benefit of the walker in this patent is that it need not be lifted off of the ground in order for the operator to move around. This patent's walker moves with the operator, using very little force to operate. Also serving as a type of wheelbarrow, the device proposed in this patent is versatile and extremely functional, especially in rehabilitation purposes for those who struggle to walk [10].

While kneed walkers have been the subject of numerous research efforts, we note the existence of significant challenges that would prevent the implementation of the hereby mentioned walkers in the context of outreach. The swinging motion of a kneed walker is akin to that of a double pendulum, as depicted by Figure 2.1. This type of mechanism requires a very precise set of initial conditions. Given the open loop dynamics of a passive walker, it is highly likely that slight deviation from the initial conditions would result in the walker falling over. With our focus on replicability as outlined by the user requirements in section 4.1, a kneed mechanism will be difficult to replicate due to our time constraints.

Fig 2.1 The above walker (Derek Coop, U. of Manitoba [7]) resembles a double pendulum. Given appropriate initial conditions, it will exhibit dynamic behavior that resembles human walking.

The single-joint walker, as shown in Fig 2.2 relies on the periodic motion of a single pendulum. single-joint walkers have been used in many entertainment applications as seen in the patents mentioned in this paper, given its relative ease of use and construction.

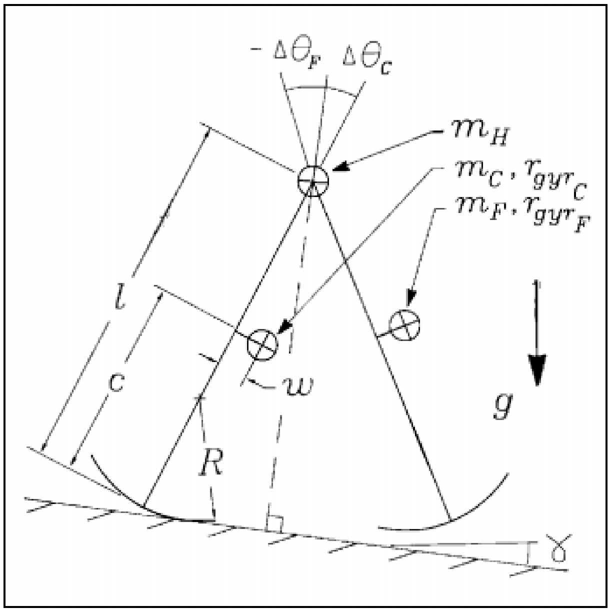


Fig 2.2 General arrangement of a 2D biped. It includes legs of arbitrary mass and inertia, semicircular feet, and a point mass at the hip (figure from Mcgeer, 1990 [2]).

As shown in Fig. 2.2, a single-joint walker will have two stiff legs and a jointed hip. Several mechanisms have been created to appropriately shorten and lengthen the lengths of the legs across each time period, in order to prevent the scuffing of the ‘feet’. We recognize that the development of the retraction/extension mechanism will be a primary focus of our engineering design.

To inspire and engage audiences, a device that incorporates a humanoid form or assimilates human gait is desired. Fig. 2.3 depicts a design by Delft U. of Technology [11] that demonstrates the use of such a humanoid form. The functionality remains unimpeded by the implementation of such aesthetics. This design is appealing as audiences can relate to such a mechanism and develop further interest in the subjects of STEM. This particular Delft walker works like the Mcgeer 2D walker but contains an anti-scuffing mechanism in the middle leg. This mechanism utilizes a spring to retract the hinged ankle, thereby emulating the raising of the whole leg, as visible in Figure 2.3.

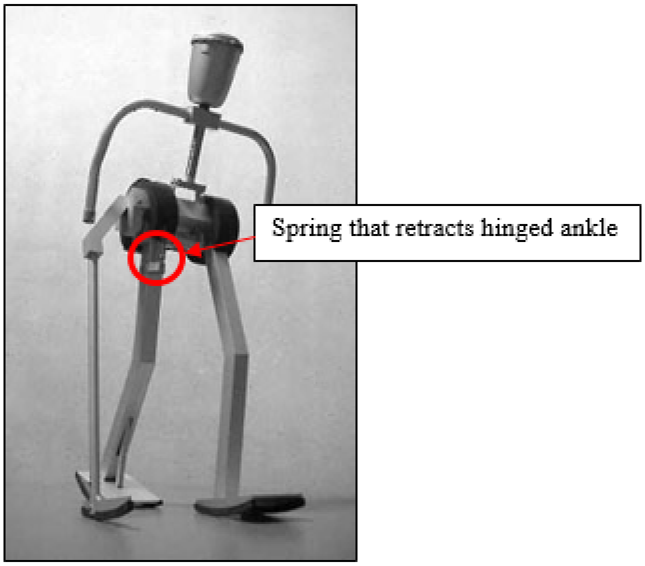


Fig 2.3: This is a fully passive walking robot, which can perform a stable walk down an incline without the need for motors or controls. It stands about 80 centimeters tall and weighs about 3.5 kilograms. [11]

Through the combination of simplistic a single-joint mechanism and a humanoid form, our passive dynamic walker will achieve functionality and inspire our audiences to develop their interests in STEM.

4. USER REQUIREMENTS & ENGINEERING SPECS

The identification of the user requirements to satisfy customer needs is crucial. The translation of user requirements to engineering specifications are fundamental steps in the design of the passive dynamic walker. In this section, we will discuss the user requirements and the resultant specifications that will guide the design process.

4.1. User Requirements

Through a meeting with our sponsors [1], Professor David Remy and Professor Art Kuo, we were able to identify a series of user requirements and elicit our sponsors’ motivation for the initiation of the project. Given that the University of Michigan is involved in several outreach efforts, our sponsors were interested in developing an anthropomorphic dynamic walker to stimulate the interests of community members of a varied age group. In addition, our sponsors wanted to allow the wider education community to be able to assemble their own passive dynamic walkers, to facilitate further scientific inquiry and engineering innovation. These requirements are listed as follows: passive mechanics, low barriers to entry, ability to traverse a smooth slope, suitability for DIY (Do-it-yourself) projects and suitability for outreach.

The manufacturing and assembly will have to be developed to maintain a low barrier of entry as well as allow anyone to replicate this device. With rapid prototyping becoming a mainstream process, it is favorable to develop a design with ease of assembly and manufacturing. Low cost and simple methods of manufacturing such as milling and lathing are also viable options for us to develop physical kits that can be manufactured in large quantities and shipped to end-users.

4.2. Engineering Specifications

With the collection of the user requirements, we were able to generate a series of engineering specifications. The corresponding engineering specifications are presented in Table 1:

Table 4.1: Engineering Specifications and the corresponding user requirements

User Requirements	Engineering Specification	
Passive mechanics	Powered entirely by gravity	
Able to traverse down a flat slope	Periodic retraction of swinging leg	
Suitable for DIY	Manufacturing / assembly parts < 2hrs	
	Assembly using rudimentary tools	
Low barriers to entry	Parts to be rapid prototyped / shipped as a kit	
	Total cost < $40	
Suitable for Outreach	Portability	Weight < 2kg
		Height < 0.5m
	Ease in operation; able to exhibit cyclic walking motion within < 3 attempts	

One key user requirement is for our walker to traverse down a smooth slope. The current walkers available to our sponsors require the use of elevated tiles to prevent the swinging leg from coming into contact with the ground. Logistical issues arise with the construction or transportation of a tiled surface. As such, our design is to allow the periodic retraction of the swinging leg such that an arbitrary smooth and inclined surface can be utilized.

To enable the general public to construct their own walkers, our design needs to facilitate the expedient construction of the walker. A two hour assembly time period was chosen given the inherent complexities of a dynamic walker. In addition, the walker should be constructed using rudimentary tools like an Allen key and wrenches. To lower the barrier to entry, our design will allow for 3D printing. By making the CAD files available online, we also enable end-users to modify our current design, and implement innovative engineering changes.

A crucial user requirement is our walker's suitability for outreach. Given that outreach activities do often occur outside of the confines of a laboratory, portability does become an important engineering requirement. The weight and dimensional specifications suggested allow for a balance between robustness in design and visibility for a member of the audience from afar. Recognizing that passive dynamic walkers are inherently sensitive systems that are difficult to operate, we aim to create a design that is sufficiently robust to allow the user to operate the walker within 3 starting attempts.

5. CONCEPT GENERATION

With the identification of our user requirements and the subsequent formulation of our engineering specifications, we then proceeded to generate a series of concepts. Concept generation was achieved by two means: functional decomposition and brainstorming.

5.1 Functional Decomposition

To facilitate the generation of concept designs, we completed a functional decomposition for the passive dynamic walker.

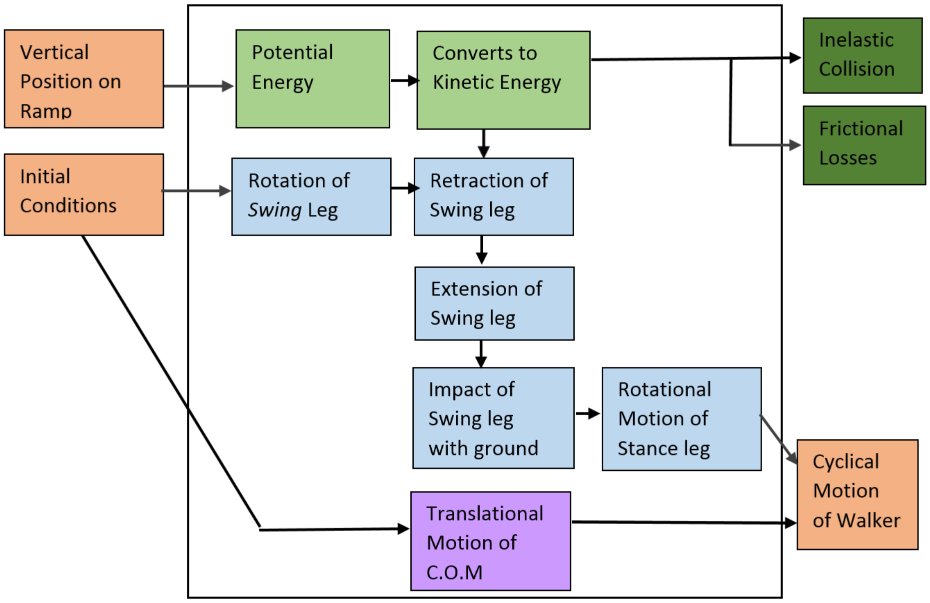


Figure 5.1: Functional Decomposition of a Passive Dynamic Walker, to facilitate in the generation of design concepts.

The central purpose of a passive dynamic walker is the sustenance of cyclical walking motion. After a series of initial conditions have been provided by the human user (e.g. forward translational velocity, rotation of swing leg), the passive dynamic walker will convert potential energy into forward motion. In doing so, the most critical component of this is the retraction of the swing leg. Failure to shorten the swing leg will result in a toe-scuffing condition that will impede any further walking motion.

5.2 Brainstorming Results

Using the elements of the functional decomposition, we conducted a brainstorming session where several concepts were generated. For purposes of brevity, only promising and feasible solutions will be discussed in this section. The full brainstorming result can be found in **Appendix B**.

5.2.1 Humanoid Aesthetics (Concept 1): Designs exist in which passive dynamic walkers take on a humanoid form. This feature is appealing, especially with outreach purposes in mind. A humanoid form will allow an audience to relate to the mechanism and potentially become engaged with the walker. A method to achieve this can be seen with the Museon Walker [11], as seen in Fig. 5.2, where a spring-like torso is achieved with a high stiffness spring. This serves the purpose of creating a countermass with the 'head' of the mechanism such that it improves the dynamics as observed through Museon's experimentation.

Fig 5.2: The humanoid aesthetics of the Museon walker serve as an inspiration to our design process as it had the potential to engage audiences through its human appearance [11].

5.2.2 Kneed Walkers (Concept 2): Kneed walkers, as shown in Fig. 5.3, have human-like anti-scuffing mechanisms that allow the stepping leg to be raised while the stance leg remains ground, allowing a successful gait to occur. The difficulty with these types of designs is caused by the level of required precision, which introduces sophistication and a higher difficulty of assembly. This, in turn, distances these concepts from the outreach goal.

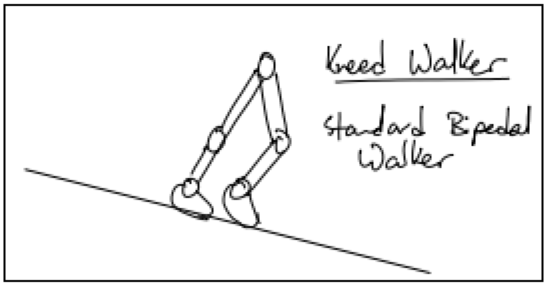


Figure 5.3: This concept relies on a double pendulum, which requires very stringent initial conditions and is very susceptible to perturbations.

5.2.3 Track/Laneway Mechanism (Concept 3): This concept shows a mechanism based of the Cornell Wooden Walker [13] that would allow for the retraction of the swinging leg. It relies on a small valve (shaded in red) that is connected to a torsional spring that keeps it in the position shown. As the outer legs move through the mechanism, they pass over the top of the valve, lifting themselves up and producing the clearance needed to prevent foot scuffing. Then, as the inner legs swing forward, the outer legs push on the bottom of the mechanism lifting up the inner, stepping legs.

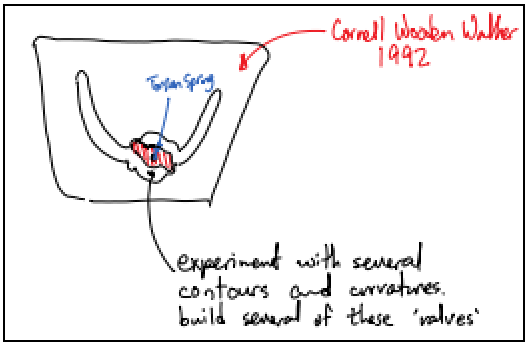


Figure 5.4: A pictorial representation of the Track/Laneway mechanism that allows for the retraction of the swing leg through the use of a spring-loaded valve.

5.2.4 Clicker Mechanism (Concept 4): This design refers to a mechanism that would simulate a common household pen clicker mechanism, which would store energy in the spring and release it upon impact.

6. CONCEPT SELECTION

With the generation of several design concepts, we proceeded to the concept selection phase of our design process. After discussing these concepts with our sponsors, some designs were deemed too unreliable and unable to inspire. These designs would not fulfil the requirements for do-it-yourself and outreach applications and hence, were eliminated. Following this elimination, a general design framework, which met all of our design requirements and was applicable to a do-it-yourself, outreach setting, was defined. We then used a Pugh chart to aid in the selection of a mechanism that would allow for the raising of the swinging leg.

6.1 Initial Selection Method

We began our concept selection process by first consulting with our sponsors. Given our sponsor's considerable expertise in field of passive dynamic walkers, they were able to help eliminate designs which lacked reliability and the ability to inspire. The research performed at the onset of the design process was also consulted further. By looking into this research and evaluating the recommendations made by our sponsors, our team was able to settle on a design framework into which a mechanism could be implemented.

This final design framework was centered on the raising of the swinging leg through the incorporation of a mechanism that would allow for it to complete its motion without the use of stepping pads. The design would also incorporate potentially interchangeable feet with bottoms of varied radii to permit the walker to descend varying slopes. In order to select the mechanism for raising the swinging legs in this design framework our team used an alternative design selection method which focused on selecting overarching design types rather than specific concepts.

6.2 Pugh Chart Selection Method

In order to facilitate the selection of a final mechanism design concept from those which we generated, we developed a Pugh chart to objectively compare concepts. This Pugh chart, seen in figure 6.1 on page 12, uses a weighting system of 1-5, with 5 being the heaviest weight, to quantitatively rank each of the functional requirements. Concept 1 in Figure 6.1 corresponds to the Museon-Type mechanisms, which utilized a spring mechanism to for leg retraction. Concept 2 corresponds to kneed walkers based on Ruina's walker [5]. Concept 3 is based on the Wooden Walker demonstrated by students at Cornell University, which utilizes a pathway cut into a plastic hip joint in order to facilitate anti-scuffing [13]. Concept 4 refers to a mechanism that would simulate a common household pen clicker mechanism, which would store energy in the spring and release it upon impact.

First, we selected a datum design for reference, being Concept 1, giving this design a score of zero in each of the functional requirement categories. Each subsequent design was then compared to the datum design and given a score of plus one, zero, or minus one for each functional requirement. These scores corresponded to superior, equal, or inferior fulfillments, respectively, of each requirement. The concept possessing the highest culmulative score was considered for our final design.

The primary function of our passive dynamic walker is to traverse down a smooth, sloped surface using only using passive mechanisms. Thus, the requirements of functionality and passive motion were weighted as fives by our team. Our walker design's suitability for DIY applications was given a weighting of four. As such, the manufacturability, ease of assembly, and minimal cost categories were crucial in facilitating this application. A weight of three was given to ease of motion, and reliability (attempts to start), as these affect the performance of our walker for outreach use. Finally, our design's sturdiness and longevity was assigned a weight of two and customizability for outreach purposes was weighted at one, as it was the least significant functional requirement of our design.

Using this Pugh chart, coupled with our team's logical assessment of each design's feasibility, we selected the track/pathway mechanism design as that which we would implement into our general design framework. This mechanism would allow us to constrain the motion of the legs of our walker to a degree to minimize the impact of initial conditions on the repeatability of our walker's motion. However, design aspects from other concepts will be considered, such as weight adjustability, feet adaptability, and humanoid aesthetics.

Functional Requirement	Weight	Concept 1	Concept 2	Concept 3	Concept 4
Manufacturability	**4**	0	-1	0	-1
Ease of Assembly	**4**	0	-1	-1	-1
Minimal Cost	**4**	0	0	0	0
Functionality (Successfully Walks Down Slope)	**5**	0	0	0	0
Passive Motion (No Motors)	**5**	0	0	0	0
Efficiency/Ease of Motion	**3**	0	1	1	0
Portable/Kit	**3**	0	-1	0	0
Customizable	**1**	0	0	1	0
Replicability/Reproducibility	**5**	0	-1	0	0
Attempts to start < 3	**3**	0	1	1	0
Sturdy	**2**	0	1	1	-1
TOTAL	**39**	**0**	**-8**	**5**	**-10**

Figure 6.1: Pugh chart used to facilitate the selection of our team's walking mechanism

6.3 Concept Description

Via the implementation of a Pugh chart, we have identified a chosen design concept: the use of a track/laneway mechanism to facilitate the retraction of the swing leg. The most crucial components of the said concept are the Hip Bracket and Valve, as shown in the Fig. 6.1.

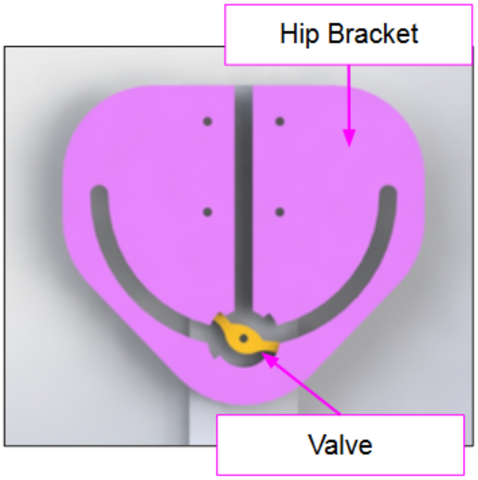


Figure 6.1: A pictorial rendering of the Hip Bracket and Valve mechanism, which are crucial aspects of the chosen track/laneway mechanism

The track/laneway works by guiding the motion of the legs onto two paths. The walker will majorly comprise of two outer legs (constrained to move in unison) and an inner leg. The Hip Bracket and Valve mechanism is attached to the inner leg. The outer legs are attached to the inner leg via two pin-slider joints. One pin-joint is allowed the slide to move vertically, while the other pin-joint is constrained to slide within the semicircular laneway shown in Figure 6.1. A valve sits at the base of the semi-circular laneway. It is attached to a spring that enables it to rest in a default position. As the outer swing leg approaches the valve, it will be directed by the valve to travel *over* the valve, thereby achieving ground clearance. The outer leg then lands on the ground thereafter functioning as the stance leg. As the outer leg (now in stance position) reverses in direction of motion, it moves *under* the valve, effectively lengthening itself, thereby generating ground clearance for the swinging inner leg.

7. ENGINEERING ANALYSIS

With the selection of our design concept, we identified several key design drivers affecting the development of our passive dynamic walker. By identifying these design drivers, we were able to pinpoint notable challenges which might arise with the development of our chosen design concept into a prototype. An engineering analysis was then conducted to address each design driver. In this section, we will be discussing the design drivers and their corresponding engineering analysis.

7.1 Natural Dynamics of Walker

Given that the walker is non-active, the passive, natural dynamics of system must allow for the sustenance of cyclical motion. Numerous studies have been conducted into the simulation of passive dynamic walkers, where the physical walker is able to execute the simulated natural gaits when experimented upon. As such, we envisage that this design driver could possibly be addressed through the use of computer simulations with the additional use of empirical testing.

7.1.1 Computer Simulations of Walker Gait and Limit Cycle Analysis:

Through the recommendation of our project sponsor, we were able to obtain and adapt a computer simulation model [15] of a 2D, non-kneed passive walker traversing down a slope. The Matlab code contains the equations of motions governing the swing leg motion of a walker. The motion of the walker is simulated by means of numerical integration.

The first step in running the simulation is to input the mass, inertia and geometrical properties (Figure7.1). Using a non-linear solver, we are able to determine a series of initial conditions for which the terminating conditions are identical with. This is indicative of the existence of a walking gait. A simulation of the walker in motion is conducted with these conditions. Upon contact of the swing leg with the ground (landing), the simulation temporarily terminates. The terminating conditions for the single step is then fed to compute the collision effects. The resultant state information from the collision is then fed forward to the next step where the step is simulated.

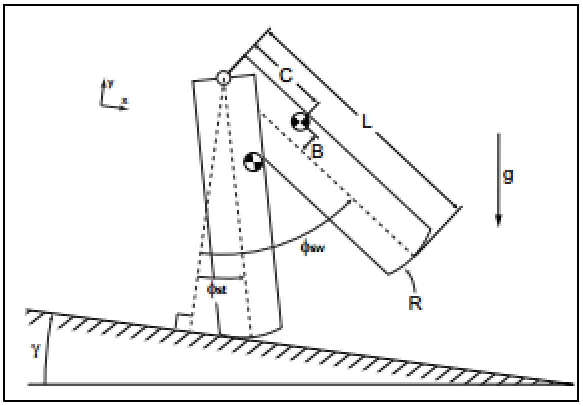


Fig 7.1 General arrangement of a 2D biped. It includes legs of arbitrary mass and inertia, semicircular feet, and a point mass at the hip (figure from Karssen & Wisse, 2008 [15]).

There are merits to adopting the above model. The first of these is the simulation's ability to rapidly compute the eigenvalues of the Jacobian of the limit cycle, thereby determining whether our walker in its current geometrical configuration has stability. The second of these merits is the ability to search for a limit cycle numerically to identify if a limit cycle indeed exists. This is equivalent to predicting whether a walking gait is mathematically plausible. In recognizing the complexities of passive dynamic walking, we find no advantages in obtaining an analytical solution for our walker trajectory. For the purposes of our project, we will be tweaking the parameters of the walker design to ensure a satisfactory walking gait is obtainable.

We do, however, recognize the limitations in the model used. First, it assumes that both legs are identical in geometry and mass distribution. This is dissimilar to the design that we are currently developing. A possible solution is to design a set of inner and outer legs that have a relatively close geometry and mass distributions. Second, the model assumes a rigid structure and no 3D effects. However, in reality, a real world system has material flex, and the inner and outer legs, while constrained to move in unison, might be subject to a various rotational motions that violate the 2D assumptions. Lastly, the model does not account the frictional losses and inelastic collisions of our mechanism. As such, while the simulation provides some intuition into the viability of our model, it is necessary to still construct multiple prototypes with the goal of iterative modifications and testing.

7.1.2 Empirical Testing of Mass Distribution

As our current theoretical model is limited in its ability to analyze the natural dynamics of our specific walker, empirical testing is required for our team to sufficiently analyze this aspect of our walker. We will be adding masses onto the walker structure, based on the insights gained from pendulum motion. In the motion of one step, the swing leg behaves like a simple pendulum while the stance leg is actuality an inverted pendulum.

The proposed simple pendulum consists of a point mass with mass m, connect to a pivot joint via a massless rod. This is diagrammatically depicted in Fig. X.

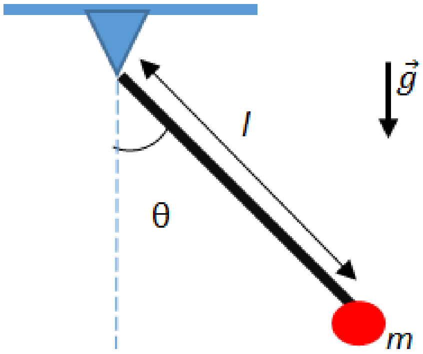


Figure 7.2: The swinging leg is modelled by a simple pendulum with length *l* and mass *m*.

We were able to generated the following equation of motion that would adequately describe the system dynamics of the above pendulum. An arbitrary damping coefficient *b* was used to simulate a damping force that is proportional to the angular velocity. This equation is listed as Eq. 1:

$$ml^2\ddot{\theta} + mgl\sin(\theta) + b\dot{\theta} = 0 \qquad \text{[Eq. 1]}$$

Using the ODE 45 function on Matlab, we are able to get trajectories of the pendulum system. This was obtained using an initial angle of 90^0 and zero angular velocity. Varying lengths from 0.2m to 0.6m were used in the simulation. The simulation results are presented in Figure 2:

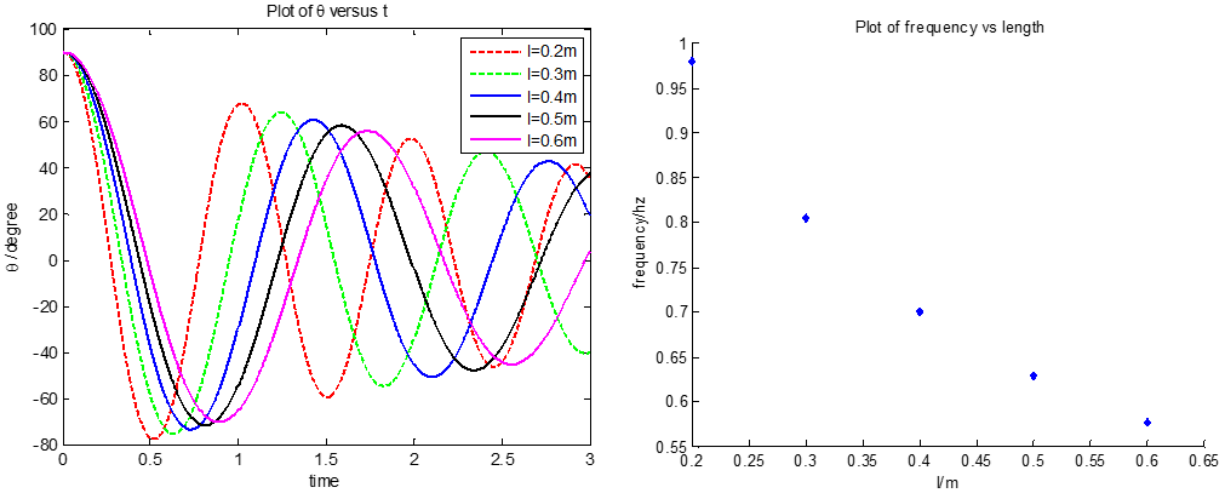


Figure 2: (Left) A plot of angular displacement of the pendulum versus time, showing that a pendulum of lesser length takes a shorter time period to complete one oscillation. Also, the further position of the pendulum distance from the pivot point make it less susceptible to damping forces. (Right), the frequency of each oscillation reduces with greater length. A shorter pendulum will oscillate at a greater rate.

There are several insights that can be gleaned from the above simulation. First, a shorter pendulum arm will result in a pendulum that oscillates at a greater rate. Second, it appears that a shorter pendulum arm has a larger sustained amplitude, that is, it is less susceptible to damping forces.

Conversely, our stance leg is in a state of unstable equilibrium if it is held vertically. There is a strong resemblance in its behavior to that of a simple inverted pendulum. Such a simple inverted pendulum is depicted in Figure 3.

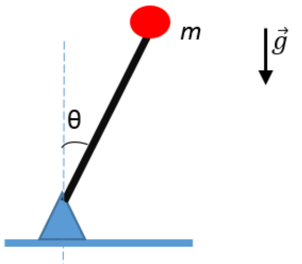


Figure 3: The stance leg is modelled by a simple pendulum with length *l* and mass *m*.

Similarly, we will be able to obtain an equation of motion, given by Eq. 2.

$$ml^2\ddot{\theta} - mgl\sin(\theta) + b\dot{\theta} = 0$$

[Eq. 2]

We note that an inverted pendulum when perturbed from an unstable equilibrium will not oscillate around that equilibrium, hence a different measure of the pendulum's rate of motion if obtained. We will model the angular velocity at the horizontal position, where $\theta=90^0$. The pertinent data is presented in Figure 4.

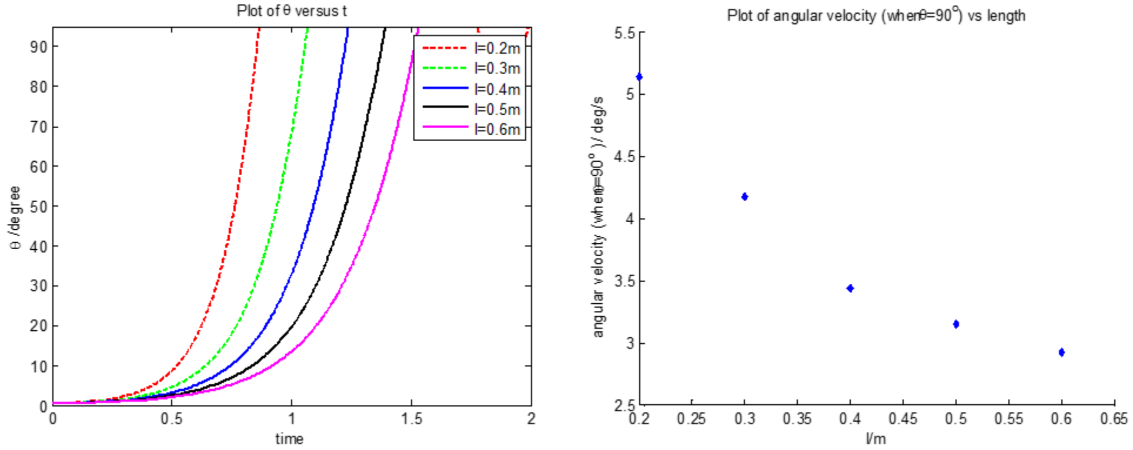


Figure 4: (Left) A plot of the angular trajectories of the pendulum versus time. (Right) The angular velocities of the inverted pendulum for various pendulum lengths show that a longer pendulum has a lesser velocity in its motion. This is expected, given the larger inertia such a pendulum would have.

In testing our Passive Dynamic Walker prototypes, we have to empirically alter the mass characteristics of the inner and outer legs by adding external masses. This study thus allows us to address the logic behind the placement of the masses (from the pivot point). If a greater rotational rate is desired, the mass needs to be places closer to the pivot point as this corresponds to a pendulum of smaller length.

Conversely, to slow down the motion of the system, we need to increase the inertia of the system. This is achieved by adding the mass further away from the pivot point. If we neglect the damping forces of the system, we note that changing the total mass of the system should have no impact in the dynamics of a swinging pendulum. However, we observe that have a larger mass might reduce the proportionate impact of the damping forces- a smallest mass of the system would mean that damping forces will dominate the system.

7.2 Efficiency of Passive Dynamic Walker

The walker must be designed to move efficiently. Given that the sole energy input into our walker system is via the conversion of gravitational potential energy, it is imperative that our walker has minimal energy losses. The sustenance of walking motion will be detrimentally affected should the energy losses caused by contact friction and inelastic collisions exceed the energy input of the system. Contact friction can be caused by rotational and sliding joints of our mechanism. The sliding joints are of particular concern. Inelastic collisions occur when the feet of the walker comes into contact with the ground surface.

7.2.1 Empirical Testing to Determine Optimal Geometrical Configurations

In order to successfully optimize the energy efficiency of our walker, our team's focus is to optimize our walker's foot radius in order to minimize the inelastic collisions which our design experiences throughout its motion. Due to the limitations surrounding our team's current theoretical model, we felt as though this optimization would be most efficiently completed through empirical testing.

The experimental setup which our team will employ for the testing of our model will consist of fairly basic elements. First, our team will construct or locate a shallow decline down which our mechanism will walk. This shallow decline could be constructed out of a thick and stable board, such as a 2"x16" board or a sheet of plywood, which could be raised on one end and supported in the middle by textbooks to create a shallow decline. Another option which our team has discussed for an experimental setup is the use of a handicapped ramp or a ramp with a shallow decline within a building for the testing of our mechanism. While this second option would give us a narrower range of slope options with which to test our mechanism, it would also eliminate the risk of the sloped material slipping as our mechanism descended the decline and would eliminate some of the human error associated with managing the level of decline of the slopes.

Our empirical testing would also require a set of feet for our mechanism of varying radii of curvature. As the foot radius of our design will have to be optimized through testing at various slopes, we have incorporated design flexibility into the feet of our design through the use of interchangeable feet. By allowing for our feet to be interchangeable, we have allowed for our design to be optimized at various slopes.

Finally, our empirical testing will be completed by placing our mechanism on a decline and applying a force to it to begin its motion down the decline (Figure 7.2). We will be testing our mechanism at varying declines and optimizing our mechanism's foot design at each decline. Thus, the sloped surfaces which we select will need to have varying degrees of slope or be adjustable to permit the testing and optimization of our mechanism at various slopes.

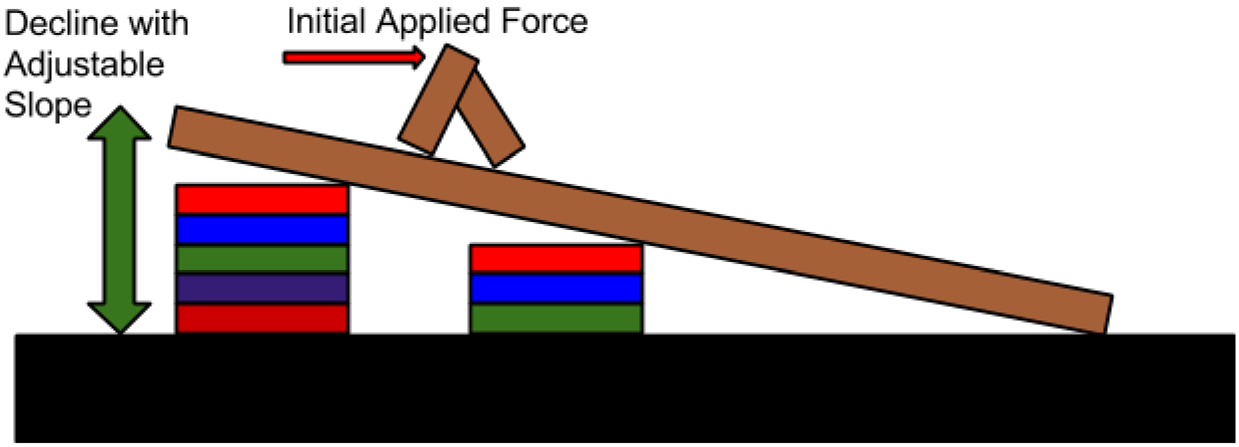


Figure 7.2: A simplified drawing of our team's empirical testing setup. This setup utilizes a wooden board and textbooks to provide us with a decline of adjustable slope.

During each test we will be recording the degree of the decline which our mechanism descended and the corresponding foot radius which provided an optimal walking motion down that slope by minimizing the severity of the inelastic collisions. This data will be investigated for patterns correlating foot radius to decline in the hopes that a generalization may be made for users which correlates the optimal foot size to the slope being descended in order to maximize energy conversion efficiency.

7.2.2 Empirical Test to Ascertain Means of Lowering Friction in Laneway

Frictional losses will adversely impact our walker's ability to traverse down the slope. Kinetic energy that is required for forward motion is dissipated via frictional losses, thereby impeding the motion of our walking. To ascertain the most effective means of lowering friction between the pin joint and the track laneway, we conducted an empirical test. A picture of the test set up shown in Figure 7.2.

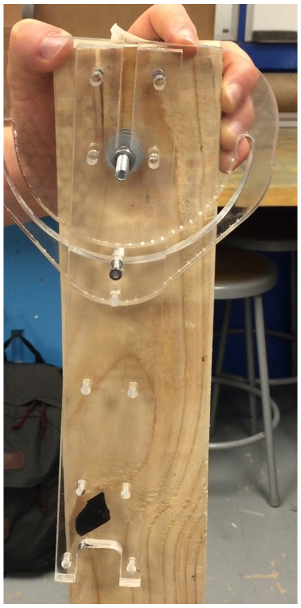


Figure 7.3: A picture of the test set up, which comprises a purpose-built hip fixture, and an outer leg attached with a fixed pin joint, and moving pin joint

Several configurations of the pin joint and laneway were tested. An initial angular displacement was provided to the inner leg, and a pendulum-type motion was induced. Given the presence of frictional force and other damping forces, the outer leg will come to a rest at its stable equilibrium. The number of oscillations and the time taken to rest was recorded. The data is presented in Table 7.1.

Table 7.1: The data obtained from the empirical testing show that the use of bearings would result in the greatest number of oscillations, indicative of a relatively low amount of friction.

	Period (s)		Total Time (s)		# Oscillations	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Flat shaft	0.66	0.66	2.03	1.83	2.50	2.50
Bearing	0.80	0.87	8.36	8.27	9.50	9.00
Flat Shaft (With Grease)	0.66	0.67	1.99	1.96	2.00	2.00

We found that the use of bearing afforded the best results. In subsequent tests, we aim to measure the amount of oscillations of the outer leg with the presence of the valve mechanism, so identify the optimal track laneway and valve geometry.

7.3 Cost of Replication

A design driver is the cost of replication and the suitability of our design for DIY production. In doing so, we will aim to ensure that the design of our components will facilitate low cost manufacturing and ease of manufacturing. Ideally, the entire design will be laser cut and assembled with off-the-shelf components, as seen in Figure 7.4; this would reduce cost, time spent on manufacturing, and eliminate the need for complex machinery, such as a lathe or mill, that could cause potential harm and require special skills. In doing so, we make the project more suitable for the intended outreach/DIY aspect of the project.

Figure 7.4: Our goal is to develop a Passive Dynamic Walker that can be mostly laser cut (if not fully) and assemble with off-the-shelf components in the least amount of time.

7.3.1: Mock Up Construction

After selecting our design concept, we were able to develop a mockup of our chosen mechanism, as seen in Figure 7.5. Our mockup successfully gave us a spatial representation of the component assembly. The process of developing the mock up also gave us the opportunity to attempt an assembly process, facilitating the identification of challenging construction procedures.

We began designing a series of mechanism geometries using Solidworks. Using a combination of wood, acrylic sheets and metal fasteners, we were able to expediently construct a design mockup, as shown in Figure 7.5. While the mockup is not able to walk down a flat slope, it serves as a very good visual representation of our final design.

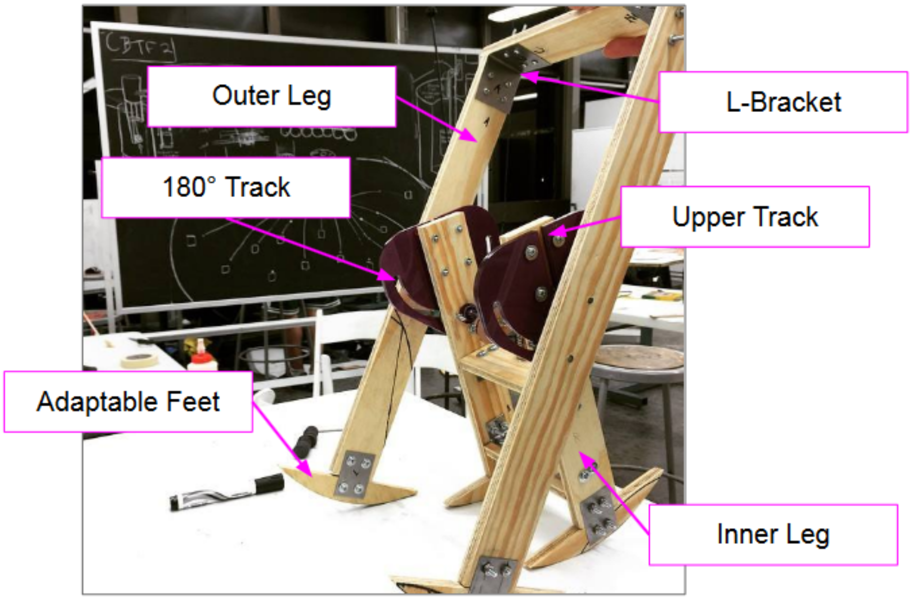


Figure 7.5: A picture of our design mockup, constructed mainly from wood and acrylic. While it is not fully functional, numerous insights have been gained from its development.

7.3.2: Lessons Learned from Construction of Mock-up

After having built a preliminary mock-up, it became apparent that the current design of the outer legs does not offer sufficient rigidity, which is crucial in maintaining the alignment between the sliding pins and their respective tracks. To overcome this lack in structural rigidity, numerous changes have been made to the current design. The legs have been shortened, reducing the moment on the L-brackets, the L-brackets have been replaced with ones of superior rigidity, and the top pins, (i.e. those sliding through the vertical slots) have been made into one continuous shaft that directly connects both outer legs. If, during the construction of our next prototype, we find that these new design features are still insufficient, we will consider building an outer cage constraining the two legs.

The spring, shown in Figure 7.6, was too stiff for our application. Its only purpose is to return the switching valve to its default position, which necessitates very little torque; however, the spring is also required to allow the outer leg to move through the valve with little perturbation, and this means that the torque provided should be negligible compared to the momentum of the swinging leg. As such, our revised design utilizes a rubber band as the torsional element.

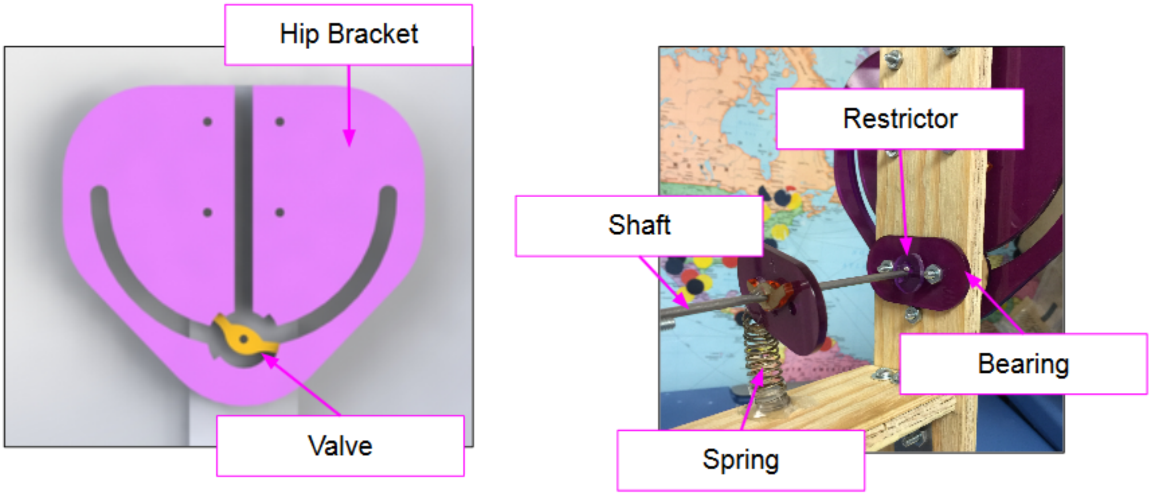


Figure 7.6: The spring mechanism was too stiff in our initial mockup configuration, requiring extensive force to make the valve rotate.

We also noticed that the dimensions of the outer legs can be further reduced. While we intend to implement an area of clearance above the inner leg, we observed that this has been overcompensated for. Making the outer leg shorter has several merits: one, it reduces the rotational inertia of the outer leg, allowing it to swing with greater speed; two, by using less material there will be less loads on the walker, reducing the chance of damage if the walker falls; third, there will be less material flex, allowing the pin-joint to be remain aligned.

The attachment of valve onto the aluminum rod was done through the use of super glue as an adhesive. Given the small surface area of the axle surface, the shear loads on the valve result in component failure, where the valve is no longer constrained to the axis. We intend to use a key-slot design in our next prototype as shown in Figure 7.7; this would prevent the valve from rotating with respect to the shaft.

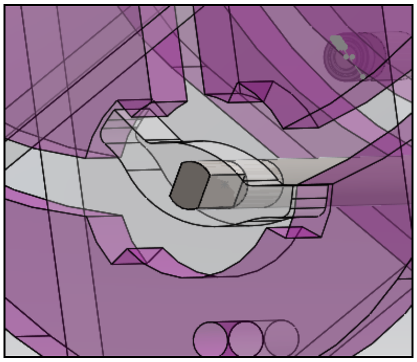
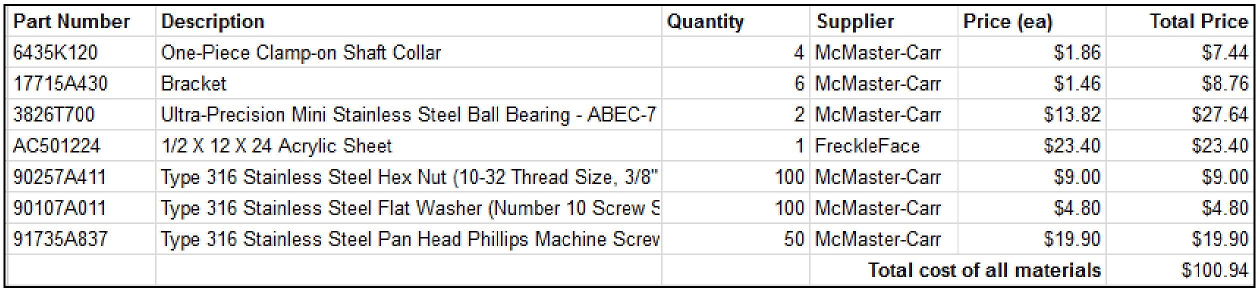


Figure 7.7: A key slot feature on our shaft and valve will permit not using a set screw and will permit the use of an adhesive to maintain structural integrity.

7.3.3 Bill of Materials

Our current bill of materials will cost the end-user approximately $100, as shown in Table 7.2. The parts listed as well as the raw plastic can be purchased at cheaper prices, but this gives an approximate price as to how much it will cost to build a Passive Dynamic Walker with our current design. We will further our research and provide lower prices from other suppliers.



Part Number	Description	Quantity	Supplier	Price (ea)	Total Price
6435K120	One-Piece Clamp-on Shaft Collar	4	McMaster-Carr	$1.86	$7.44
17715A430	Bracket	6	McMaster-Carr	$1.46	$8.76
3826T700	Ultra-Precision Mini Stainless Steel Ball Bearing - ABEC-7	2	McMaster-Carr	$13.82	$27.64
AC501224	1/2 X 12 X 24 Acrylic Sheet	1	FreckleFace	$23.40	$23.40
90257A411	Type 316 Stainless Steel Hex Nut (10-32 Thread Size, 3/8"	100	McMaster-Carr	$9.00	$9.00
90107A011	Type 316 Stainless Steel Flat Washer (Number 10 Screw S	100	McMaster-Carr	$4.80	$4.80
91735A837	Type 316 Stainless Steel Pan Head Phillips Machine Screv	50	McMaster-Carr	$19.90	$19.90
				Total cost of all materials	$100.94

Table 7.2: The current bill of materials approximately costs about $100.

8.0 FMEA ANALYSIS

Process Step	Potential Failure Mode	Potential Failure Effect	Potential Causes	Current Process Controls	Action Recommended
Parts Manufacturing	Laser cutter doesn't work	Can't manufacture parts	Technical issue with laser cutter	Wait for fix	
	Materials unavailable	Can't manufacture parts	Out of required material	Wait for restock	
	Wood is not smooth	Splinters	Rough cuts or broken wood	Handle with care and sand the wood	Replace wood with acrylic
	Lathe or mill accident	Injury to customer	Improper use of equipment, proper precautions not taken, or defective equipment	Follow proper procedures and safety guidelines	Design parts that do not require the customer to use these equipment
Parts Assembly	Parts don't fit together	Walker cannot be made	Bad manufacturing or imprecise manufacturing plans	Design carefully modelled using CAD and prototypes assembled based on CADs	
	Minor misalignments	Walker assembled but not functional, or reduced functionality	Poor manufacturing/plans or poor assembly by user	Careful design and use of laser cutter for accuracy	
	Pinching	Injury to customer	Misuse of assembly tools	Follow proper procedures and safety guidelines	
Walking	Does not walk	Very dissatisfied customer	Bad design, assembly or used in wrong setting	Designed to be able to walk on specified slope range	
	Cannot take more than 3 steps	Dissatisfied customer	Bad design, assembly or used in wrong setting	Designed to be able to walk on specified slope range	
	Falls and breaks	Dissatisfied customer	Bad design, assembly or used in wrong setting	Designed with large base to avoid falling and designed with materials and part to minimise chances of breaking	
	Pinching	Injury to customer	Fingers or skin caught in moving joints	Handel walker with care and be cautious not place hands where they might get caught between moving parts	

Table 8.1: There are numerous potential failure modes in the making of our walker, the most dangerous of which are associated with manufacturing.

Numerous failure modes and risks are associated with our design. Those most upsetting to the customer are likely to be associated with the product's inability to walk well or falling and breaking; these risks are also the most likely to occur as the mechanism is highly dependent on initial conditions, and small errors in design, manufacturing or assembly could affect these enough to cause failure. Such a failure would undermine our project, for our main goal is to engage our user and inspire them to pursue a career in STEM. Existing controls for these failure modes rely on a strong, functional design and a manufacturing process that simplifies the entire process of making the walker, while maintaining high accuracy. Additional actions that we can take to reduce the probability of these occurring include refining our design, and providing an assembly manual along with a user guide that would help reduce any possible mistakes that would be made during assembly and ensure the user creates an environment that gives the walker the best possible chances of functioning.

The highest risk factors are associated with tools and machinery, such as getting hair, limbs or garments caught in the lathe or mill. Although these are less likely to occur than the failure modes mentioned above, the potential hazards are far more serious. The lathe and mill have the greatest associated dangers. By making most parts fully manufacturable by laser cutting, the current design makes minimal use of both these machines, reducing exposure. However, exposure is not completely eliminated, and the risks still exist. In addition, to minimizing the use of these tools, we suggest that anyone operating such machinery be familiar with it and follow standard safety procedures and guidelines. Moving forward, we will continue to improve our design with the hope of eliminating any need for the lathe and mill.

10.0 FINAL DESIGN

Using the insights gleaned from the construction of the mockup, we proceeded to develop a Final Design through the use of Solidworks. In this section, we will discuss the key components of our final design and our second prototype, MK II.

10.1 Use of Acrylic for Structural Components

In general, the use of ½” acrylic was utilized for the construction of major structural components. This decision was made based on the increased structural rigidity of a thicker material, when compared to wood. In addition, ½” acrylic is a material that can be laser cut, thereby allowing the end user ease of manufacture. The overall CAD depiction of our walker is shown in Figure 10.1

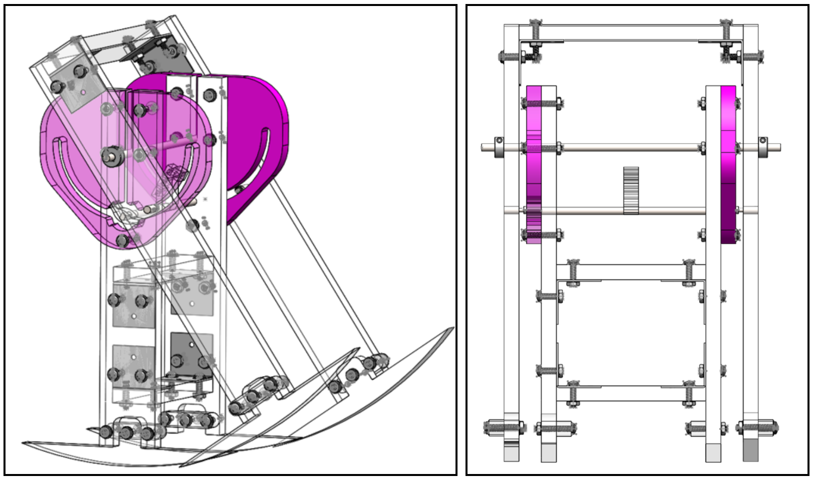


Figure 10.1: (Left) The outer legs in a swinging forward position. (Right) A frontal view of our MK II prototype.

10.2 Solid Steel Shaft for Outer Legs

In the development of the mock-up, we recognize that flexing of the material will result in the misalignment of the pins from the fixture laneways. In order to reduce this flexing, a solid steel shaft is inserted across the width of the outer legs, in place of the original pins. This will further constrain the outer legs.

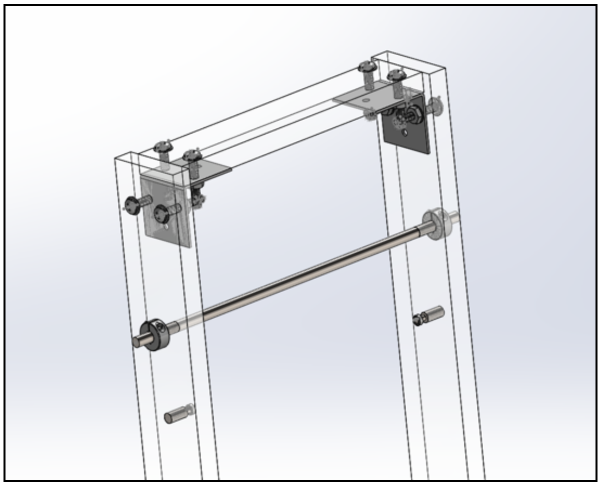


Figure 10.2: A steel shaft was inserted to constrain the relative flexing of the outer legs, improving structural rigidity.

10.3 Detachable Feet

Recognizing that different feet radius would be required for different ramp heights, we are required to conduct empirical tests to verify and appropriate foot geometry. To facilitate this testing, we have made the feet detachable from the leg structure. To allow the expedient replacement of the foot, we adopted the use of a puzzle-fit structure. This allows the the foot to be fastened with 3, instead of 4 bolts. In addition, such a design allows for lesser motion of the foot with respect to the leg structure.

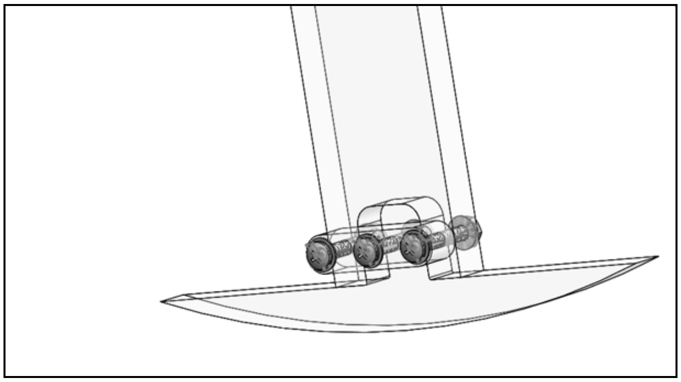


Figure 10.3: Detachable feet in this configuration allows ease of testing.

10.4 Updated Valve Assembly and Lane Track

While constructing the mock-up, we found that the design of the valve and lane track geometry was not conducive for the motion of the pin slot. Further changes have been made to these geometries by smoothing out the contours.

In our walker design, a valve axle to synchronize the motion of the valves on each side of the inner leg. Previously, we utilized glue to attach the valve to the valve axle. Consequently, given the limitations of the strength of glue, shearing between the valve axle and the valve occurred. To rectify this, we decided to machine square edges to the ends of the valve axle.

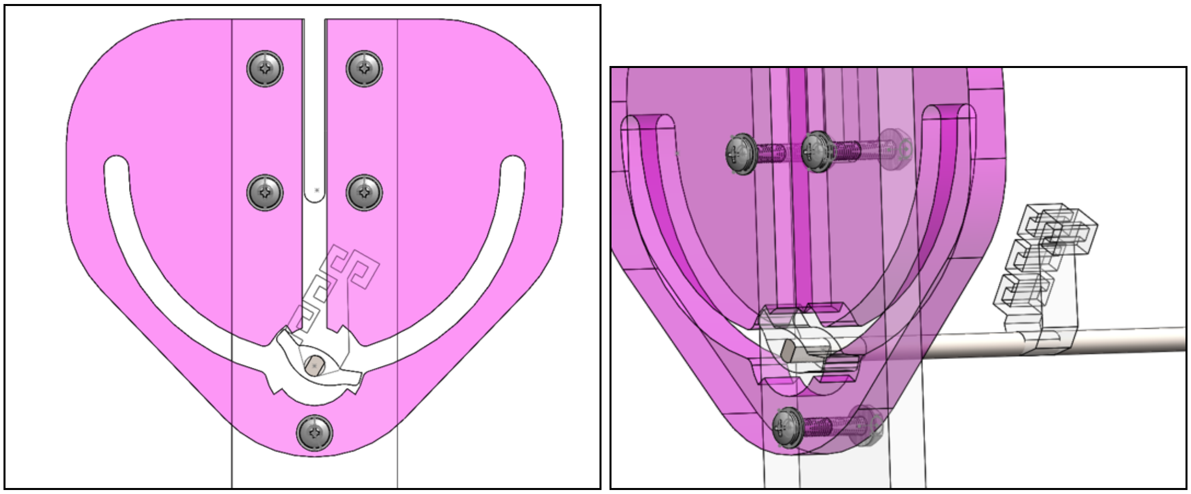


Figure 10.4: (Left) The contours of the valve and the laneway track have been smoothed. (Right) The joint between the valve and the valve axle has been squared out increasing its durability. The spring hook was designed to allow a spring motion of the valve, facilitates adjustability.

To bring the valve back to its default position, a spring is required. To lower the costs of production, we have opted to use a rubber band as the spring. One end of the rubber band will be attached to the valve via the spring hook. The spring hook has multiple grooves allowing for greater adjustability in our design; our end user who may have an arbitrary rubber band with unknown tension will be allowed the freedom to use the rubber band hook of his choice.

10.5 Construction of MKII Prototype

With the development of our CAD design, we proceeded to construct a MK II prototype. The structural components of the prototype were largely laser printed. The Slot Pins and Valve Axle were machined from stock metal. The fasteners and L-brackets were procured. In testing our MK II prototype, we observed marked improvement of our walker's structural rigidity and the general reduction undesired relative 3D rotations between the inner and outer legs. However, our current prototype is not able to walk down a slope without human assistance. A detailed discussion of the issues affecting our walker's ability to carry out walking motion is included in the subsequent section. A photograph of our MK II prototype is shown in Figure 10.5.

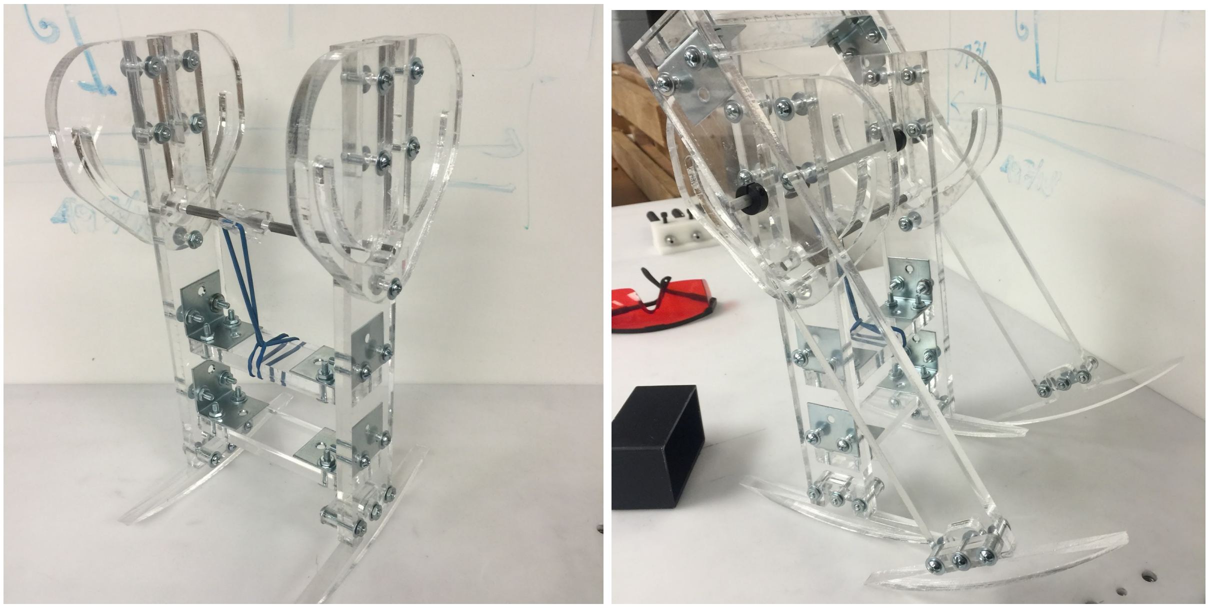


Fig 10.5: (Left) The inner leg assembly of the MK II prototype; a rubber band was used as our spring. (Right) The complete passive dynamic walker, note that further work is to be carried out to ensure walking motion.

10.6 Construction of MK III Prototype

Given that our team has adopted an evolutionary design strategy, the various improvements and optimizations we have thus made culminate in the MK III prototype. In particular, changes have been made to reduce the cost of production, reduce the mass of prototype, and improve ease of assembly. While we will be highlighting key changes in this section, a detailed Engineering Change of Notice (ECN) can be found in *Appendix J*.

10.6.1 Update to Top Bridge Connecting Outer Legs

In our design, the outer legs consist of a bridge that connect the two limbs to form a rigid structure. Previously, two metal L-brackets and mechanical fasteners hold these three substructures together. In order to reduce the cost of production, the L-bracket have been replaced with an acrylic piece that is glued onto the top bridge and limb. This design is shown in Figure 10.6

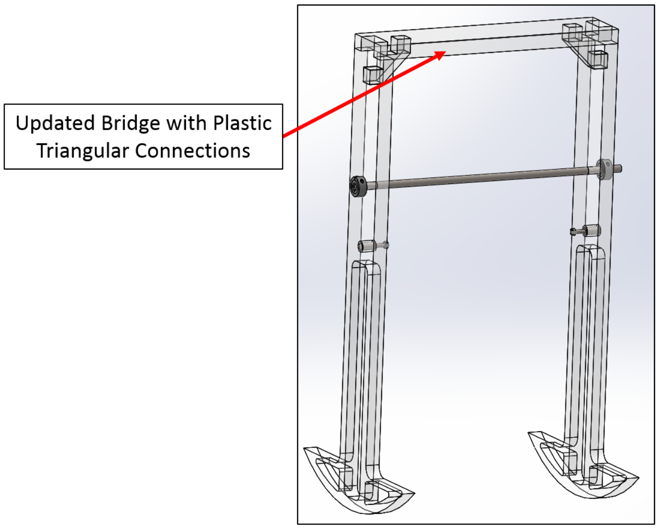


Figure 10.6: The acrylic piece will be glued onto the top bridge and limb, forming a rigid angle joint

10.6.2 Update to Structure of Inner Legs

The inner legs are held together using two bridges and four L-brackets. This has been replaced by a single X-brace. The X-brace is a piece of laser cut acrylic, attached to the inner legs by glue, thus negating the use of mechanical fasteners. In addition, the X-brace is significantly lighter than the previous configuration, while affording very similar structural rigidity. This design improvement is depicted in Figure 10.7.

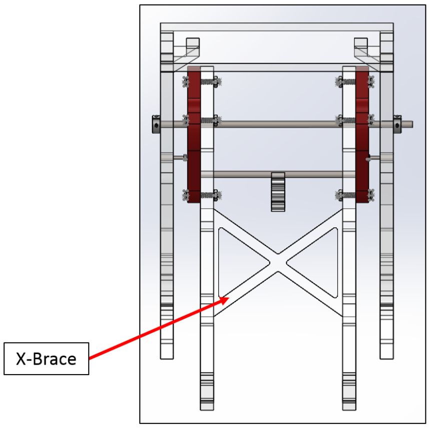


Figure 10.7: The inner legs are held together rigidly using an X-brace, that can be more expediently assembled.

10.6.3 Reducing of Mass of System

We have reduced the mass of the system by hollowing out several acrylic components. While there is a structural compromise in doing so, the new feet have been tested and have shown to be able to undertake the stresses of our passive dynamic walker in motion. More crucially, reducing the mass of the walker makes it a safer product, and makes the overall mass properties of the system more malleable to the adding of ballasts.The feet of this prototype and legs are one continuous acrylic piece thus enabling greater ease of manufacturing. These design changes are presented in Figure 10.8.

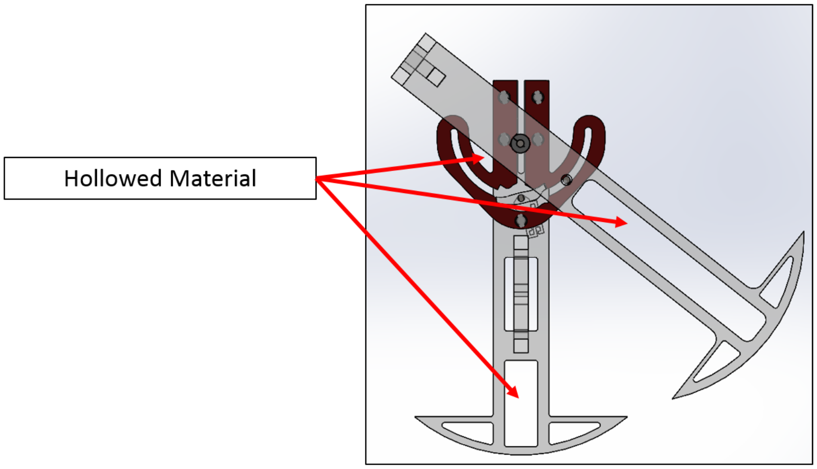


Figure 10.8: The overall mass of the walker is reduced by hollowing out acrylic components.

11.0 CURRENT CHALLENGES

With the construction of our second prototype, we will address the challenges we have faced with the development of our passive dynamic walkers.

The first of our key design challenges is the geometric profile of our walker’s feet. Currently, the feet of the MK II impedes the motion of walker, because they are too lengthy and thus scruffs against the ground. They will need to be shortened. In addition, the feet of the walker, when coming into contact with the ground surface, experiences inelastic collisions. The optimal shape of the feet of a walker is critical to the conservation of energy in our walker’s motion- we hope to reduce the energy losses associated with these collisions.The optimization of the feet geometry is to be conducted through trial and error. We will iteratively build and test feet of various geometrical profiles.

A second key challenge is the construction of a physical walker with the necessary inertial and geometric attributes that enable our walker to execute a walking gait. In recognizing the limitations of simulations in accounting for inelastic collisions and frictional losses, we expect the use of trial-and-error methods to be of great significance in the identification of optimum weight distributions. Currently, the simulation results for our prototype require the addition of masses near the bottom of each leg in order to lower the center of gravity. We have attempted to accomplish this by shifting several components to a lower position. Using means of trial and error, we will be experimentally adding ballast masses to the walker, until a walking gait can be successfully executed.

A third key challenge is the dominance of frictional forces in our walker design. Specifically, there is significant frictional force between the pin slot and the laneway track. This can be attributed to the use of a thicker material: in laser cutting ½” acrylic, two passes of the laser cutter are required thereby melting the acrylic material twice, thus causing a rougher surface finish. Also, in the construction of our prototype, we were unsuccessful in the assembly of a roller bearing pin joint. As such solid pin joint was used in place of a roller bearing, generating a larger friction force. Another crucial source of friction is the valve axle and the inner leg. This is caused by the inaccuracies of our manufacturing process, resulting in a minor misalignment of the valve axle. The implication of this high friction joint is the undesired dissipation of kinetic energy of the swing leg as it passes through the valve axle.

12.0 FURTHER TASKS

We are currently nearing the completion of our development of the passive dynamic walker. However, three main efforts will need to be undertaken to ensure that our sponsor requirements are met: to ensure the successful execution of walking motion, optimization of design and the documentation of our walker design.

12.1 Successful Execution of Walking Motion

One of the focuses for our team in the coming weeks is to ensure that our walker can successfully fulfill its primary function- to traverse down a flat incline. This is achieved by modifying aspects of our current prototype. We will be focusing on optimizing the feet, inertial properties, and efficiency of our walker's motion. By optimizing the design of the feet of our walker, we will be ensuring that our walker does not trip over its own feet while descending a slope. The current feet will need to have their radii reduced in the next design iteration to accomplish this goal. We will also be optimizing the inertial properties of our walker for the same purpose of ensuring that the walker does not trip itself while descending a slope. The mass properties, and thus the natural frequency of oscillation, of the inner and outer set of legs will have to be matched to achieve this goal. Finally, the efficiency of motion of our walker will need to be optimized through the reduction in frictional and impact energy losses which our walker experiences. This will permit our walker to descend a slope without being halted by a lack of sufficient energy to allow motion due to excessive losses. In order to achieve this goal, our team is considering optimizing the profile of the valve in order to reduce energy losses derived from impact between it and the bearing which is following the curved track of the hip, greasing the curved track of the hip to reduce frictional losses, and inserting bushings into the inner legs to reduce friction between them and the valve-holding axle.

12.2 Optimization of Design

As soon as our team is able to successfully obtain a walking motion in our current walker, we will begin to focus on the optimization of our design. The focus of this optimization is an increase in the ease of manufacture of our design, an increase in the capability of our walker, and a reduction in our walker's cost. In order to optimize our design in these areas, our team is proposing a removal of any of the parts on our walker which requires machining beyond laser cutting, including our current axle and the pins which currently hold the bearings in our design. The axle, which has been milled to fit into the valve in a key slot fashion, could be recreated as a simple, cylindrical rod to which the valves are glued. The pins could be replaced by small bolts in order to increase the ease of manufacturing of our design. Additionally, to cut the cost of our machine, our team is proposing the use of puzzle-like snug joints to replace some of the costly brackets on our design. These laser cut snug joint pieces would then be glued in the frame of our walker to ensure stability. The removal of these brackets and the fasteners which accompany them would also increase our design's capability and performance, as a weight reduction would accompany the removal of these fixtures.

12.3 Documentation of Walker Design and Assembly Instructions

After our design is optimized, our team would like to distribute the information about the construction of our walker to the public to facilitate the use of this design as a do-it-yourself project. In order to do this, our team is considering constructing a website on which we will provide the CAD models and .dxf files of our design to be used for 3D printing or laser cutting, respectively. Also on this website, a set of assembly instructions, written by our team, would be included to aid the do-it-yourselfer in his quest to construct our passive dynamic walker. We would also like to include additional information and links to sources which we found useful in our benchmarking exercise at the beginning of this project to facilitate learning about the science and engineering behind passive dynamic walking.

13. VALIDATION PROTOCOL

To achieve a successful gaite our walker will undergo three parallel sets of design validation. Our critical issues have been caused by the mass distribution across the walker, the profile of the dynamics created by the valves and respective brackets, and the roller mechanism that rides the slot. As such, we will be conducting three separate but parallel validation protocols to ensure that the optimization of the position of the added weights, the valve and bracket profile, and selected roller design, are achieved respectively.

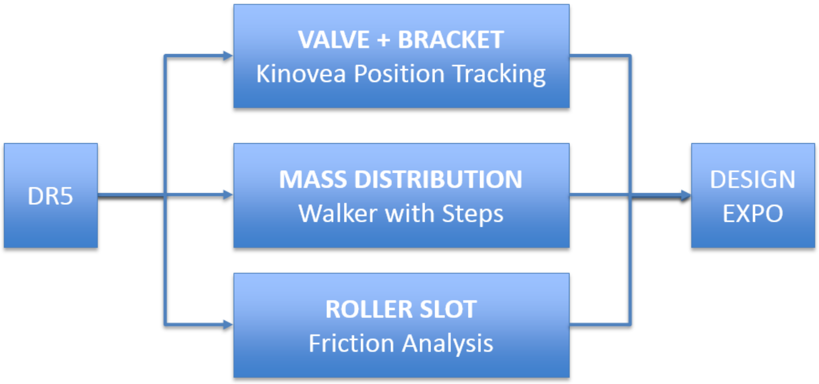


Fig 13.0: There will be three validation protocols in order to achieve a successful gaite which will involve the optimization of the valve and bracket profiles, mass distribution, and slot roller design.

13.1 Kinovea Position Tracking to Characterize Valve and Bracket Profiles

Through trial and error we have noticed that the profile created by the valve and brackets significantly affects the dynamics of our gait; the valve does not only serve to raise the swinging leg as it also affects how the walker takes the respective steps. Figure 13.1.1 shows the evolution of our valve designs.

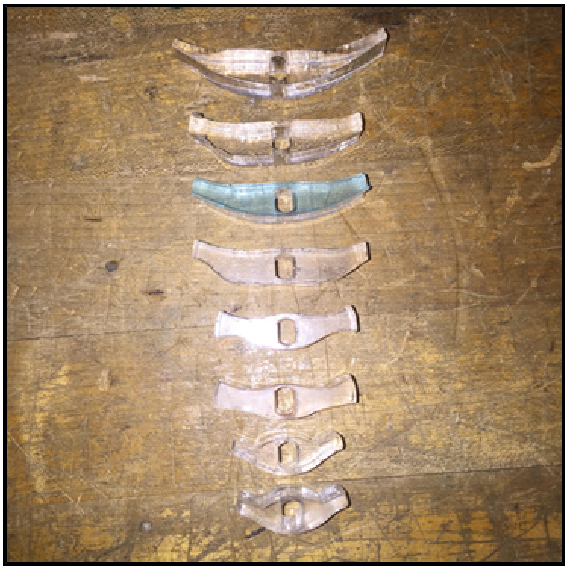


Fig 13.1.1: From bottom to top, the design of the valve has changed as the horizontal length highly affects the length of our stride as well as how long the swinging leg is actually raised.

To successfully characterize the improvement in the valve design we will identify the profiles of each valve's dynamic through the use of Kinovea. This software analyzes video footage and can track the characteristic dynamics of each valve by tracking a specific assigned point. Through calibration of the known lengths, the software can provide accurate locations, as seen in Figure 13.1.2.

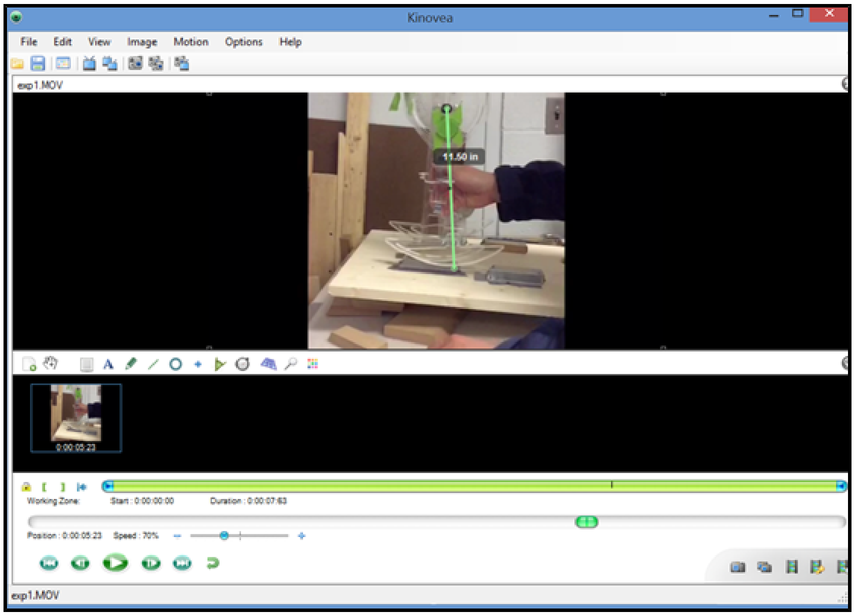


Fig 13.1.2: Kinovea allows us to calibrate known distances and then track the position of a selected point in video footage of our gaites.

Kinovea allows us to export position over time, quantifying the exact time in which there might be sudden changes in the profiles that can lead to extensive loss of energy. We will overlay the different sets of data from each valve profile and in such way characterize performance, in which smoother trajectory profiles will be of preference; impacts and sudden changes of directions will be seen as 'bumps' in our plots.

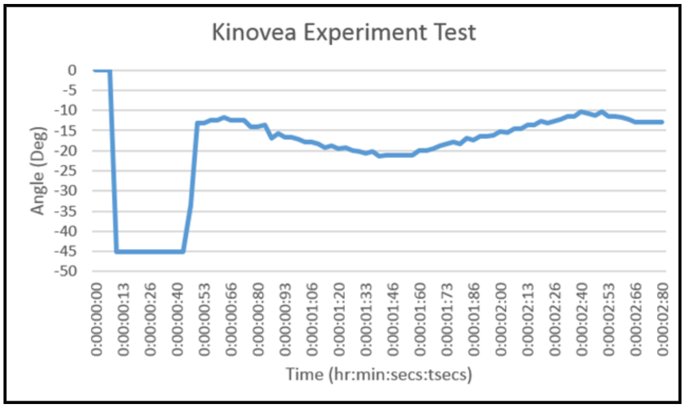


Fig 13.1.3: Kinovea exports the location in x and y coordinates defined through a local coordinate system, allowing us to convert such coordinates into angles over time.

The distortion and visual noise in the footage can be seen as noise in the plots, as seen in Figure 13.1.2. This will be lessened through the use of lighting techniques as well as using a clamp to hold the camera steady.

13.2 Mass Distribution Utilizing Step-Walker

The distribution of mass highly affects the dynamics of our walker. By modifying a bracket to not require a valve but instead make use of stepping stones as shown in Figure 13.2.1, we are able to shift the positions of added masses to achieve a gait that walks with a natural frequency. This will validate the mass distribution and center of gravities. Once this is determined, we will ideally add the valve with the smoothest profile as determined by the process in section 13.1 and achieve a successful gait that does not require the use of stepping stones.

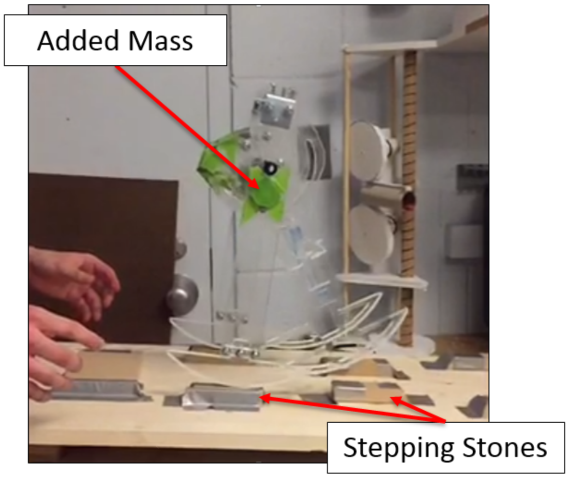


Fig 13.2.1: The use of stepping stones allows us to remove the valve mechanism to focus on the mass distribution of the system, thus achieving a mass distribution that will successfully achieve a natural frequency of the gait.

13.3 Roller Slot Analysis by Tracking of Periods

As determined in section 7.3, the use of a bearing on a roller is essential for the legs to travel smoothly per the respective valve's profile. However, using bearings requires machining on a lathe which is against our requirement of not using skilled machining processes. We have come up with an alternate design that uses a nylon bushing and roller bearings that might serve as an alternative due to not using any machining. Using Kinovea, we will conduct further characterization of our roller mechanisms to determine which design suits our needs best while using a valve and bracket mechanism.

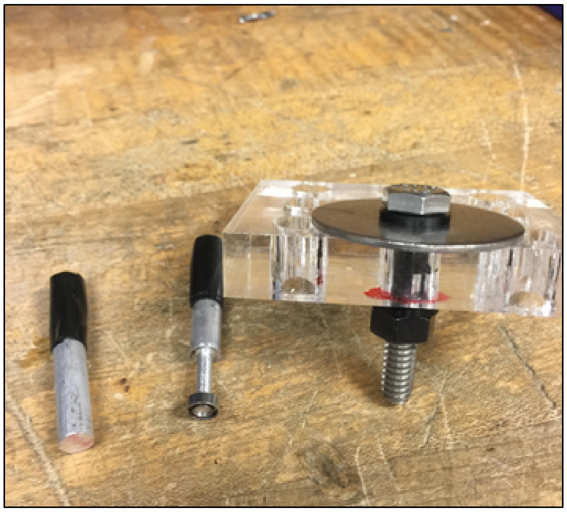


Fig 13.3.1 From left to right, the spin-less roller, the machined roller with bearing, and the #10-32 ¾" fastener with roller bearings and flange. All are to be tested with Kinovea to determine which shows the best performance by measure of period.

14. VALIDATION RESULTS

Through the parallel implementation of our validation methods, our team was able to successfully obtain a walker which performed its required task of descending a slope without the aid of stepping stones. In order to develop this final iteration of our design, two validation paths were focused upon. Our team systematically analyzed the valve profile of our walker and the mass distribution in our design in order to develop a successful product.

14.1 Valve Profile Validation

In order to ensure that our team's walker would successfully traverse a slope without the aid of stepping stones, we needed to quantitatively validate the efficiency of the valve profile in our walker. Doing this would allow us to adjust the valve's profile to ensure that impact and frictional losses in the valve were low enough to permit the walker to take steps downhill. To begin this process, our team designed a test setup which is shown in figure 14.1.1.

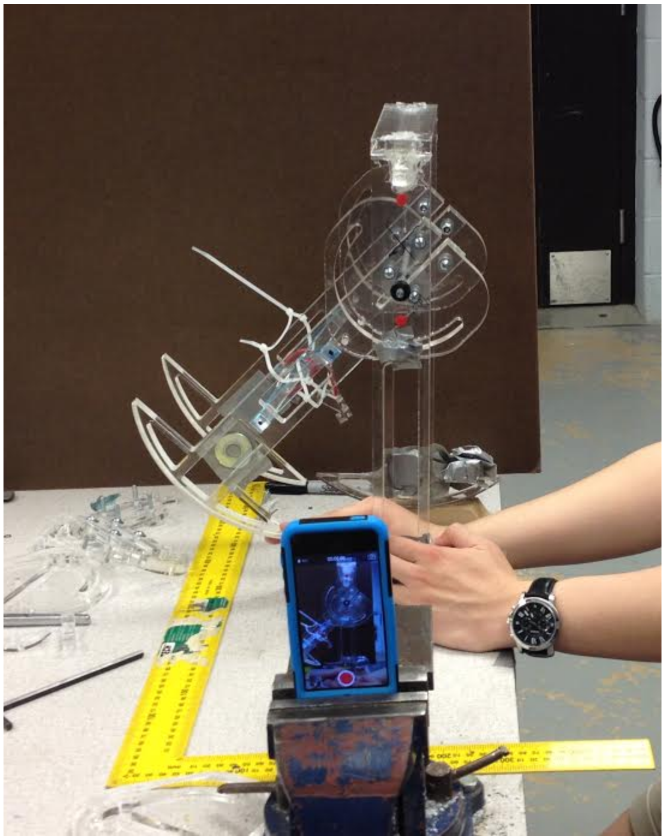
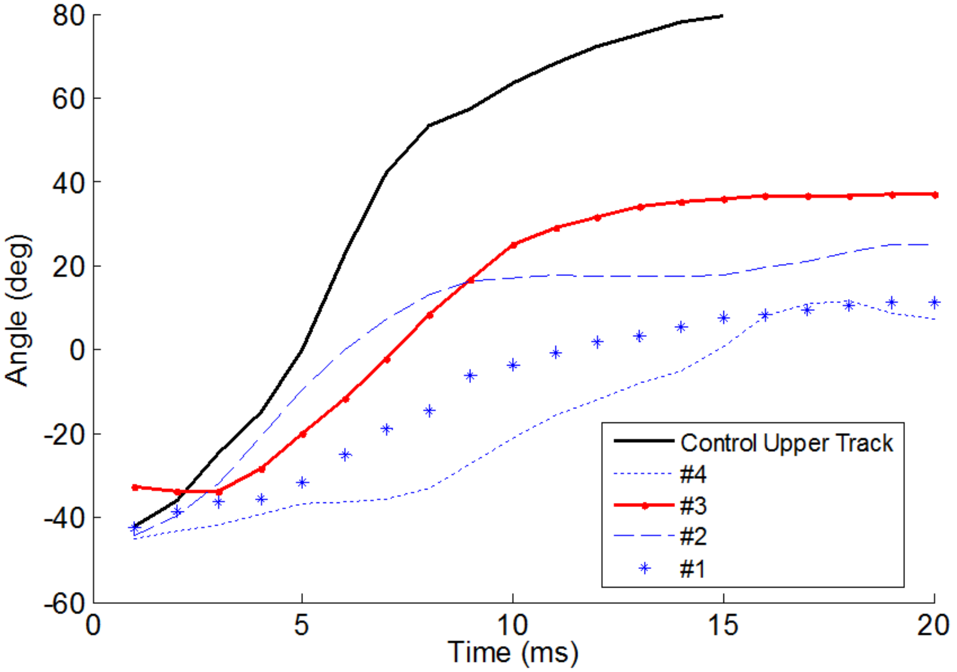


Fig 14.1.1: The inner legs were held stationary, while the outer well allowed to swing through, the opposite was then done with the inner legs swinging through. Using Kinovea and numerous different valve profiles, an optimized profile was selected.

In the test setup, the inner set of legs of the walker was held stationary on raised blocks which permitted the outer legs to swing freely. The walker was held at a marked, consistent distance from an iPhone which was used as a video camera. Two points were then arbitrarily marked on the outer legs as tracking points and a board was placed behind the walker as a solid background on which video could be recorded. The motion of the outer legs over the upper half of one valve profile was then recorded using the iPhone. This test was then repeated for each valve profile. The stance and swing leg in the test was then reversed, permitting our team to test the lower half of each valve profile for efficiency by allowing the inner legs to swing along it. During these tests, an iPhone was also used to record the motion of the inner legs over the surface of each valve with the aid of tracking points which were marked on the inner legs. Finally, our team also recorded the motion of the inner and outer legs as swing legs in a control test setup. In this setup, the tests described above were repeated on brackets which lacked valves. This permitted our team to compare the performance of each valve against an ideal control scenario.

Once each video was recorded, the recordings were subsequently analyzed using the Kinovea software, as described in section 13.1 of this report. Using Kinovea, our team was able to develop plots of the position of the tracking points versus time for the upper and lower tracks of each valve and the control. The resulting plots are shown in figure 14.1.2.

From these plots, our team was able to select the valve that behaved most like the control, which theoretically has ideal efficiency along the valve profile, as the most efficient valve. This valve was then used in our design to facilitate the functionality of our walker. The most efficient valve could also be iterated upon in order to produce higher efficiency valves and more reliable and sustained walking motion.



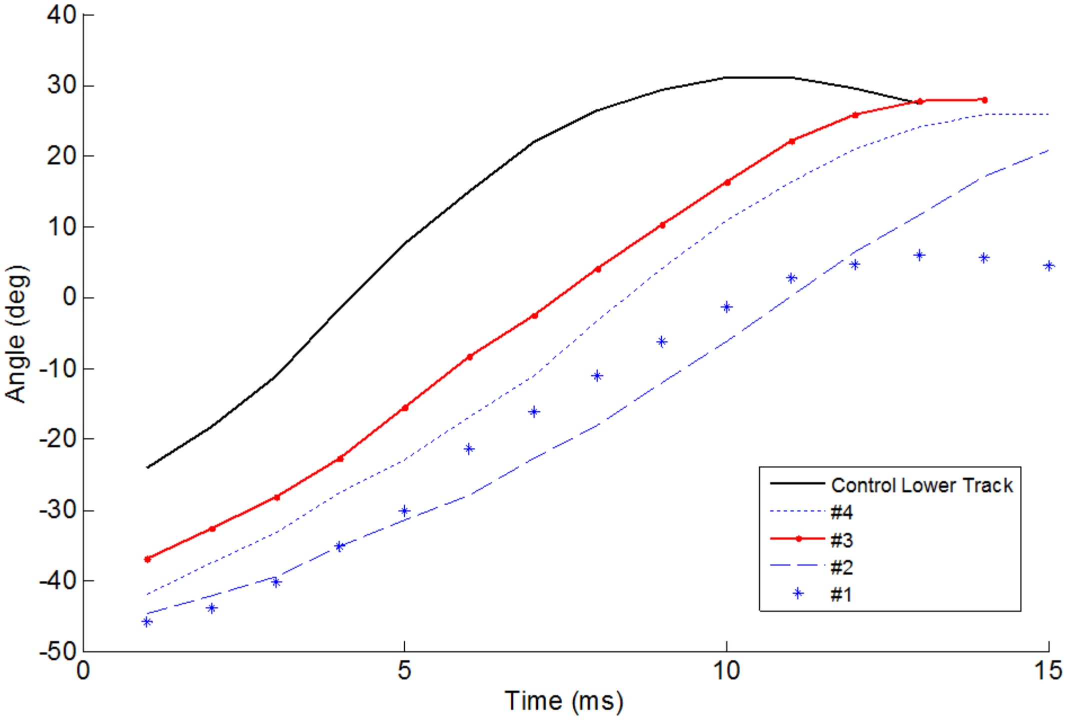


Figure 14.1.2: (Top) Plot of the upper valve track trajectory demonstrates that valve #3 affords the best performance when compared to control. (Bottom) Plot of the lower valve track trajectory confirms the selection of valve #3

14.2 Mass Distribution Validation

In parallel with our valve efficiency analysis, our team also performed a mass distribution analysis. Using the same valve-less bracket which was utilized in the operation of our control in the valve efficiency test, our team was able to isolate the mass distribution variable in our walker. Through the construction of a ramp with stepping stones, our team was able to empirically adjust the mass distribution of our walker through the use of added masses and the adjustment of the walker's foot profile. At each iteration, the design's walking properties could be rapidly tested on our stepping stone ramp and the mass distribution could be adjusted based on how the walker performed. This test setup allowed us to quickly and efficiently test large numbers of mass distribution combinations in a short period of time. The test setup which was used to perform this analysis is shown in figure 14.2.1.

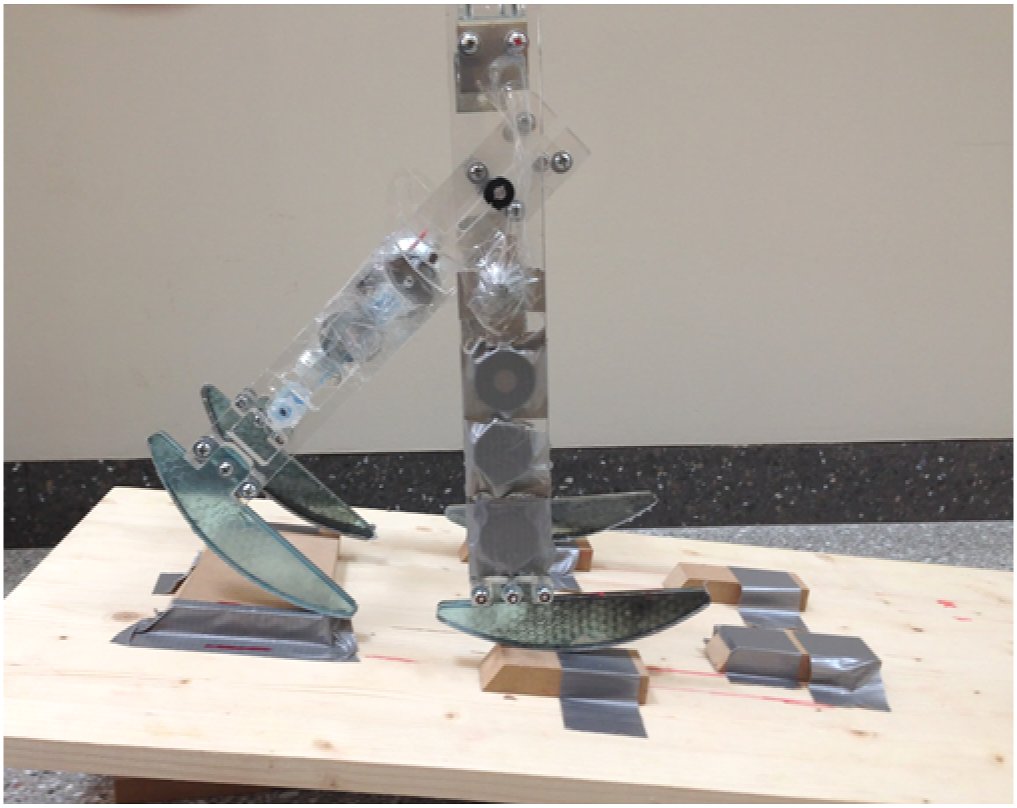


Figure 14.2.1: Walker descending the "stepping stone" ramp

Using this test setup, our team was able to determine the ideal mass distribution which would allow for our walker to attain sustainable, repeatable, and reliable walking motion. It was empirically found that the ideal walking conditions for our walker on a 12% grade slope corresponded to equal masses of the inner and outer leg sets of approximately 1.1 kg each. Additionally, by balancing each set of legs on a metal pipe, the centers of mass of each set of legs was found. For the outer legs, the center of mass was determined to be 200 mm above the bottom of the foot. In the case of the inner legs, the center of mass was located at a distance of 170 mm above the bottom of the foot. Using these mass properties, our team was able to obtain a walker which was nearly successful in descending a 12% grade slope using stepping stones.

In order to increase the robustness of our design's performance and ensure that our walker would be mobile by the design expo, our team also manufactured various foot profiles to test empirically. It was determined through testing that the foot radius and its attachment point to the leg had a significant impact on the dynamic properties of our walker, as the impact of the foot with the ground was very important in attaining a repeatable walking motion. Figure 14.2.2 shows the various foot shapes which our team empirically tested.

Figure 14.2.2: The various foot profiles which were empirically tested on our walker. The optimized foot profile is shown on the walker itself in figure 14.2.1.

The performance of the feet was quantified by the distance the walker traveled down the slope with each profile. The farther the feet permitted the walker to travel, the more efficient they were deemed. Using this methodology and the detachable foot feature of our walker design, our team was able to rapidly iterate foot design in order to optimize the foot profile of our walker. By combining the optimal foot design, mass properties, and valve profile which our team's validation methods suggested, we were able to obtain a walker which performed extremely successfully at design expo.

15.0 DISCUSSION

With the conclusion of our project, we are able to evaluate our team's ability to meet the given user requirements. In this section, we will discuss the outcomes of our design and its strengths and weakness and make recommendations for future work.

15.1 Outcomes of Design

In evaluating the outcomes of design, our team found that we were successful in meeting several of the stipulated user requirements. First, we have successfully created a passive dynamic walker capable of locomoting down a smooth incline. It has, with great reliability, traversed down a slope 48 inches in length. Secondly, the passive dynamic walker is manufacturable using DIY methods and tools. Most of the structural components are laser cut, and the walker is assembled using rudimentary tools like a screwdriver, hand saw and a hot glue gun. Thirdly, we note that the cost of procuring the parts (per unit walker) is approximately \$75. While this exceeds our user specifications, we envisage that the cost of parts will be less if bought in bulk quantities. Lastly, we observe that our final design is indeed suitable for outreach. This is because most members of the public were largely able to successfully operate the walker during the Design Expo within their first attempt. While the size dimensions of our walker are within specifications, the walker, which weighs approximately 2.2kg, is significantly heavier that our initial user specifications.

15.2 Strengths of Design

The most crucial strength of our design is the large basin of attraction that our walker possesses. This means that the walker is not overly sensitive to the initial conditions provided by the human user, thereby enabling ease of operation.

In addition, our walker is able to traverse over a range of slope sizes, from an 8% gradient to a 12% gradient. This was achieved using a feet radius of 8.5”. We have, however, designed our walker with detachable feet. In doing so, we allow the user to adapt the walker to best perform on any available slope.

15.3 Weaknesses of Design

While the performance of our design as a dynamical system is exceptional, there are numerous weaknesses that affect the suitability of our design in a DIY context. In its current iteration, our walker costs approximately 87.5% more than the intended cost. We are able to attribute this to the proportionately high cost of the roller bearings. Given that frictional losses will greatly diminish the ability of the walker to sustain sufficient kinetic energy, a low friction contact surface was implemented, albeit at high financial costs. In the use of the roller bearing, there currently exists a trade-off between performance and cost.

In creating our walking, the majority of our efforts were focused on the dynamical performance. We are cognizant of the manufacturing challenges a DIY manufacturer will face. During the assembly of the inner leg, it is essential that the inner leg structure is completely aligned before the process of adhering the substructures with a hot glue gun is completed. It is also possible that the contact of the hot glue gun with the structure would cause it to shift out of alignment. Failure to align the structure would result in the constriction in motion of the valve and an ultimate failure in the walker’s performance.

15.4 Recommendations

In response to the weaknesses of our project, we have come up with a series of recommendations for our sponsors, future teams, or members of the public to undertake.

15.4.1 Manufacturability Improvements

To aid in the ease of manufacturability of the inner leg, we recommend the addition of snap fit joints onto the inner leg. This can be achieved by making minor modifications to our current CAD designs. More importantly, a considerable effort is required to identify the necessary dimensions required (vis a vis the material properties of acrylic) for a snap fit to be feasible. This is challenging, given the variance in the laser cut part dimensions due to inaccuracies in the manufacturing process.

Another manufacturability improvement is the integration of ballast into walker design. This would thus negate the need for additional ballast masses, which are current adhered by means of duct tape.

15.4.2 Cost Optimization

To further reduce the unit cost of manufacture and assembly, we would recommend the redesign of the roller bearing component. Our team's efforts to utilize lower cost, off-the-shelf-components were unsatisfactory, given the high friction generated by the less expensive components. In recognizing the trade-off between performance and costs, we recommend that further efforts be undertaken to piece together a low cost, yet fully functional roller bearing assembly.

We also recommend the exploration of the use of a thinner sheet of acrylic, or even the use of less expensive materials. It is likely that a thinner sheet of acrylic would still be sufficiently structurally robust to support the demands of a passive dynamic walker.

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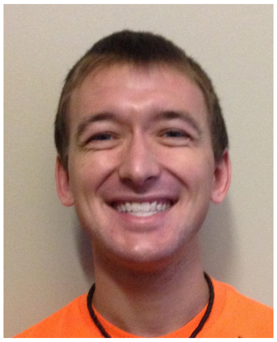
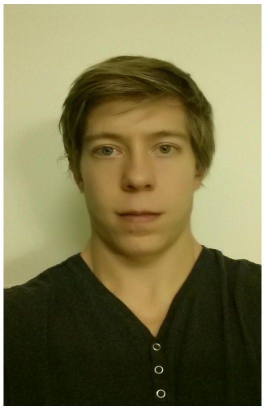
He has worked at GE Aviation with the F414 program, Space Exploration Technologies with the Crew Dragon space capsule, and for Boeing's Direct Attack organization.



Joshua Rumsey was born in Ohio in 1993. He is currently pursuing a B.S. Degree in Mechanical Engineering at the University of Michigan and plans to graduate in May of 2015. His academic interests are structural and systems design.

Josh has worked at Boeing on the F-15 program as a structural designer for the past two years. He looks to continue working at Boeing upon graduation and further his work as a structural designer.



Peter Mardaleichvili was born in Switzerland in 1993. He is currently pursuing a B.S. Degree in Mechanical Engineering at the University of Michigan. His academic interests include physics, philosophy and classical civilization.

He has interned in the European Organization for Nuclear Research at CERN and has worked on developing a business plan for a water venture in the city of Tbilisi, Georgia.

Appendix A: DR2 Project Plan

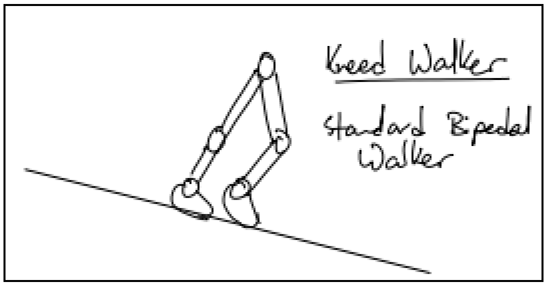
- Generate Concepts
    - describe major categories of concepts generated and methods used to generate concepts (brainstorming and functional decomposition at minimal) - revise and finalize reqs in pugh chart by 1/29 - josh
    - all concepts must be well-organized in appendix, include even obviously unfeasible ones. finalize concept generation by 1/31 - all
    - in main text, several concepts should be discussed in detail. describe major categories of concepts and methods used to create them
- Concept Selection
    - use logical/objective scoring method to meet user reqs. Assess concepts through pugh chart by 2/3/2015
    - assess feasibility in write up
        - describe weighting and process in detail in the main text
        - discuss advantages and disadvantages
        - make strong argument for chosen concept
- Chosen Design Mockup
    - will communicate final design concept idea
    - what are design drivers, problems expected
    - create CAD model by 2/6 - Elio
    - Makeathon 2/6 - 2/8 - all
    - analyze design specs and identify the engineering fundamentals that need to be addressed

- physical model and describe key insight gained in write-up

Task	Date	Owner
Revise Pugh Chart func. reqs.	1/29/2015	Josh
Describe major categories of concepts generated and the methods that were used to generate these concepts	1/29/2015	Josh
Finalize concept generation (at least 20)	1/31/2015	All
document all concepts in appendix	1/31/2015	Peter
describe weights and method to select final concepts. Discuss advantages and disadvantages.	2/3/2015	Josh
Assess pugh chart and choose final concept	2/3/2015	All
Several Concepts must be described in detail in the text	2/4/2015	
CAD model for Makeathon	2/6/2015	Elio
Write what aspects of the design will be the most challenging per user reqs. What's difficult per project limitations. What are drivers. What problems are to be expected and how to address them.	2/10/2015	

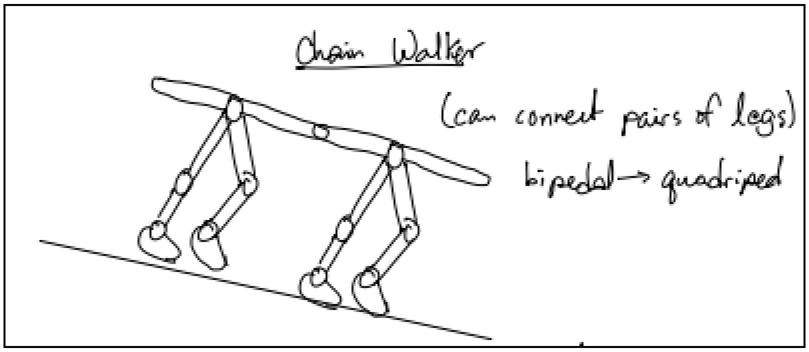
Appendix B: Detailed List of Generated Concepts

Concept 1:



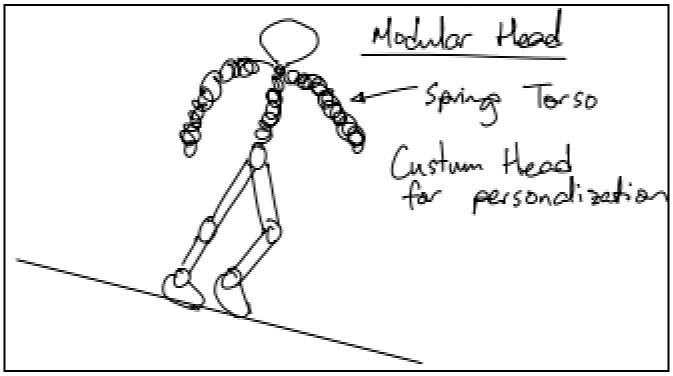
This concept is referred to as a “kneed” walker in that, in addition to having a hip joint, it has a joint separating the leg into two parts. This concept relies on a double pendulum, which requires very stringent initial conditions and is very susceptible to perturbations. For a successful movement, the swinging leg is bent, creating the required ground clearance to successfully walk down a slope.

Concept 2:



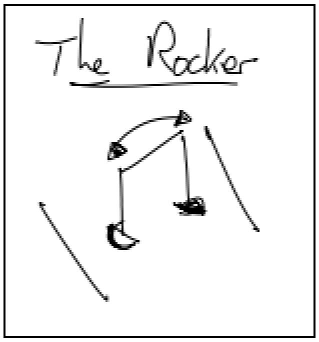
This concept is almost identical to the concept above, however, instead of having two limbs, it has four. Everything mentioned above is true for this concept, however, some of the issues with getting the multiple pendulums working in time are increased with four limbs rather than two, while some of the perturbation caused by balance issues could be decreased by the increased stability created with four legs.

Concept 3:



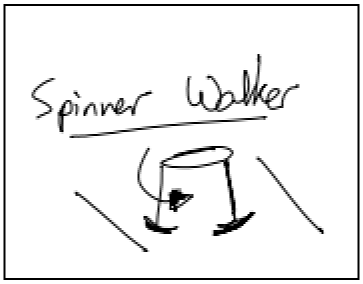
This concept allows the user to modify the upper half of the walker, such that it can be personalized to a person's particular interest, possibly generating more interest and getting more people involved with the walker.

Concept 4:



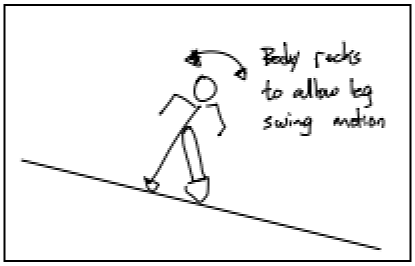
This concept relies on bowl like feet that allow rocking from side to side; as one of the legs lifts off gravity causes it to shift down the slope and as it lands, it rocks out, causing the other leg to repeat the action.

Concept 5:



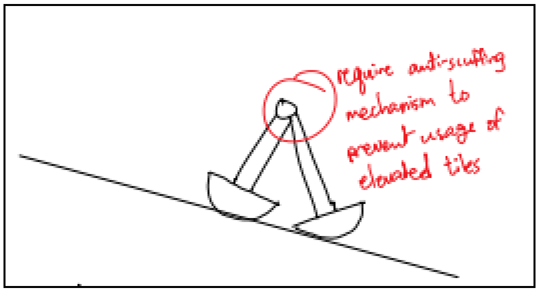
This concept is started by spinning and then, in a way similar to the rocker, it transfers its mass from one leg to the next through a rocking motion caused by the spinning. This concept is very unstable and has a tendency to veer off path, in the direction of rotation.

Concept 6:



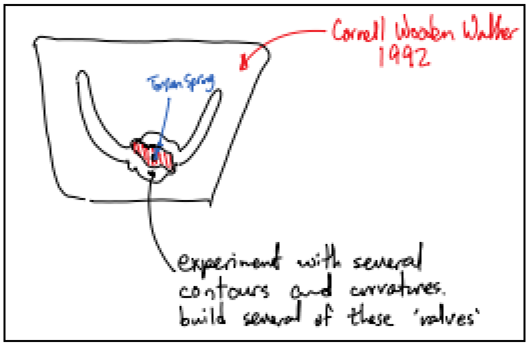
This concept is derived from the Museon walker's dynamics. It combines one of its leg limbs with a weighted torso and head. By rocking this torso front to back, the device's swing leg is permitted to complete its motion. The aesthetical aspect of this design is very appealing as it resembles a crude human form.

Concept 7:



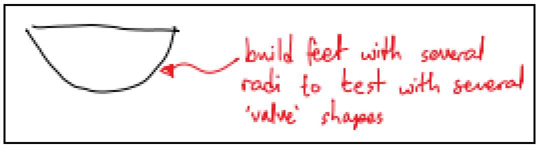
This concept shows the leg attachment from a side view. The hip area requires a mechanism to retract the swinging leg, as to create ground clearance for the leg moving from the back to the front. It is a basic concept using two similar pendulums and their oscillatory behavior to permit the walker to descend a slope.

Concept 8:



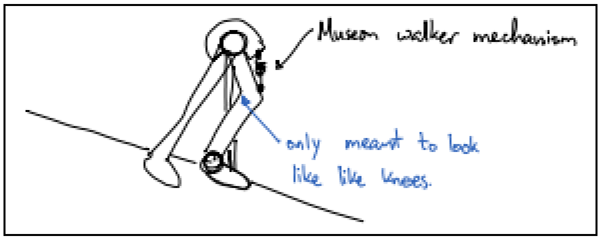
This concept shows a mechanism based off of the Cornell Wooden Walker [13] that would allow for the retraction of the swinging leg. The mechanism relies on a small valve (shaded in red) that is connected to a torsional spring that keeps it in the position shown. As the outer legs move through the mechanism, they pass over the top of the valve, lifting themselves up and producing the clearance necessary to prevent foot scuffing. Then, as the inner legs swing forward, the outer legs push on the bottom of the mechanism lifting up the inner legs and allowing for them to complete their swinging motion.

Concept 9:



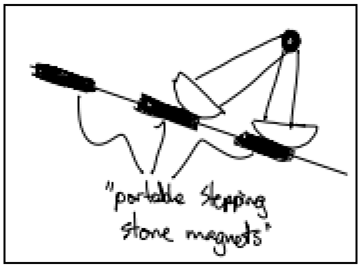
Given that the impact of the foot and ground is an inelastic condition, we anticipate that it will be difficult to predict the resultant energy dissipation of the foot upon impact. Therefore, a trial-and-error approach is best suited for the design of the foot. To facilitate the said approach, we will design detachable feet structures that vary in their radial profile.

Concept 10:



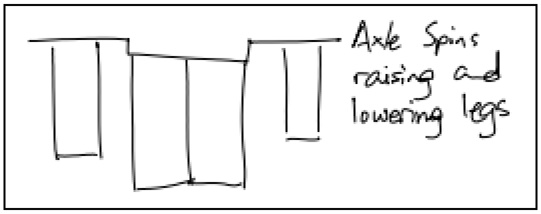
Designs exist in which passive dynamic walkers take on a humanoid form. This feature is appealing especially for outreach purposes in mind. A humanoid form will allow an audience to relate to the mechanism and potentially become engaged with the walker. A method to achieve this can be seen with the Museon Walker [11], where a spring-like torso is achieved with a high stiffness spring. This serves the purpose of creating a countermass with the 'head' of the mechanism such that it improves the dynamics as observed through Museon's experimentation.

Concept 11:



This concept incorporated the use of magnets in order to extend the stance legs to allow for the swing legs to complete their motion. As the swing legs swing past the stance legs, a rod within the stance leg pushes the magnets off of the stance legs so that they can reattach to the swing legs via magnetic attraction. This allows for a cyclical walking motion without foot scuffing.

Concept 12:



This concept incorporated a bent rod exhibiting a crank-like motion in order to permit the raising and lowering of the swing leg. As the bent rod turns, alternating sets of legs are raised such that they can swing through their motion.

Appendix C: DR3 Project Plan

- Update Executive Summary
- Detailed engineering design of your prototype, including rough draft engineering drawings for all parts generated in CAD :
  -
- An analysis of each design driver utilizing theoretical modeling, empirical testing, or mock-up construction
- Failure Modes and Effect Analysis (FMEA) and/or Risk Analysis
- Refined mock-up from DR2
- Initial Manufacturing Plan Update your current design description from DR2 to incorporate any information resulting from your analyses, while noting any remaining challenges or gaps of information

Theoretical Model

- Computer generated model from simulation
- Governing equations and describe variables
- show results, not intermediate steps

Empirical Testing

  - Experimental Setup
  - List steps, include enough detail for replication
  - Present any results in any appropriate format, highlighting notable results

Mockup Construction

  - Include figure of mockup with labels
  - Describe manufacturing process and assembly process
  - Describe lessons learned from building mockup, what materials/manufacturing methods to use in future

Task	**Date**	**Owner**
REPORT		
Update Executive Summary	2/25/2015	all
CAD of mechanism	2/20/2015	Elio
Analysis on theoretical modeling	2/20/2015	Garry
FMEA risk analysis	2/23/2015	Peter
Initial Manufacturing Plans	2/23/2015	Elio
Computer Generated model from simulation	2/20/2015	Garry
governing equations	2/20/2015	Garry
results from simulations	2/20/2015	Garry
Experimental setup for testing mechanism, with enough detail for replication	2/20/2015	Josh
Present relevant results of experimental data	2/26/2015	Josh
Mockup construction with labels	2/20/2015	Peter
Describe mockup manufacturing process and assembly process	2/20/2015	Peter
Describe lessons learned from mock-up construction	2/20/2015	Peter
Submit Report	2/27/2015	All
BUILD		
Design new outer leg with corrected alignment	2/15/2015	Peter
Construct New Outer leg	2/20/2015	Peter
Build new spring mechanism onto current mockup	2/22/2015	Josh

APPENDIX D: DR4 PROJECT PLAN

- Update Executive Summary
- Finalize Matlab model and pick most effective geometry
- Final CAD Design and Drawings

    - include tolerancing where necessary
- Write manufacturing plans for each component to be manufactured
    - lasercutter instructions
    - assembly instructions
- Build Final Prototype
    - laser cut respective components
    - order parts that are off-the-shelf

	Owner	Due Date
Report		
Update Executive Summary		
Finalize Matlab model and pick most effect geometry	Garry/Elio	6-Mar
Finalize CAD model and Drawings	Elio	9-Mar
Write manufacturing plans	Peter	11-Mar
laser cutter instructions	Peter	11-Mar
assembly instructions	Elio	11-Mar
Build	Josh	
Laser cut respective components	Josh	15-Mar
Mill respective rods	Elio	16-Mar
Order Parts	Josh	9-Mar
Assemble	All	16-Mar

APPENDIX E: DR5 PROJECT PLAN

EXPERIMENTS: ENSURE FUNCTIONALITY AND SIMPLIFY DESIGN FURTHER

1. FRICTION LOSSES – determine what mechanism would act as best roller that will follow track
    a. Single pin joint – to use as control
    b. Pins (no valve) – easiest to incorporate to design (requires no machining)
    c. Two pins (valve) – theoretically reduces losses due to friction, but requires machining of shaft to press fit and accommodate onto walker
2. SLOPE VS FOOT RADIUS – tabulate foot radius to be used on specific slope ranges
3. FIND CENTER OF MASS – document procedure to experimentally determine center of mass on each leg and add masses to match each leg's. Must also match masses.

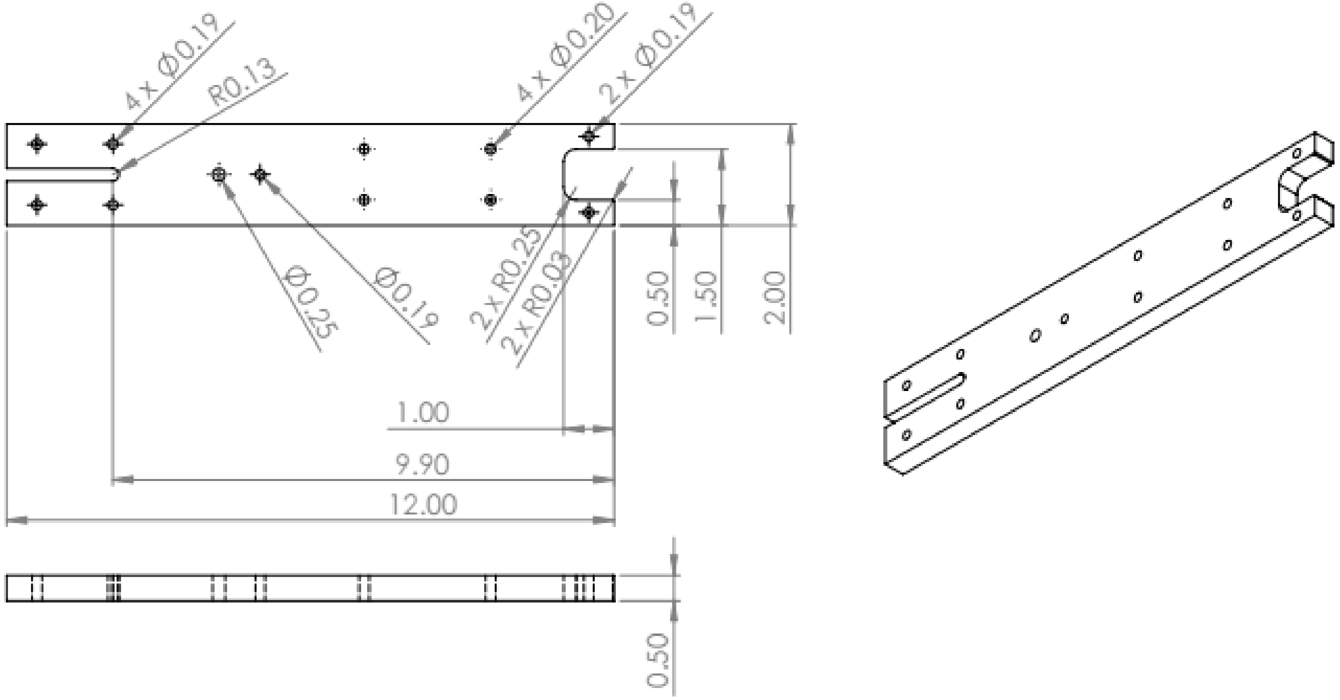
NEXT STEPS

Focus: Optimization to lower cost and assembly time and raise efficiency in motion

Proposed Methods:

1. Reduce friction losses – replace 0.5” valve and hip bracket with 0.25” or less.
    a. Reduce weight of inner leg by removing fasteners and use puzzle-like features to assemble inner leg. Also use 1/4” plastic instead.
    b. Redesign valve to account for a smoother path for the roller, as suggested by sponsors
2. Create website for DIY enthusiasts
    a. Include videos on Passive Dynamic walkers
    b. Include video of our assembly
    c. Include materials to be used in outreach (intro. to engineering, design process, dynamics, etc)
    d. Include CAD models and .dxf files to be downloaded for replication and distribution.
    e. Include assembly manual to be easily read
    f. Include explanations to engineering solutions

APPENDIX F: MANUFACTURING DRAWINGS



PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY	USED ON	
APPLICATION		DO NOT SCALE DRAWING

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Acrylic
FINISH

	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

ME 450

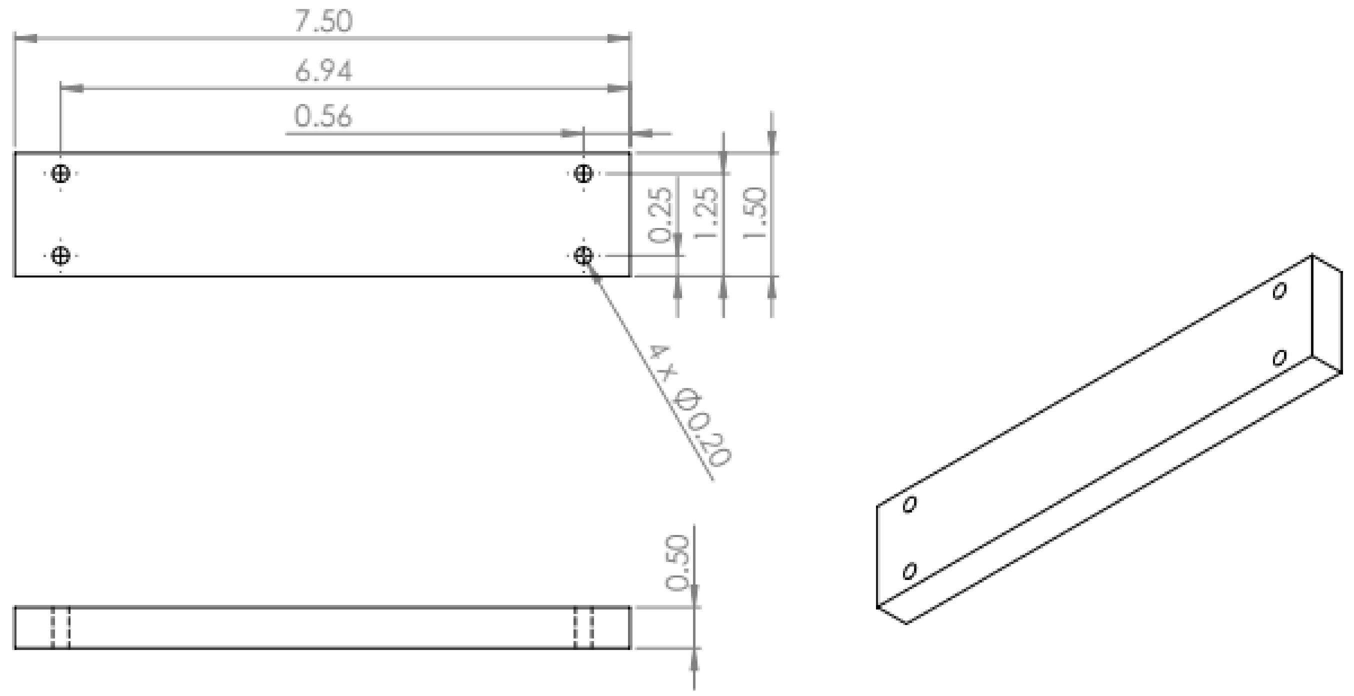
TITLE:

Inner Leg (x2)

SIZE A DWG. NO. 2 REV

SCALE: 1:3 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



ME 450

TITLE:

Outer Leg Top Bridge (x2)

	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Acrylic

FINISH

DO NOT SCALE DRAWING

NEXT ASSY	USED ON

APPLICATION

SIZE A
DWG. NO. 3
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

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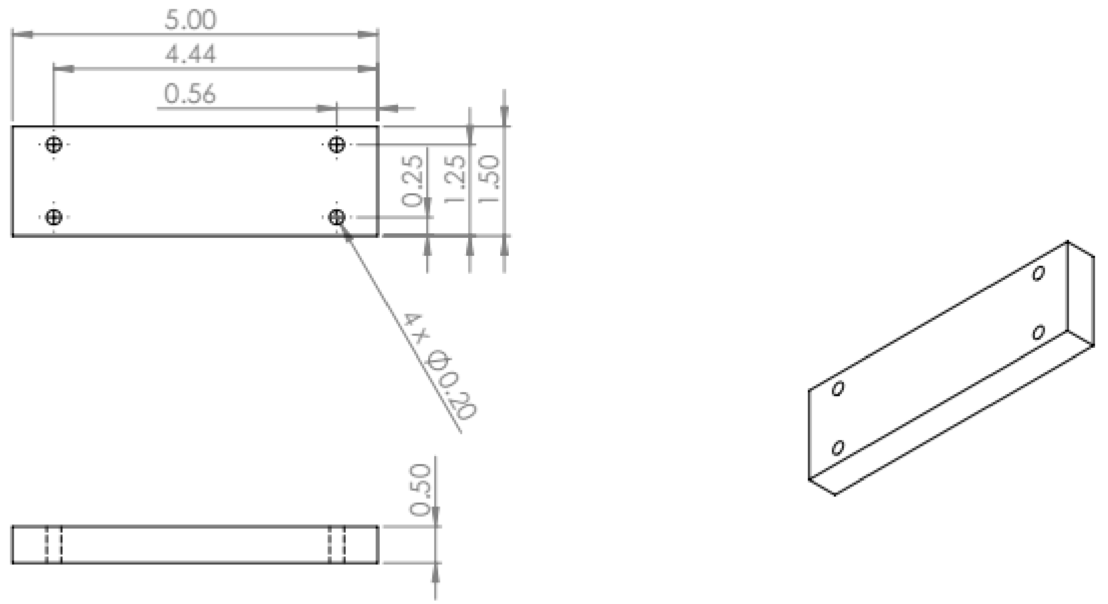
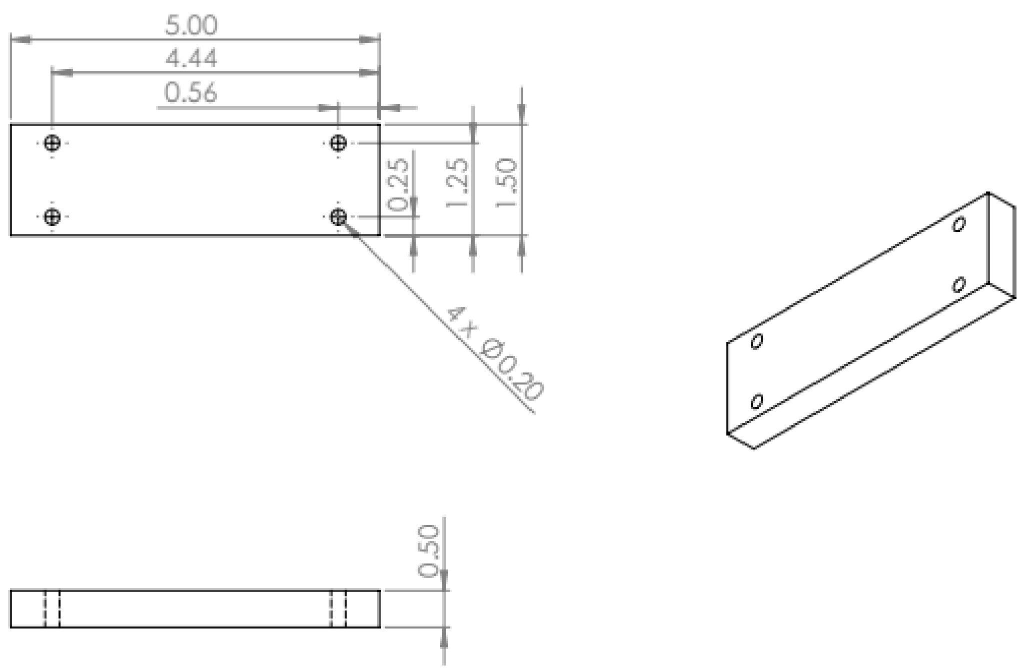
5 4 3 2 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	ME 450
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	Team 15	03/13/15	TITLE: Inner Leg Top Bridge (x2)
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Acrylic	COMMENTS:			SIZE A DWG. NO. 4 REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: Acrylic
FINISH
DO NOT SCALE DRAWING

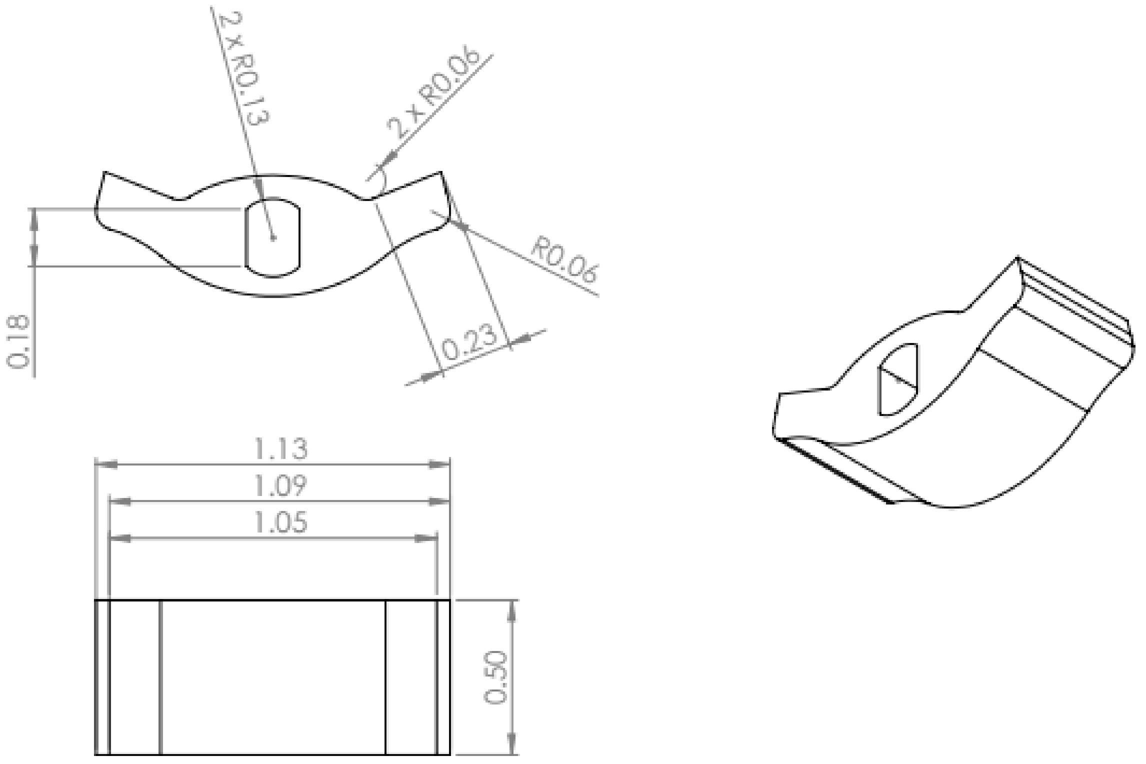
	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

ME 450

TITLE:
Inner Leg
Bottom Bridge (x2)

SIZE: A
DWG. NO.: 5
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Acrylic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

Most feautures cannot be made into lines or circular arcs for dimensioning puposes, however, can be cut by the laser cutter

ME 450

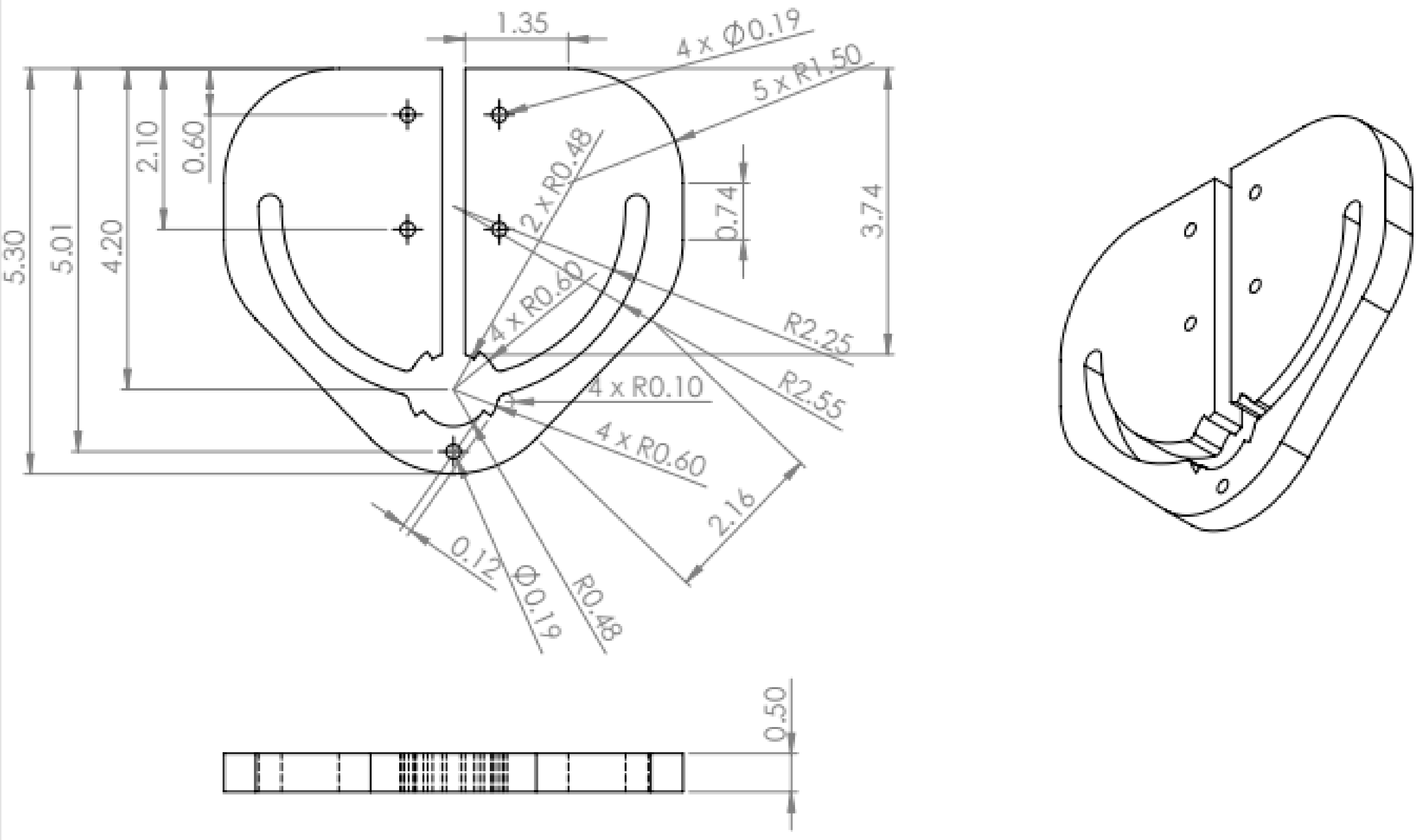
TITLE:

Valve (x2)

SIZE	DWG. NO.	REV
A	6	

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Acrylic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
The part is symmetrical, all the dimensions dimensioned on one side are the same on the other. This part will be laser cut,however, if more clarity is needed for the dimensions, multiple drawings with fewer dimension can be provided.

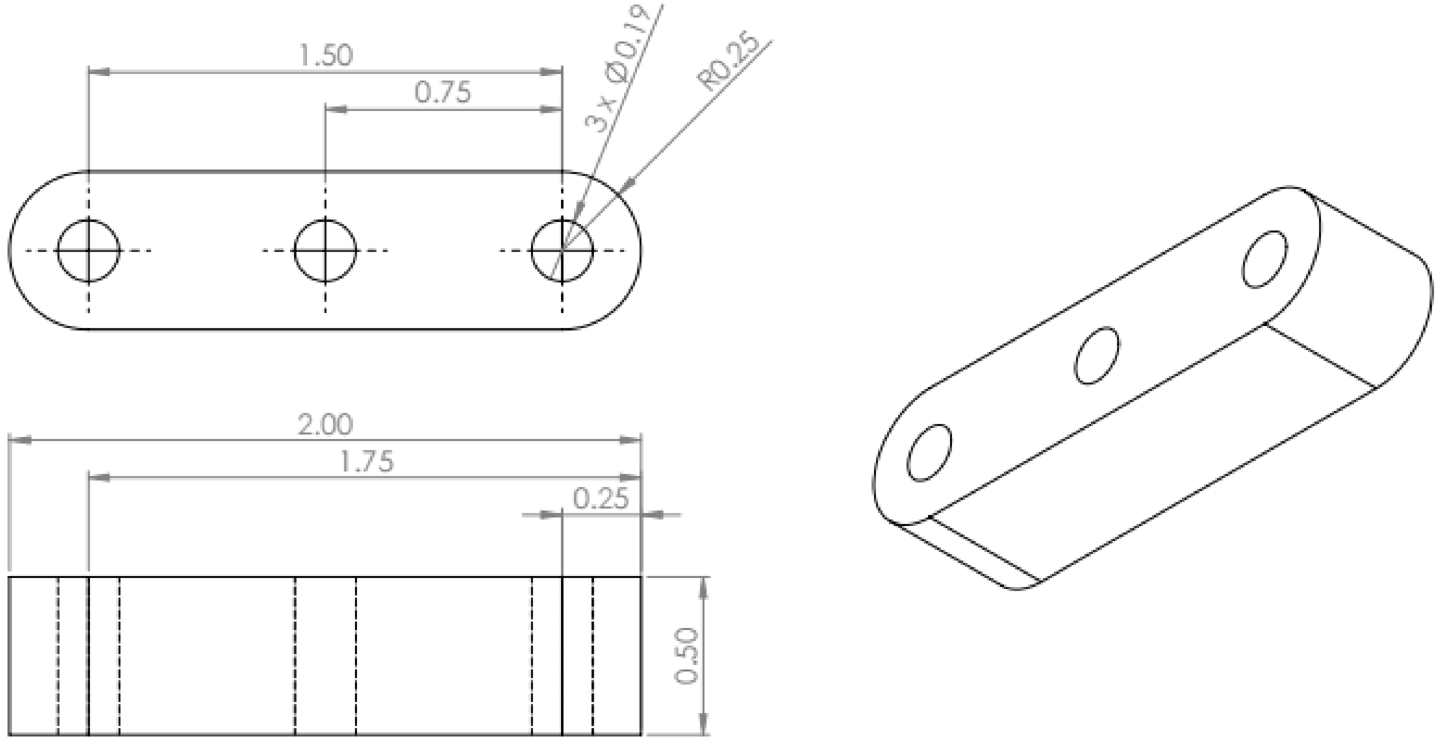
ME 450

TITLE:

Acrylic Fixture (x2)

SIZE	DWG. NO.	REV
A	7	
SCALE: 1:2	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Acrylic
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

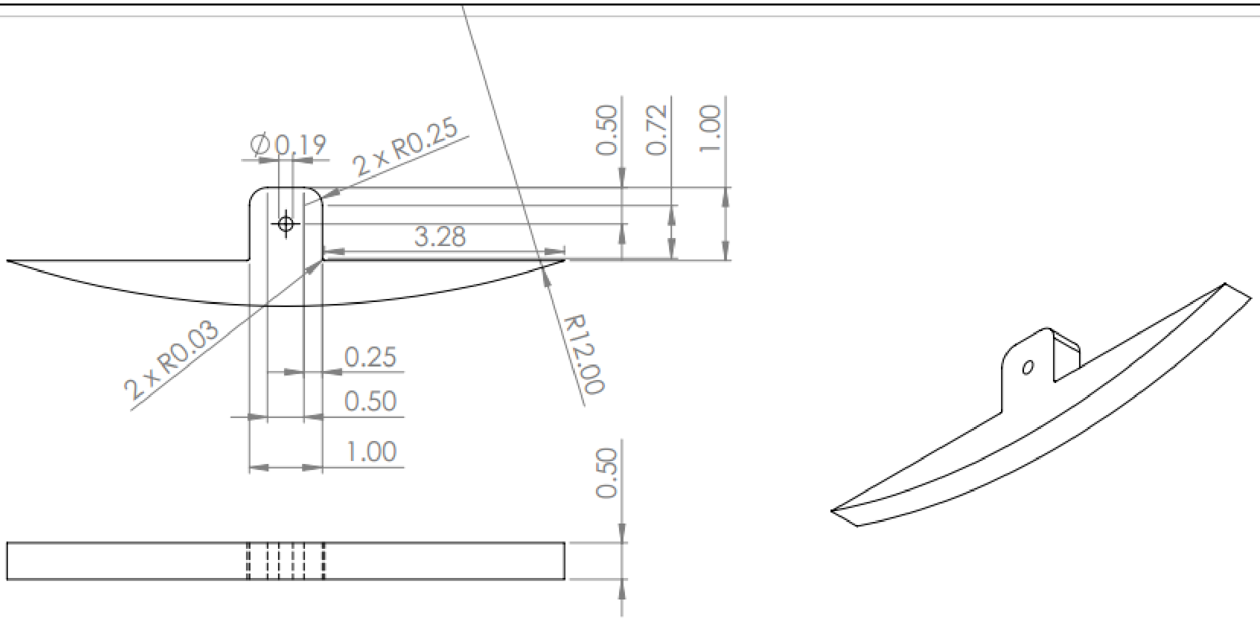
ME 450

TITLE:
Foot Bracket (x2)

SIZE A
DWG. NO. 8
REV

SCALE: 2:1
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Acrylic

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

ME 450

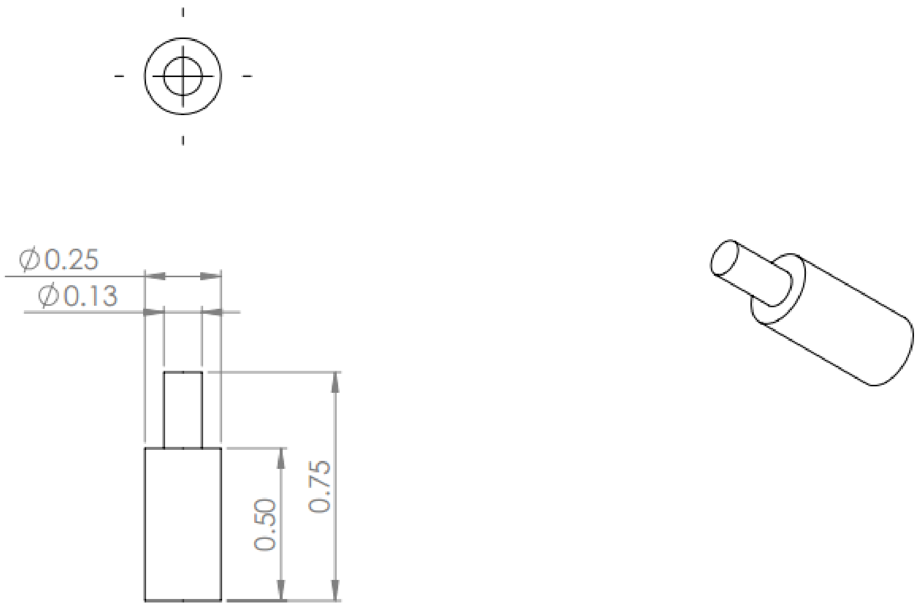
TITLE:

Foot (x2)

SIZE A
DWG. NO. 9
REV

SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±.020
THREE PLACE DECIMAL ±.005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Aluminum

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

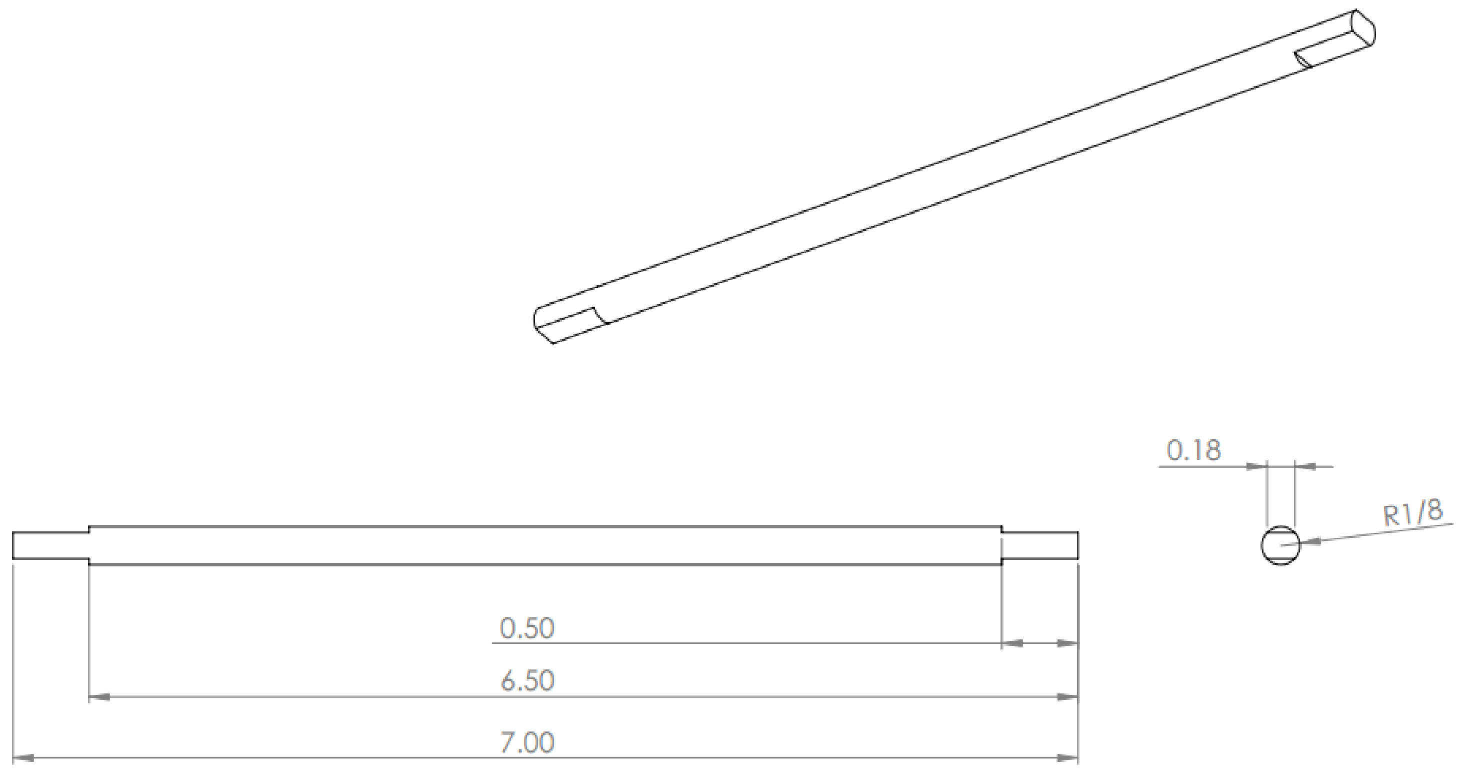
ME 450

TITLE:

Slot Pins

SIZE A DWG. NO. 10 REV

SCALE: 2:1 WEIGHT: SHEET 1 OF 1



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	ME 450
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ±.020 THREE PLACE DECIMAL ±.005	DRAWN	Team 15	03/13/15	TITLE: Key Slot Axle
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL Steel	COMMENTS:			SIZE A DWG. NO. 11 REV
NEXT ASSY	USED ON	FINISH				
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:1 WEIGHT: SHEET 1 OF 1

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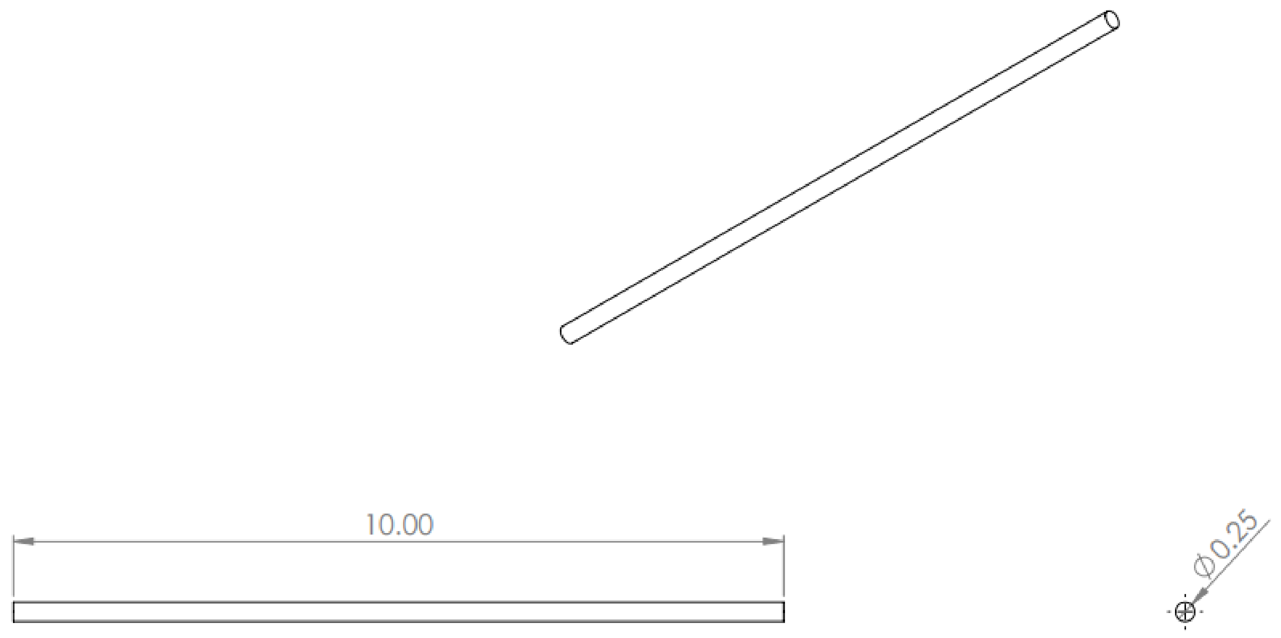
5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL Aluminum
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	Team 15	03/13/15
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

ME 450

TITLE:

Upper Axle

SIZE A
DWG. NO. 12
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1

APPENDIX G: MANUFACTURING PLANS

Part Number: 010
Part Name: Slot pins
Team Name: Team 15 (Passive Dynamic Walker)

Raw Material Stock: Aluminum shaft, 1/4" diameter

Step #	Process Description	Machine	Fixtures	Tool(s)	Speed
1	Measure 2 inches and cut with band saw	Band saw			900 rpm
2	Place cut piece into lathe	Lathe	3 jaw clamp		
3	Machine down .25 inches off end to 1/8 inch diameter by facing	Lathe	3 jaw clamp	Facing tool	900 rpm
4	Leave part in lathe and us splitting tool to cut part to size (.75 in)	Lathe	3 jaw clamp	Splitting tool	900 rpm
5	Leave part in lathe and brake edges	Lathe	3 jaw clamp	file	800 rpm
6	Remove part from lathe.				

Part Number: 012
Part Name: Upper Axle
Team Name: Team 15 (Passive Dynamic Walker)

Raw Material Stock: Aluminum shaft, 1/4" diameter

Step #	Process Description	Machine	Fixtures	Tool(s)	Speed
1	Measure 11 inches and cut with band saw	Band saw			900 rpm
2	Place cut piece into lathe	Lathe	3 jaw clamp		
3	Machine to correct length by facing	Lathe	3 jaw clamp	Facing tool	900 rpm
5	Leave part in lathe and brake edges	Lathe	3 jaw clamp	file	800 rpm
6	Remove part from lathe.				

APPENDIX H: ETHICAL DESIGN & ENVIRONMENTAL IMPACT STATEMENTS

by Garry Lim

Ethical Design: Our team has been tasked to undertake the design and construction of a Passive Dynamic Walker. The walker serves two major roles: a demonstration artefact to engage an audience to pursue a career in STEM and to serve as a blueprint for DIY projects. This statement seeks address the ethical concerns and considerations in the context of these two roles.

The Passive Dynamic Walker will be used to inspire future budding engineers. In doing so our project's intended goal is in line with Fundamental Principle III of the ASME Code of Ethics, which stipulate that engineers should strive '*to increase the competence and prestige of the engineering profession*'.

More crucially, the safety of the demonstrator or outreach participants is of utmost importance. We recognize that the nature of our design, in its very essence a *toy*, bears a considerably low risk to the user. The walker locomotes down a ramp of around 0.2m high, and has a mass of less than 2kg. These parameters entail that the chance of an injurious outcome if the walker lands on a user is remote. In light of user safety, in our final iterations of the prototype, we will design components that has few or little sharp edges. All possible edges will be blunted by design or sanded down.

The second role of our design is to provide a blueprint for science enthusiast to construct their own walker with provided CAD drawings. While we recognize that the safety of a DIY home user is largely his responsibility, we can seek to provide designs, production methodologies and safety instructions that mitigate the risks of DIY production and personal use of the walker device.

The main steps of DIY production are laser cutting of acrylic material and the fastening of components with mechanical fasteners and glue. Most laser cutters are have an in-built safety feature, that is, to deactivate the laser when the cutting chamber has been opened. We will be recommending the laser cutter settings pertinent to the laser cutter we utilized in the prototype construction, as suggested by the University of Michigan Mechanical Engineering Department. To reduce the sharp edges on the walker, we will provide instructions on the necessary steps required to sand down certain features of the laser cut material. In the fastening of the walker components, we sought to ensure that the walker can be assembled with rudimentary tools not uncommon in most household settings.

A safety advisory will be attached to the CAD drawings when the walker designs are circulated. We will underscore the dangers of ingesting any walker components, especially for young children. All use and production of the device is to be supervised by an adult. Only fully functional laser cutters should be utilized in the implemented in the cutting of acrylic parts. In addition, all parts procured or manufactured should only be used in the intended purpose of the passive dynamic walker. A video of how a passive dynamic walker is used will be attached, to show the general public the intended purpose and correct means of use.

Environment Impact: The production of a physical product bears an environment impact. It is expected that the construction of our passive dynamic walker will inevitably bear an impact. However, these have been considered, and we will discuss the efforts taken to address these impacts.

The passive dynamic walker is constructed predominantly out of acrylic. This brings several environmental advantages. Firstly, acrylic is recyclable. Secondly, acrylic can be laser cut. While we recognize that a laser cutter can possibly consume a considerable amount of energy, the construction of passive dynamic walker is an expedient process (<40 minutes). A laser cutter is fairly accurate, reducing the chances of producing defective components. Lastly, we will circulate CAD drawings of our walker where the laser cut components are systematically arranged to involve the use of least material, hence reducing material wastage.

A fully passive design has several advantages. The lack of active electronic components, (as a demonstration of Newtonian Physics in educational institutes) will result in the long-term relevance of our product. Our walkers should not be discarded as they cannot be considered as antiquated. The procured components of our walker are easily replaceable and acquired, meaning that the overall lifespan of the walker structure is considerably long.

At the end of the user lifecycle of the passive dynamic walker, the walker can be discarded, where the acrylic is recycled. Alternatively, we suggest that such a walker be donated to an education institute, given the wide range of uses for such a walker.

by Elio Morillo

Ethical Design Statement: The design of our Passive Dynamic Walker revolved around educational purposes. This implied that we had to consider simplicity for our end-user as well as the potential exposure to end-users with little to no technical experience. Our end-user would have to be able to manufacture and assemble the Walker without worrying of harm. With the exception of the roller bearing, which is currently needed to achieve functionality and requires a lathe, we have designed our parts to be made on a laser cutter and be complemented with off-the-shelf parts. As we move towards a final product we will utilize Kinovea to develop a roller that will be easily assembled and requires no machining.

By nature, the laser cutter process will create rough edges on the acrylic material. In our final website, as we distribute our parts to the public, we will note that filing the edges is required to prevent minor cuts. With that, we will also point out potential pinch points. As the mechanism walks down the slope, there will be locations within the mechanism that will cause pinching if the end-user places their hands in such locations. The pinching points are created by the natural dynamics of the mechanism, so we will make sure the end-user understands this. In assembly, the user will need to utilize glue for the plastic and some screwdrivers and wrenches for the nuts and bolts. With that said, if young children are to use this device, we will specify the need of adult supervision to prevent the ingestion of small components and to provide assistance in the assembly process.

The Do-It-Yourself aspect of our project will ultimately give the end-user the ultimate responsibility for their safety. We will be providing CAD files to be used with laser cutters. However, there is the chance that the end-user will want to alter the material used and the manufacturing process to achieve precision. We will emphasize that this particular design has only been tested on acrylic and laser cutter, other materials and manufacturing processes would be up to the end-user's discretion.

Our walker is intended to be used with diverse audiences. We will need to be sure that our walker is not offensive to anyone. The outreach purpose of the walker, alongside its scientific presentation, will have to be toned to not offend our audiences. With that said, we hope to inspire our audiences to become intrigued by dynamics and with such curiosity we hope to see more interest in STEM. By doing so, we are promoting the Code of Ethics and promoting the engineering profession.

Environmental Impact: Acrylic, being our primary construction material, is considered a category 7 plastic which is difficult to recycle as current recycling processes of such materials are expensive. Realistically speaking, the production of our walker will be limited. This mechanism is not intended to become a mass-produced educational product. Even so, in the case of disposal, there are processes in place that do recycle acrylic and repurposes its usage. It is also up to the user to repurpose the usage of the material once it is decided that the Walker no longer serves any usage.

We are working to fit every component per walker on a 12" x 24" x 0.5" piece of acrylic. This will keep costs down for the end-user as well as reduce the usage of acrylic. Using a laser cutter requires significant amounts of energy, however, it is not mass produced, so we use relative low power per walker. The steel bolts and nuts can most definitely be recycled and repurposed as we are using commonly used #10-24 ½" fasteners and respective nuts.

The educational purpose of this device allows for its end-user to pass it onto another user in the case they are trying to get rid of it. There is a need to promote STEM across different audiences, which gives the end-user the option of donating the mechanism to an educational entity rather than dispose of it.

A major advantage of our passive system is the absence of electronic components. This prevents the disposal of the such and greatly reduces the negative environmental impact generally caused by electronic components.

by Josh Rumsey

Ethical Design: In addressing the problem of designing a passive dynamic walker, our team considered engineering ethics in each step of the design process. The first of these was in the design selection phase of our project. After our team conducted a literature search in the field of passive dynamic walking, we found that numerous different solutions to the problem which we were addressing had already been proposed. In light of this information, our team wanted to focus on creating an original design which, while building off of the work of others in the field, was unique to our specific project and represented ethical engineering practices. Thus, our team selected a final design which was based on the foundational principles and features of other successful walkers which had been created, but which also was extremely unique in its size, structure, and functionality. Our walker's originality highlights our team's engineering ethics in our design selection.

Ethics were also considered in the manufacturing of our passive dynamic walker. Our team has striven, and continues to strive, to create the safest walker possible for public use. In order to do so, our team plans to eliminate as many sharp corners in our walker's design as possible. This will reduce the risk of injury to our end user and will ensure that our design is ethical in regard to safety. Additionally, our team plans to create an assembly manual for our device. This manual will highlight important safety tips during the course of the manufacturing and assembly process and will further reduce the risk of injury associated with our device. The manual will also serve to provide a guideline as to the correct use of the components used to manufacture our walker.

Finally, our team has considered engineering ethics in the distribution of information regarding the design and engineering work involved in the creation of our walker. Our project is to be completely open source. Therefore, our team is not particularly concerned with intellectual property restrictions or guidelines. Our project's scope is within the realm of public knowledge and we are, in fact, promoting the idea that our end user would be able to replicate our design using engineering principles surrounding the dynamics of passive dynamic walking. We would like to inform the public as much as possible in regard to our engineering work in this project. Additionally, we seek to promote an increase of engineering knowledge in the youth and the general public as a result of our project. Thus, in our consideration of engineering ethics surrounding the distribution of information about our project and our specific design, we have determined that our project and design details can and should be made publicly available.

Environment Impact: The current environmental impact of our proposed solution to the problem of creating a passive dynamic walker is fairly low. Due to the relatively small size of our proposed design, the amount of material used in its manufacture is reasonably little. Being powered in a purely mechanical fashion, our design will have zero environmental impact during its lifetime as it will require no electricity or batteries to provide entertainment and education to the public.

Our team is considering how to minimize the environmental impacts which do surround the creation and disposal of our product, however. We have used various methods to minimize this impact and look to continue to move towards a more environmentally friendly solution. Throughout the design iteration process adopted by our team to create the most efficient walker possible, we have sought to decrease the amount of material, parts, and hardware used to construct our walker. This reduction results in a simultaneous decrease in the environmental impact surrounding the creation of our walker. By removing hardware from our design, we are also eliminating the damage to the environment surrounding the manufacturing of those pieces. Additionally, we can reduce the manufacturing time and energy demands from the laser cutter, used to manufacture the pieces of our design, by reducing material demands and the part count of our walker.

Moving forward, while continuing to minimize the environmental impacts of the manufacturing and assembly of our product, our team would also like to consider ways to reduce the environmental footprint of the disposal of our device. Currently, our device is made of acrylic which significantly harms the environment when it is disposed of, due to its resistance to being naturally broken down. In order to reduce this impact, our team has considered the creation of a fully, or at least partially, wooden walker. In doing so, our team would substitute a material with a large environmental footprint with a biodegradable material possessing a very small footprint. This would be a very positive change to our design which would enhance its environmental appeal. It is also a change that our team would certainly like to investigate if time permits.

by Peter Mardeleichivili

Ethical Design: Our project requires us to design and build a Passive Dynamic walker that can be used to engage an audience through demonstration and hands on engagement with the walker, and also allow people able to make one themselves using instructions and part files provided to them. In doing so, we hope to encourage people to wonder about how things work and gain an interest in pursuing a career in STEM.

The ASME *Code of Ethics of Engineers* contains three fundamental principles through which engineers will uphold and advance the integrity, honour and dignity of the engineering profession; they will:
I. use their knowledge and skill for the enhancement of human welfare;
II. be honest and impartial, and serving with fidelity their clients (including their employers) and
d d the public; and
III. strive to increase the competence and prestige of the engineering profession.

In reaching out to the wider community, and trying to encourage people of all backgrounds to find a passion in engineering we hope to be able to, in some way, achieve the principles I & II.

The second principle talks of honesty, impartiality and serving the public. When dealing with honesty, there are numerous aspects of the project that must be kept in mind. Before deciding on a final concept, we performed a lot of background research and benchmarking. During that process, we came across a mechanism that particularly appealed to us and, although our system is not identical, it is heavily based on seeing said mechanism at work. In giving credit to the team at Cornell for this, and also acknowledging other researchers who have shown which concepts can be quickly rejected due to extreme difficulties in having them work, we try and meet this principle.

Fidelity to the public is also of great importance to us. Our research, files and engineering work will be accessible to everyone for free, and any difficulties we had, or that we may expect them to have will be shared, in the hope of truly serving the public.

In addition to the fundamental principles, the ASME *Code of Ethics of Engineers* has Fundamental Canons. These canons address the way in which engineers work, and the work they produce. Our clients are reputable professors from the University of Michigan, who have asked us to undertake take a task to help the community at large (make something that is as accessible as possible to as many people as possible) in a small way by creating a Passive Dynamic Walker. While working for them, we are complying with many of the Fundamental Canons.

One major aspect of the canons deals with engineers holding safety, health and welfare of the public paramount. In some ways, our project can be regarded as a toy, and as such holds fairly little risk to the user (some toys can be more dangerous to users than others, in this case we believe it falls on the less dangerous side).

However, there are many other aspects in which safety, health and welfare must be considered. In designing our walker, we have chosen to eliminate the use of seriously dangerous machinery, and sticking to simply using a laser cutter for the manufacturing process, a device that already contains numerous safety features and is usually located where trained professional can help. Additionally, we will provide safety instructions along with the other instructions and files, however, we hope that as people will be undertaking these tasks themselves, they also try and act in a safe manner throughout, realising that it is their responsibility to be safe when using various tools for manufacturing and assembly.

Our hope is that our project will inspire people and bring joy to those who get to experience, in a small way, the work of engineers, increasing the overall welfare of the public.

Environment Impact: Our walker is almost exclusively made out of acrylic, with a few minor components being of the shelf bought metal components. There are numerous environmental issues associated with this material.

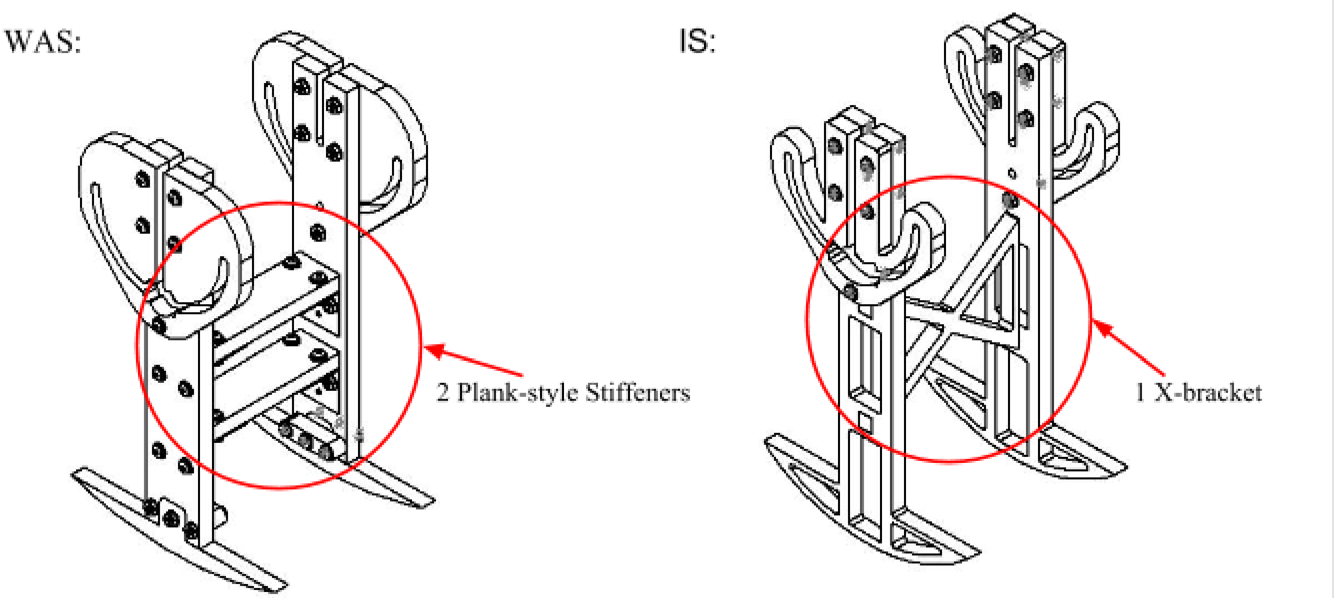
The manufacturing of acrylic requires substances that are highly toxic, and consequently must be stored, handled and disposed of carefully. Fumes produced during the manufacturing process are toxic, however, there is legislation in the United States requiring the cleanup of such fumes. Additionally, as the plastic is highly flammable, if the process is not monitored properly, explosions or other emergencies can occur.

It is possible to recycle acrylic. We encourage users to find alternate uses for the leftover plastic when making a walker, and also to reuse the plastic from the walker after the walker is decommissioned. As for industrial recycling, acrylic is listed as a type 7 plastic. These are difficult and expensive to recycle, and in many areas is not taken in for recycling.

The manufacturing process employed in our project requires laser cutting. Although this process might be quite energy demanding, as all the parts can be placed on a single sheet and the project is to be undertaken by individuals, I do not believe the impact is significant.

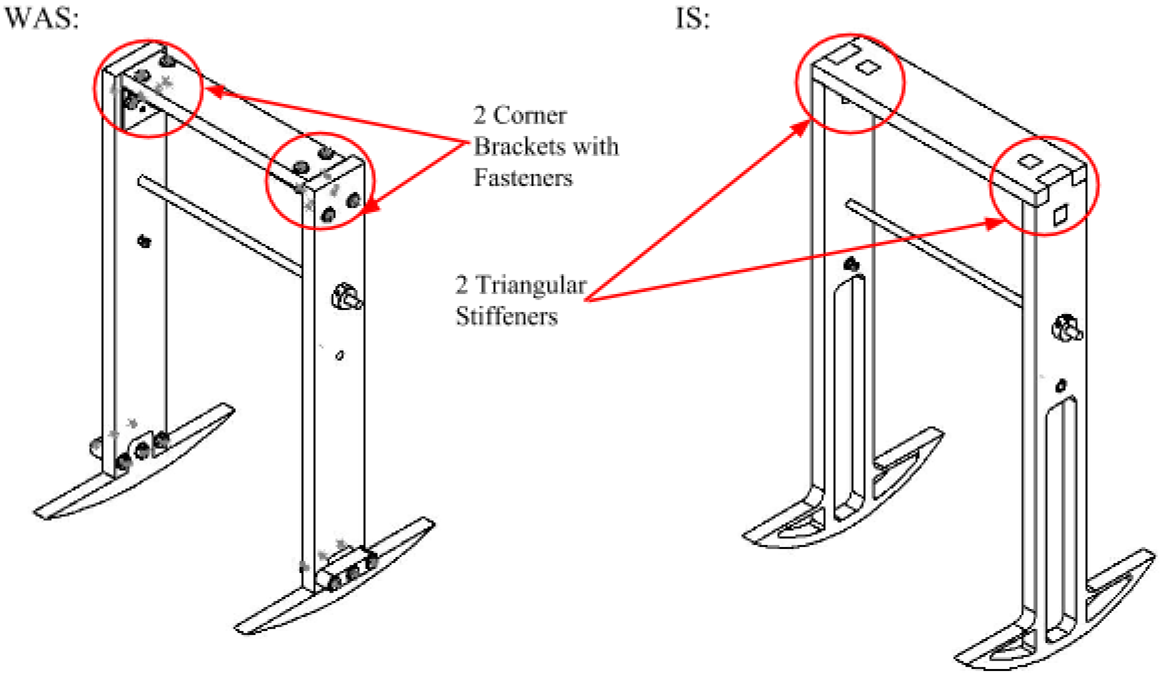
Our project is not intended to be produced on a massive scale and so we do not expect it to have too big of an impact, however, one solution to the use of acrylic, is switching the acrylic out for another material such as wood.

APPENDIX I: ENGINEERING CHANGE NOTICES



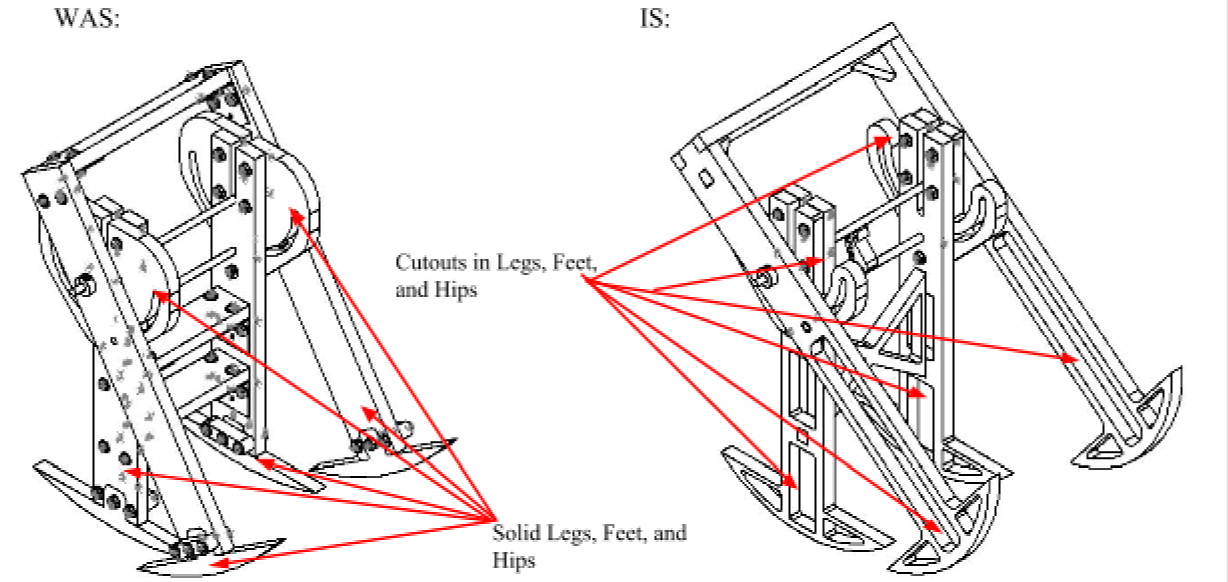
Notes:
2 plank-style stiffeners were replaced with a single X-bracket in order to reduce mass and eliminate fasteners. 4 brackets, 16 fasteners, 16 nuts, and 16 washers were removed in total.

Team 15	
Project: Passive Dynamic Walker	
Ref Drawing: Inner Leg Assembly	
Engineers: Garry Lim, Peter Mardaleichvili, Elio Morillo, and Josh Rumsey	3/30/15
Sponsors: David Remy and Art Kuo	3/31/15



Notes:
2 brackets were replaced with acrylic stiffeners in the outer leg assembly in order to reduce the mass of the assembly and to eliminate fasteners. 2 brackets, 8 fasteners, 8 nuts, and 8 washers were eliminated in total.

Team 15	
Project: Passive Dynamic Walker	
Ref Drawing: Outer Leg Assembly	
Engineers: Garry Lim, Peter Mardaleichvili, Elio Morillo, and Josh Rumsey	3/30/15
Sponsors: David Remy and Art Kuo	3/31/15



Notes:
Needed to create cutouts in the legs, feet, and hips of the walker to reduce the mass of the inner and outer leg assemblies of the walker. Additionally, the feet were merged to the legs in a single piece construction to eliminate fasteners and mass. 6 fasteners, 12 washers, and 6 nuts were removed.

Team 15	
Project: Passive Dynamic Walker	
Ref Drawing: Walker Assembly	
Engineers: Garry Lim, Peter Mardaleichvili, Elio Morillo, and Josh Rumsey	3/30/15
Sponsors: David Remy and Art Kuo	3/31/15