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Utilizing a Computational Model for the Design of a Passive Dynamic Walker

by

Craig Honeycutt

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
Department of Mechanical Engineering
College of Engineering
University of South Florida

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Abstract

Recent interest in using passive dynamic walkers (PDWs) for gait rehabilitation studies has presented a need for a robust, easily built mechanism. Unfortunately, these passive robots are hypersensitive to many variables outside of the usual design considerations that are studied when constructing them. By accentuating previous failures instead of suppressing them, this thesis presents a number of problematic situations commonly experienced when testing and tuning a PDW.

Further, through a complete design of a 4-legged PDW with knees, simple design axioms brought about by myself and others are put into a practical context and applied directly to design. This thesis aspires to present a systematic design process, and highlight how a computational model can be used with both hand calculations and CAD packages. Using the insight from those researchers before me, I strive to further their designs and present relevant information in a design compendium that makes it more useful to those who have an application for the device.

This thesis resulted in two novel designs for a PDW. First, a changing radius foot was developed to increase knee flexion upon toe off. The decrease in radius increases joint angular velocity resulting in ramp up. Further investigation of these feet could result in more stable and efficient walking patterns. The other design brought to attention is the planar crossbar mechanism for coupling the inner and outer legs. The crossbar provides a rigid coupling without changing the rotational inertia between the coupled pair about the hip axis.

Chapter 1: Introduction

Legged locomotion provides us with the unique ability to traverse many types of terrain with little conscious effort. These subconscious actions are greatly realized when someone suffers from a gait impairing condition such as cerebral palsy or stroke. As engineers, we would like to solve this problem by developing devices and models to help those with impairments regain stable motions and to ease the daily challenges that arise. With this in mind, our recent research has focused on looking at the dynamics of gait and how physical parameters can affect walking subconsciously. To separate the neuromuscular control system from the natural dynamics that arise from the physical attributes of a person, a passive dynamic walker (PDW) can be used. A PDW is a mechanical device that can descend shallow slopes without any inputs except those due to gravity. PDWs are passive devices with no controls. They can exhibit their motion because of the precise tuning of their inertia and link lengths, which provides those who tune them with a challenging task. However, for rehabilitation, there is less focus on the design and tuning and more on its potential uses both as a model and a physical test bed.

1.1 Rehabilitation Applications

An important trait of a PDW that makes it valuable to walking studies is its repeatable human like gait [15]. Garcia et al. [6] compared the gait of a bipedal PDW to an actual human gait both by way of a model and by physically analyzing the gaits side by side under a strobe light. The natural gait created by these walkers makes them a great

model for investigating asymmetries from a purely physical standpoint. Two recent studies have incorporated PDW models to effectively display asymmetries [10], [7]. In [10], an asymmetric model was developed by taking a standard five-mass bipedal system and specifying parameters with respect to each leg. Then, by iterating through each parameter a physical asymmetric walker was modeled. By way of step length and limit cycle trajectory plots, asymmetric patterns were found. While these gait patterns were not given direct analogs to asymmetries in humans, there is a possibility that they could match up to an actual step pattern if studied further. Gregg et. al [7] on the other hand found similar asymmetries using a completely different approach. Here, the environment was changed around the walker which created instabilities due to the kinetic energy lost at impact.

Both of these cases provide an interesting niche for PDWs in the future.

To illustrate the usefulness of a PDW in this regard and to link it to a physical project, the following example is given: Consider a case for which a blindfolded subject is given the physical asymmetry of added mass and length to one of their legs. As they walked, they would no longer use all of their cognition (their sight is taken away), and therefore they might not consciously correct for the variations in their gait patterns. A few simple tests of this experiment were performed on middle school students and can be seen in more detail in Appendix B. The same test could possibly be applied to a PDW. To test a rehabilitation device, a researcher could affix an analog of their device to a PDW and analyze its natural effects on the gait, before applying it to human subjects. While this is a goal of future work, it is just speculation for now.

1.2 Motivation

The following example can be used to further the motivation for this thesis in that the previous speculated case would be much more feasible if a PDW was easily developed and easily tuned. The simple actuality is that this is not the case. In fact, it is quickly

realized by the designer how difficult it is to find applicable literature on PDW design.

While there have been significant contributions to the development of PDWs in the past two decades, information regarding PDWs is generally split into two categories. One is highly theoretical and only delves into the dynamics of the ideal system, while the other produces the end result of a physical walker without the details of the design. There have been several other papers that have looked into specific design issues such as [2], [21] and [11], nevertheless these leave out some valuable information. The disarray of information prompts the main aspiration of this thesis, which is to discuss the most prevalent design issues while generalizing some techniques used to construct a successful walker. This thesis strives to become a useful compendium for those who would like to construct a PDW and use it for other means of research. To further clarify the intentions of this research, the following goals are set:

1. *Illustrate practical applications for PDWs within gait rehabilitation research:* This research ultimately stemmed from a project that was meant to use a PDW for gait rehabilitation research. When the process of building a PDW became a project of its own, the cognizance of a thorough design paper became more relevant. Because PDWs have generally not been used for this application in the past, it is important to discuss briefly the benefits that it has to offer in this sense.
2. *Identify design pitfalls and offer practical solutions:* As the common aphorism goes, you learn more from your mistakes than your successes. Many papers in this realm do not discuss the many problems encountered when building a PDW. From the intensive process of setting a PDW into motion to the surface interaction between the feet and the inclined plane, there are many variables that can upset the stable walking of these machines. While a PDW is said to have failed if it does not enter its stable gait cycle, it should be noted that failure in this sense is upheld to a very high standard. As with any other machine designed with a purpose, the user

expects it to operate in a predictable manner. In this thesis, some specific failure conditions will be discussed with insight offered on how to troubleshoot them.

3. *Further previous designs and discuss the motivation for these improvements:* As mentioned briefly before, there have been several contributions to the design of PDWs. It is beneficial to look through some of the previous designs offered by other researchers and to discuss how the designs presented in this thesis extend their concepts.
4. *Offer a full design of a 4-legged passive dynamic walker; discuss its components:*
A goal is made to look at the design procedure for each component on the walker. Each component needs to be analyzed and given a basic form before any design is finalized. There are many basic axioms of PDW design which can be applied at a high level and then refined by computer models or CAD programs. By the end of this thesis, the design procedure used by the author should be clear and ultimately useful to anyone building a PDW.
5. *Compile a useful list of relevant methods for the development of a successful PDW:*
A major goal of this thesis is to end with an exhaustive tabulation of the practical techniques learned from designing a functional PDW. It is believed that there are those researchers who could benefit from incorporating a PDW into their research. This thesis should provide those in need with a good starting point thereby expediting the design process and making the process less frustrating.

Chapter 2: Background

While the advancement of Passive Dynamic Walkers (PDWs) has progressed steadily throughout the last few decades, the use of these passive mechanisms to aid gait rehabilitation research is relatively new. Before discussing a PDW's use in gait studies, it is important for it to be fully defined. A PDW is a legged robot which can descend a shallow slope without any input forces except those due to gravity. It generates a steady gait pattern as its natural system dynamics overcome energy losses by way of inelastic collisions during the knee strike and heel strike events. Heel strike collisions account for most of the kinetic energy lost by the system [17]. Following the walker throughout its gait cycle, there are two different phases which repeat. The three-link phase occurs just after toe off of the swing leg while the two-link phase begins as soon as knee strike occurs on the swing leg. The three-link phase is identified by the knee unlocking, creating another pendulum with its center at the swing leg knee. It is also assumed that the knee of the stance leg stays locked throughout the stance phase. This is better seen in a simple diagram of the walking cycle, shown in Figure 2.1.

2.1 Gait Models

A simple and mathematically facile representation of the system's exchange of energy can be seen from McGee's rimless wheel concept [15]. Imagining a wagon wheel without an outer rim, as each spoke makes contact with the ground, there is a collision which can be modeled as inelastic. If angular momentum is conserved at the point of

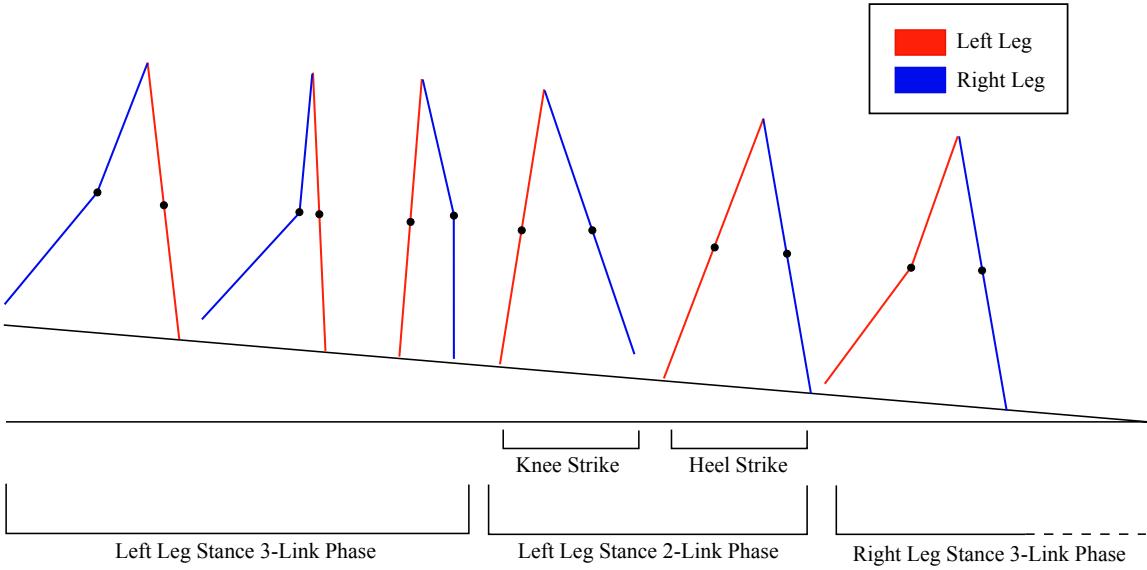


Figure 2.1: Three-link and two-link step phases throughout a full gait cycle

contact, the velocity after each impact will converge to a constant value over time. This steady state condition will of course depend on the ramp angle and the mechanism's total inertia. McGeer went on to further develop the rimless wheel with the compass gait model [15]. The compass gait is the basis for non-kneed walkers, so it does not provide us with many benefits; keeping in mind that our focus is to develop design generalizations for a kneeled PDW. In 2005, Chen's model furthered McGeer's compass gait and is the basis for our computations [2]. Her model uses a LaGrangian approach to compute the inertial, damping, and gravitational matrices. It includes five masses, one at the hip and one at the center of mass of each thigh and shank. Also, taking into account the collision events mentioned earlier, the model allows for calculations of each joint velocity before and after each impact. Figure 2.2 shows the evolution of models terminating with Chen's 2005 model.

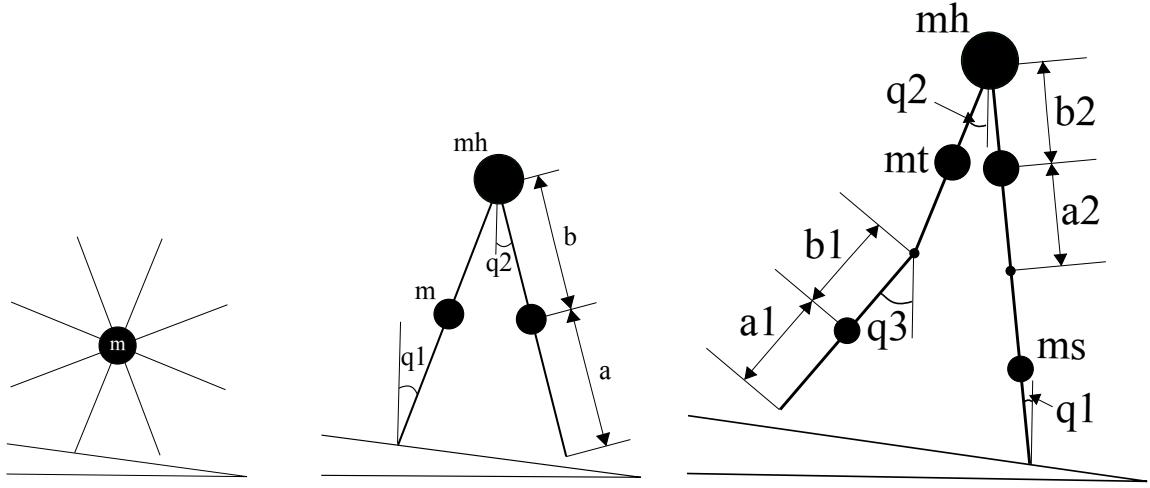


Figure 2.2: Evolution of walker models. Left to Right: Rimless wheel, compass gait, and five-mass model

2.2 Passive Dynamic Walkers and the Human Gait

In previous research, there has been interest in using PDWs for studying the dynamics of human gait [10]. PDWs differ from most walking robots due to their dynamic stability. Robots such as the Honda Asimo walk with a quasi-static gait meaning that their center of gravity never leaves the stability polygon (a common measure of stability). Because of their dynamic stability, PDWs correlate better with human ambulation, making them useful tools in studying the dynamics of walking without the complex human control systems. The human gait and that of a passive walking robot can be modeled by a basic pendulum system. As the swing leg moves through the three-link phase, it can be viewed as a pendulum with its pivot at the hip. Conversely, the stance leg is seen as an inverted pendulum with its rotation point located at the foot.

More similarities between human walking and that of a PDW arise while examining the center of mass (COM) throughout a gait cycle. Viewing the walking cycle in the Sagittal Plane, the center of mass goes through a repetitive arc motion with the COM at its highest position while the stance leg is completely vertical. Also, in both cases, the

COM stays almost directly above the contact points of the feet. Contrary to the COM condition of the Honda Asimo, the **COM of a PDW can leave the stability polygon so long that it re-enters upon collision occurrences.**

An important **contrariety between human strides and those of a passive walking robot** arise **from the main source of forward propulsion.** The inclined plane traipsed by the PDW provides energy and the curved feet provide the knee joint torque to unlock the knee at the beginning of each three-link phase. Humans accomplish the same actions **using the plantarflexors which rotate the foot around the ankle.** Simultaneously, the contraction of the iliopsis lifts the leg starting the three-link phase [13]. In other words, PDWs demonstrate an anthropomorphic gait in every fashion except they use an **incline for propulsion rather than ground reaction forces.** The vast similarities are what make these passive robots very promising for future humanistic gait studies.

2.3 Rehabilitation Applications

In the previous section it was said that PDW gait patterns mimic that of humans, but why is this useful? It would be interesting to study **the effects of changing physical parameters on a human without their own cognition interfering.** With this being said, there is promise for the analysis of gait patterns from a purely dynamic perspective. Using a PDW model, **different parameters could be changed making the gait pattern asymmetric.** Then, **physical parameters could be changed differently to bring the model back to symmetry.** Similar research was done in [10] where multiple physical parameters were **changed resulting in gait patterns that could possibly replicate those from someone who suffered from stroke or joint spasticity.** These gait patterns were classified by their step lengths and limit cycle trajectory plots as seen in Figure 2.3. The step length plots are particularly important because a clear asymmetric gait can be realized. These interesting

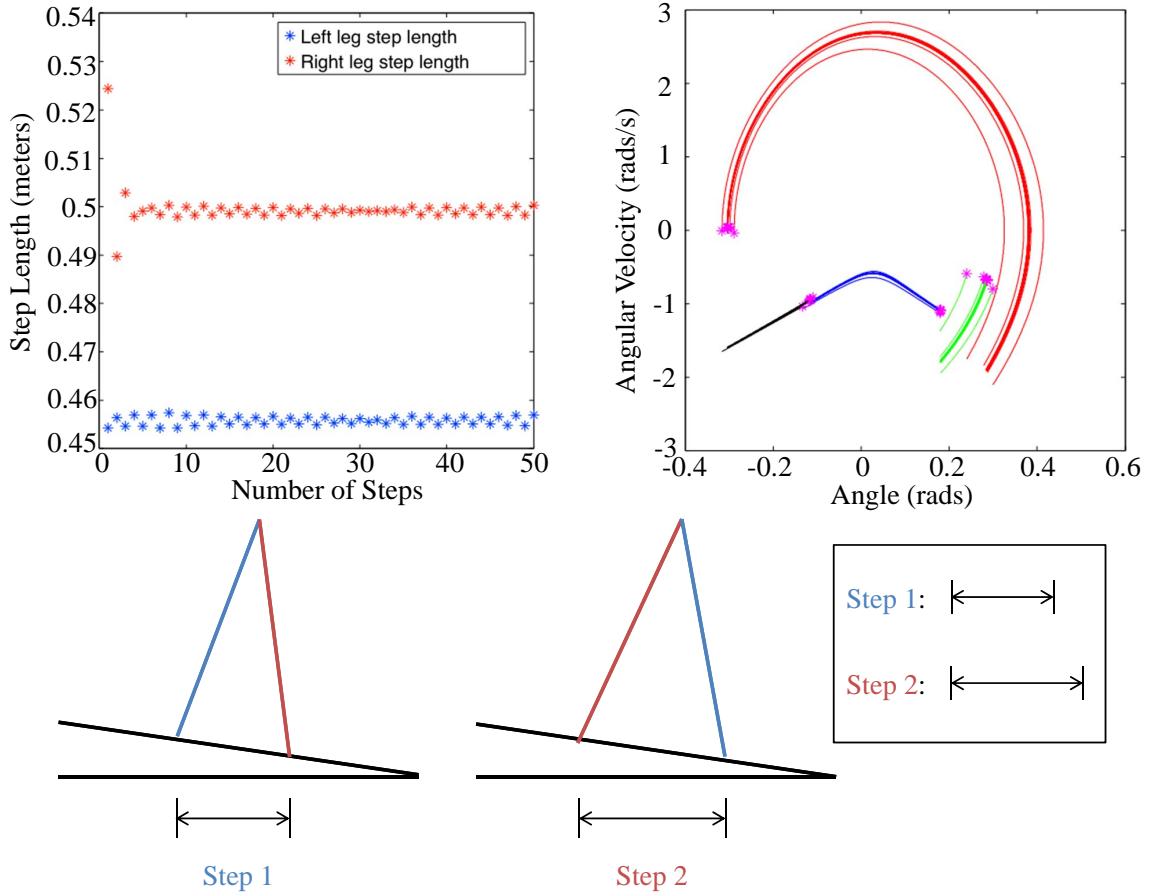


Figure 2.3: Double step pattern exhibited by an asymmetric PDW model. From the step plot (top left) it can be seen that there are two distinct step lengths throughout the walker's gait cycle.

gait patterns could aid in future gait rehabilitation devices and models such as those for prosthesis.

Sushko [19] used a PDW model that categorized physical parameters with respect to each leg allowing him to vary the location of the knee on a prosthetic leg. Ultimately, this led to a lighter prosthetic model with a stable and symmetric gait. Here, a PDW model was used to analyze the step length changes resulting from the physical asymmetry, enabling the concept to be tested before there was any human interaction.

On the other hand, previous research done on a gait corrective shoe aspired to bring the human cognition back into the equation [8] and [5]. The Gait Enhancing Mobile

Shoe (GEMS), was created to mimic the rehabilitative effect of walking on a split-belt treadmill while including the cognitive sensations that one experiences walking over ground [9]. The first design by de Groot et. al [5] used a rack and pinion device to transform the user's downward motion during the stance phase into backwards motion, just as a belt does on a treadmill. More recently, the design evolved into a 4-wheeled shoe with changing radius wheels and a magnetic particle brake to stabilize the backwards motion [9]. If however, these researchers wanted to look at the effect of the added weight from the rehabilitative shoe in a purely dynamic sense, there is a possibility that a PDW model could assist. Rehabilitation models and devices like the ones described above either already utilize or could utilize PDWs to further their research. Figure 2.5 shows the two GEMS Shoe designs discussed above.

2.4 Previous Passive Dynamic Walker Designs

Before describing in detail the arduous design and tuning procedure for a PDW, it is important to look at a few existing walker designs to develop a thought process and an indication of what has and has not already been investigated. Limiting the discussion to 2-D four-legged kneeled PDWs, there are three somewhat recent designs in which we will discuss. These are of Garcia et. al [6], Chen [2], and Trifonov et. al [11], published in 1998, 2005, and 2009 respectively. Each of these walkers incorporate different knee mechanisms ranging from the simplest "stop type" mechanism of Garcia et. al to the more complex active locks of Chen and Trifonov et. al. Chen further developed the knee lock by applying electromagnetic clutches to keep the knees from hyperextending and used suction cups for added knee stability. Also varying amongst the models were the foot designs. While Chen used the most basic point foot, Trifonov et. al and Garcia et. al preferred a curved type foot. To compare these designs, see Figure 2.6.

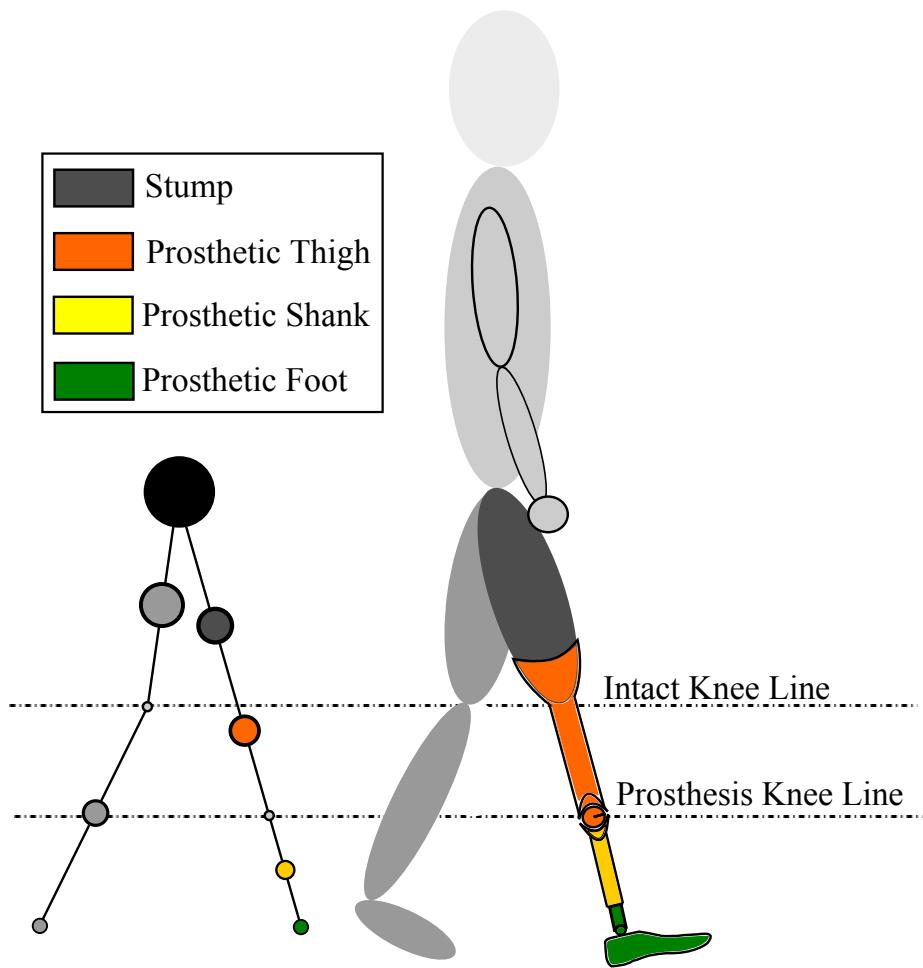


Figure 2.4: Changed knee location prosthesis. The left model corresponds to the nine-mass model developed by John [19]. This model has physical implications to a prosthesis design with a varied knee location (right)



Figure 2.5: GEMS Shoe designs. The left shoe was developed by de Groot et. al [5] in 2009. This completely passive shoe uses a rack and pinion to convert the user's energy into a backwards motion. While the right shoe is also completely passive, it uses a magnetic particle brake to generate a more controlled motion.

Each designer also offered heuristic generalizations that further defined their designs. For instance, Chen mentions that from her simulation a mass ratio of 10:1 relating the upper mass to the lower mass is optimal for stability [2]. Trifonov et. al observes that the most important design requirement for the hip is to keep friction to a minimum [11]. Unfortunately, these axioms are not discussed in great detail. Additionally, problems encountered during testing are rarely mentioned in PDW publications. Chen and Trifonov et. al do a substantially better job than most, but there generally seems to be an lack of detail on basic troubleshooting techniques. This thesis will address some of the problems commonly encountered during the testing phase and strive to come up with directly applicable solutions.

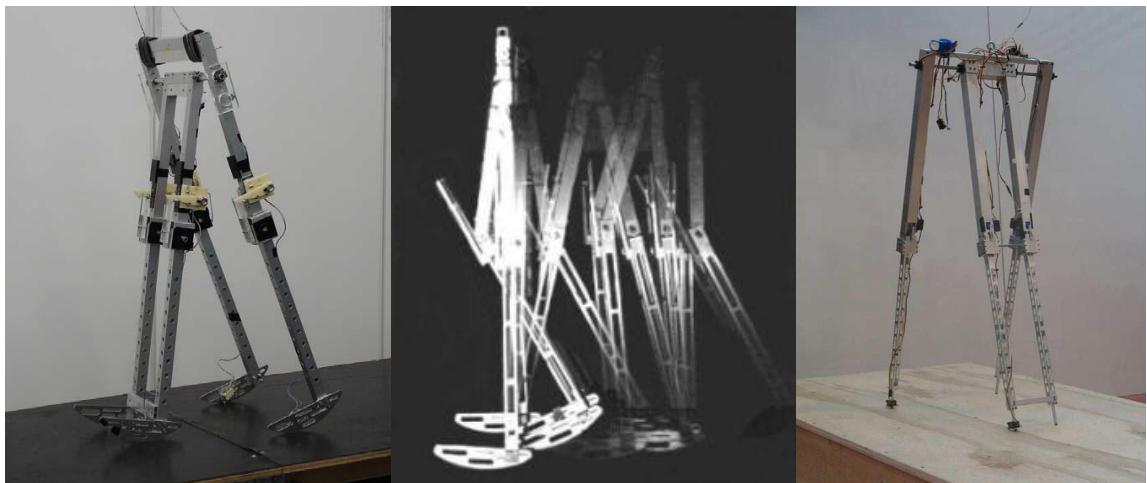


Figure 2.6: Various 4-legged PDW Designs. Left to Right: Trifonov(2009), Garcia(1998), Chen(2005).

Chapter 3: Design

Before starting a PDW design, one should decide on the type of walker needed for their application. There are several types of walkers each with unique physical characteristics that define their walking patterns. These categories are usually defined by the following: the number of legs, if the walker has knees or does not have knees, and if the walker has two dimensional or three dimensional motions. The last categorization is usually based upon the number of legs. Three dimensional bipeds require the most modeling and tuning due to the added degrees of freedom created by roll and yaw. Wisse et al. did a comprehensive study on these 3-D behaviors and built a PDW with an upper body to compensate for undesirable motions [14]. Clearly the need for upper body motion to counter-balance the natural tendency to rock and turn creates a more complex design challenge.

Another type of PDW is the compass walker which is much less complex but still presents some unique hurdles in the design process. For one, some sort of actuation usually needs to be applied for foot clearance as these walkers do not have knees. McGeer used a clever design that rotated the feet up to the side during every swing phase [15]. Also, for two legged compass PDWs, there is a lot of focus on preventing the walker from turning as it descends a slope. Foot friction is generally cited as the culprit, so designers have often used rubber coating and wider feet in compass walker applications [20].

The final category and the one chosen for review in this thesis is a 4-legged two dimensional PDW with knees. This category of PDWs has its own advantages and disadvantages. The main advantage is provided by the additional legs. Four legs give the

walker better lateral stability than similar bipeds. Additionally, this allows for thinner and therefore lighter feet because the friction does not have to overcome roll motions. A disadvantage is caused by the coupling of the legs. The inner legs are easily coupled at the hips and the knees, whereas the outer legs can only be coupled by the hips. A problem arises if the outer legs swing slightly out of phase, sometimes caused by initial conditions. Also, care has to be taken to make sure that the knees of the inner and outer couplings lock and unlock at precisely the same time. Another design challenge is foot clearance of the swing leg immediately after toe off. A solution to this problem is usually found by designing the foot such that there is adequate friction to initiate knee bend at the beginning of the swing phase. With this being said, PDWs of all types are difficult to design and tune. The design process can vary from purely trial and error methods to extensive modeling techniques. This thesis chooses to review the design of a 4-legged PDW for a few reasons. First, because a 4-legged walker's legs are coupled, its gait acts bipedally. Bipedality is needed for an accurate representation of the human gait. Secondly, it is the author's belief that experience is needed with a two dimensional PDW before moving on to more complicated three dimensional bipeds. In fact, a very basic compass gait PDW was built and tuned before the design process of the current walker. It is constructed out of Tinker Toys and is based off of the design by [3] seen in Appendix A. Exercises like these are great to get a feel for tuning because you are able to visually see the effects of changing masses.

Reverting back to the design at hand, there was a basic design procedure followed in order to successfully develop each component on the walker. Because it is very generic, following this procedure gives the designer freedom to design each component with minimal constraints. With an accurate mathematical model, tuning is possible as long as the overall design closely follows the axioms presented in this chapter. The general steps in the design procedure are outlined below:

1. Concepts and general axioms are used at a high level to approximate sizes and shapes for each component on the walker. From general shapes, approximate masses are found and recorded.
2. Using SolidWorks, each component is drawn and put into an assembly. Mass and inertia properties are constituted at this stage and recorded so they can be compared with the final machined part.
3. Utilizing a computational model generated in MATLAB, ranges of mass magnitude and location are input and solutions for stable gait are found. This model is explained in a subsequent section.
4. Masses are added in specific locations to tune the walker.

Stepping through the above processes briefly, the shape of the entire walker is sketched with generic shapes for each component. At this stage, there are several axioms that can be applied to guide the design process in the right direction. There is a general rule of thumb brought to attention by McGeer that the mass of the hip and thighs should be much greater than the mass of the shanks and feet [15]. Chen later quantified this axiom by simulation, finding that a walker is most stable when the ratio of the hip and thigh mass to the rest of the walker is greater than 10:1 [2]. Using this as a very low level design constraint, designs for each of the main components are carried out. Another axiom to take into account at this stage was presented by Baines where it was found that gait is more efficient from an impact standpoint if the legs are closer together [1]. Also during this step, material selection is performed. Because the upper portion of the walker should be around ten times heavier than the lower, it is common to use steel for top components and aluminum and plastics for lower components. It should be mentioned that tuning often takes place many times and the designer should be aware of the effect this has on the life cycle of the most commonly used parts.

Once the parts are designed and machined, they are massed and compared with their mass properties in SolidWorks. SolidWorks Mass Properties Tool is a very useful tool for the design because once each part is drawn, it will calculate the moments of inertia, center of masses, and give the total weight of the part. Once these properties are established, final designs are drafted and parts are machined. Before finalizing the designs, each component is put into an assembly in SolidWorks to check for tolerances and clearance issues. Mass and inertia properties can then be found for the entire walker assembly. These properties are very useful and can be compared directly to dynamic characteristics of the system such as the natural frequency the walker legs.

Because a PDW is very sensitive to variations in mass distribution, great attention is taken to make sure tuning is possible. Starting at the hips, there needs to be a portion coupling the inner and outer legs together while also having ample surface area where weights can be applied. Next, the legs need to be designed so that weights can move up and down and have some way of being affixed. Many walkers built have traditionally used perforated C-channel or box beams for legs such as the walker made by Garcia et. al [6] and McGeer's early designs [15]. Instead of using a channel section where weights either have to be fastened or adhered to, my design utilizes steel bar stock for the thighs and hollow aluminum tube for the shanks. Because of the geometry, these allow for high resolution when locating masses. The masses used are 1/2" diameter shaft collars held in place by set screws. When relocating these masses, only one set screw is loosened and the collar is slid up and down depending on the need. The knees and hips also utilize set screws for quick removal, making it easy to add or remove masses. Finally, the feet are designed so that delrin inserts cut from a laser plotter can be fitted quickly and effectively. Designing for tunability as well as the features of each component of the physical walker are discussed in more detail in the following sections:

3.1 Hip Design

The design of the hip assembly was conducted under the following design constraints:

1. The hip has to be coupled to another hip, making the four legged walker act bipedal.
2. Bearings have to be used so that each hip is free to rotate about a common hip axis.
3. The hip has to accept the 1/2" diameter steel thigh that was chosen earlier.

Compared to the radial load capacity and the rpm threshold of common ball bearings, the weight and rotational speed of the PDW is seemingly low. Because of this, fatigue analysis on the bearings generally does not need to be performed. More importantly, minimizing friction should be paramount due to the sensitivity of the machine.

Because the hips must include several mounting holes, bearings, and threaded set screw holes, aluminum is used due to its good machinability. The hips are designed to rotate around a 1/4" diameter steel shaft, their thrust motion limited by 1/4" shaft collars and the crossbar connectors. Two set screws are used to hold each thigh within the hip assembly and to eliminate rotation about the vertical axis. Two blind threaded holes are used in the top surface of the hip for mounting the crossbar assembly. A CAD drawing and rendering of the hip is shown in Figure 3.1. Considering the amount of weight located at the top of the walker, stainless steel heli-coil inserts are used within the aluminum to keep the threads from pulling out under high load conditions. Also, because the walker is meant to be tuned many times, these threads offer better wear resistance. Just because a large portion of the total mass is located at the hips does not mean the hips must be large. An easier and more tunable method is to attach most of the weight to a crossbar assembly which has substantial surface area to attach and detach weight from. The design of this assembly is mentioned in the following subsection.

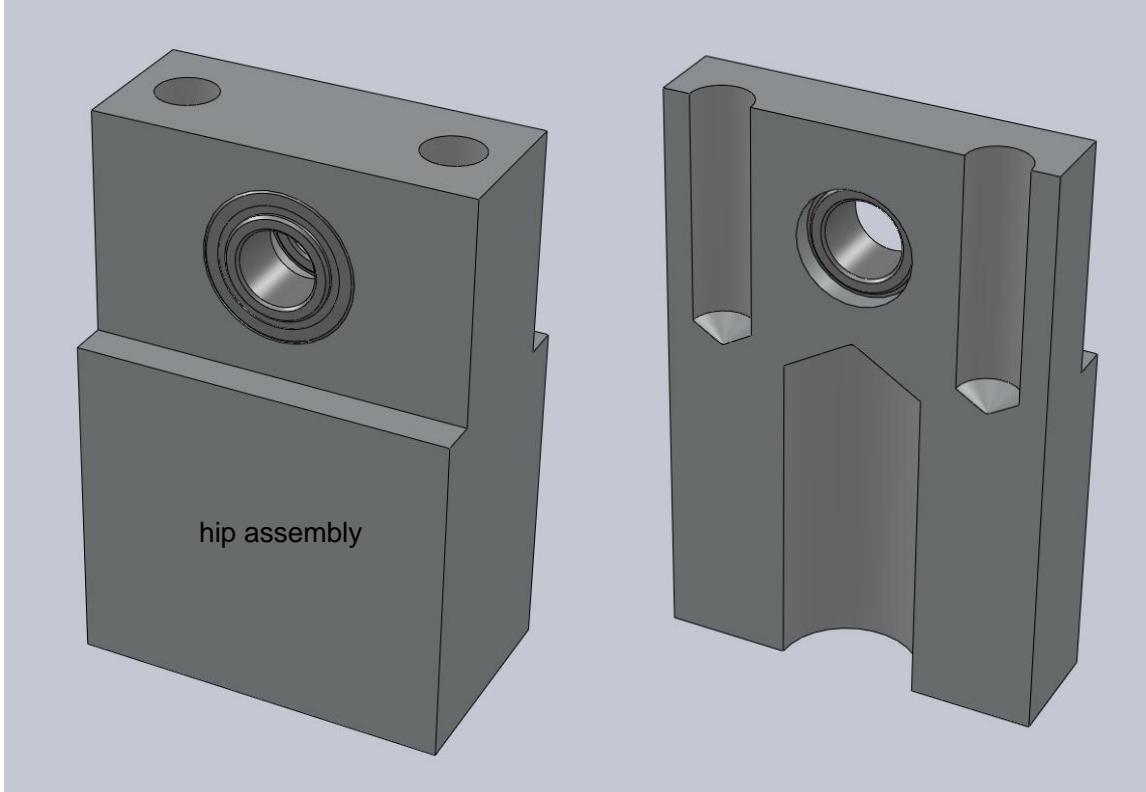


Figure 3.1: SolidWorks Model of the hip assembly. A 5/8" diameter bearing is press fit into the aluminum part. The threaded holes on top affix the crossbar assembly to the walker, while the bottom hole accepts the thigh

3.1.1 Crossbar Assembly

The crossbar assembly is designed to couple the outer two legs and the inner two legs into two pairs forcing bipedality. While others in the past have created an upper crossbar (connecting the outer hips) and a lower crossbar (connecting the inner hips), this design was not used because of an inherent problem. Because the upper crossbar sits well above the hip axis, it has a considerably longer moment arm than the lower crossbar. This creates a rotational inertia difference between the outer legs and the inner legs, which must be fixed by tuning in order to avoid gait asymmetries. The need to tune an asymmetry before the walker is even constructed is extraneous in the author's opinion. A better solution is to make both of the crossbars on the same plane with equivalent moment arms. In order to do this, the outer legs are connected by an oval piece machined out of 1/4" thick steel plate. The thickness of the steel gives rigidity while the piece's open center allows for the inner crossbar to swing freely. Overall, this design allows for both the inner and outer crossbar to be on the same plane, making it initially more stable than previous designs. For an illustration of this component see Figure 3.2. Also, a comparison of the current design previous crossbar designs is shown in Figure 3.3.

3.2 Knee Design

An early example of knee design can be seen in McGeer's seminal paper [15]. He used a mechanical stop to resist knee flexure in the stance phases of the gait cycle. To do this, he positioned the foot forward anthropomorphically so that the reaction at heel strike kept the knee locked (and slightly hyper-extended). A design that furthered McGeer's design was that of Trifonov et al. [11]. They first used a magnetic stop and then tested an active release mechanism. From their testing, they found that 44 percent of their tests

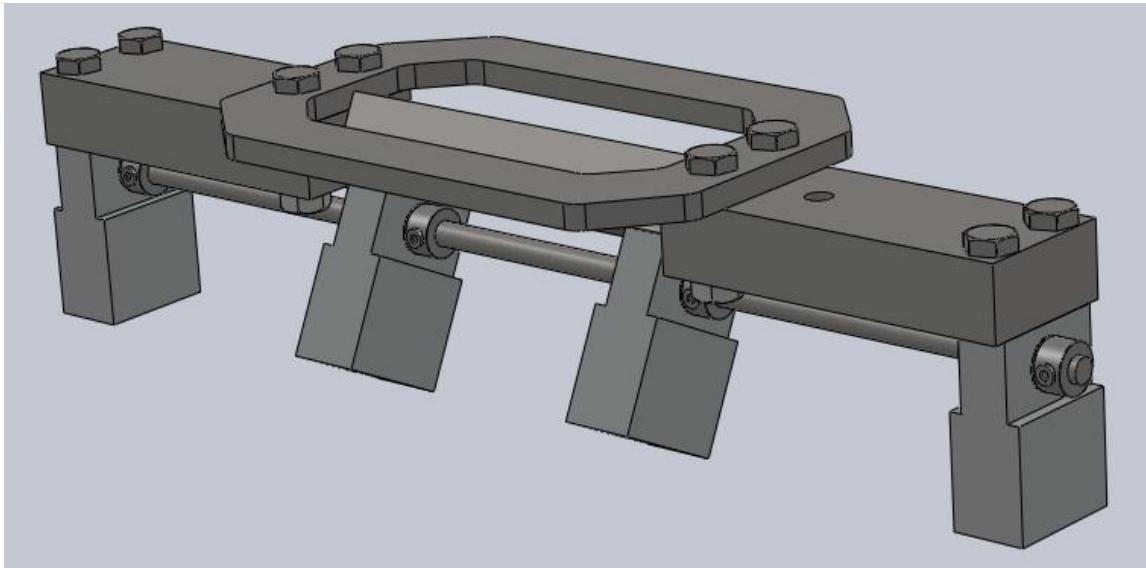


Figure 3.2: SolidWorks Model of the crossbar assembly. This planar crossbar mechanism lets the middle legs swing through an opening in the oval connector. Because the large top bars comprising the connector are all within one plane, no difference in moment about the hip shaft is created between the inner and outer legs

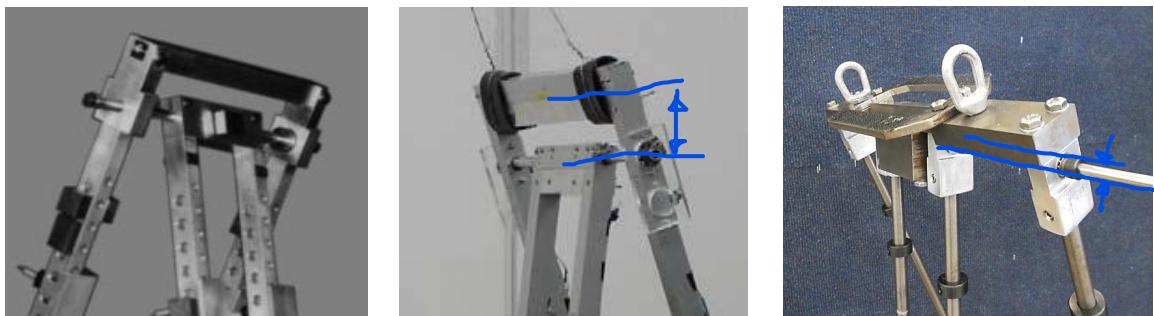


Figure 3.3: Comparison of several crossbar assemblies. Left to right: Garcia et. al crossbar [6], Trifonov et. al crossbar [11], and the current planar crossbar mechanism.

were successful for the actuated release system while only 7 percent were successful for the magnetic system.

The knee is simply a revolute joint comprised of an upper and lower segment. The upper portion is of fork type giving support to the pivot shaft at two locations. The lower piece houses the ball bearing and includes mounting holes for the knee stop. Each part of the joint accepts a 1/2" diameter shaft (either the thigh or the shank), and secures it with two set screws. The upper portion also uses a set screw to fix the pivot shaft so that rotation is solely handled by the bearing. The material of choice is aluminum, again for its machinability and relative light weight. However, because one of the knee designs includes a DC Motor, this design uses delrin for the upper knee portion to make the total weight equal to its aluminum counterpart. The two upper knee designs are explained in more detail in the following section.

There are two different designs covered by Trifonov et al., mentioned briefly previously. The plan is to further both of these designs and ultimately come up with a design that is robust in the sense that it produces a repeatable locking and release action. The magnetic system will be covered first due to its simplicity. It is comprised of the standard knee joints with a neodymium-iron-boron magnet affixed to each upper portion. On the stop, a standard steel hex bolt is used as the ferromagnetic counterpart of the magnet. Utilizing its threads, the bolt can be adjusted out of contact with the magnet to give some adjustability to the magnetic force. Also, low stiffness foam is used at contact to reduce the coefficient of restitution. This setup can be seen in Figure 3.4. Overall, the system is quickly implemented but does not produce a repeatable locking action. The knee release event is inconsistent at best and does not allow for a stable gait at any time. Possibly there is merit for a design similar to this in the future. It is beneficial because it is completely passive. Also, since there is no need for any contact between the magnet and the bolt, wear on the parts is eliminated. Possibly an electromagnet in this arrangement could pro-

duce a more repeatable result in future designs. However, it proved too heavy compared with the suggested mass found from calculation.

The second design by Trifonov et. al uses an actuated latch mechanism to lock and unlock the knee at precise times. Because the DC motors add weight to the assembly, delrin is used to make the total mass comparable to the aluminum upper knee. The motors are also mounted in a unique way to make the knee as compact as possible, therefore making it easier to model as a point mass. The motor is mounted within a blind hole that is transverse from the thigh axis. The thigh is offset a distance of 0.45" to make room for the motor assembly. A latch cut from delrin is directly attached to the motor's slotted shaft using a miniature hub with set screws. The delrin material gives the latch the benefit of low rotational inertia which in turn reduces stall torque needed by the motor. Also, because delrin and steel have a low dynamic coefficient of friction, the friction upon release is minimal. The latch goes through a simple up and down motion traveling a short arc length about the motor's rotational axis. To limit the motion of the motor, a delrin bracket is used. Figure 3.5 shows an isometric drawing of the assembly while Figure 3.6 gives a visual of the movement of the ratcheting latch mechanism. As the shaft affixed to the knee stop contacts the latch it forces it up and into a groove. Since the motor applies a constant force, the shaft is held in the down position until release at heel strike. This effectively locks the knee until the opposite pair of legs contact the ground in which the cycle is then repeated.

3.2.1 Knee Latch Control

To actuate the motors, a control logic was used. The system is comprised of four DC motors, four pressure sensors, two motor control boards, one sensor board and one power supply. A diagram to supplement the following description of the control logic can be seen in Figure 3.7. Since the two-link phase and three-link phase of one leg hap-

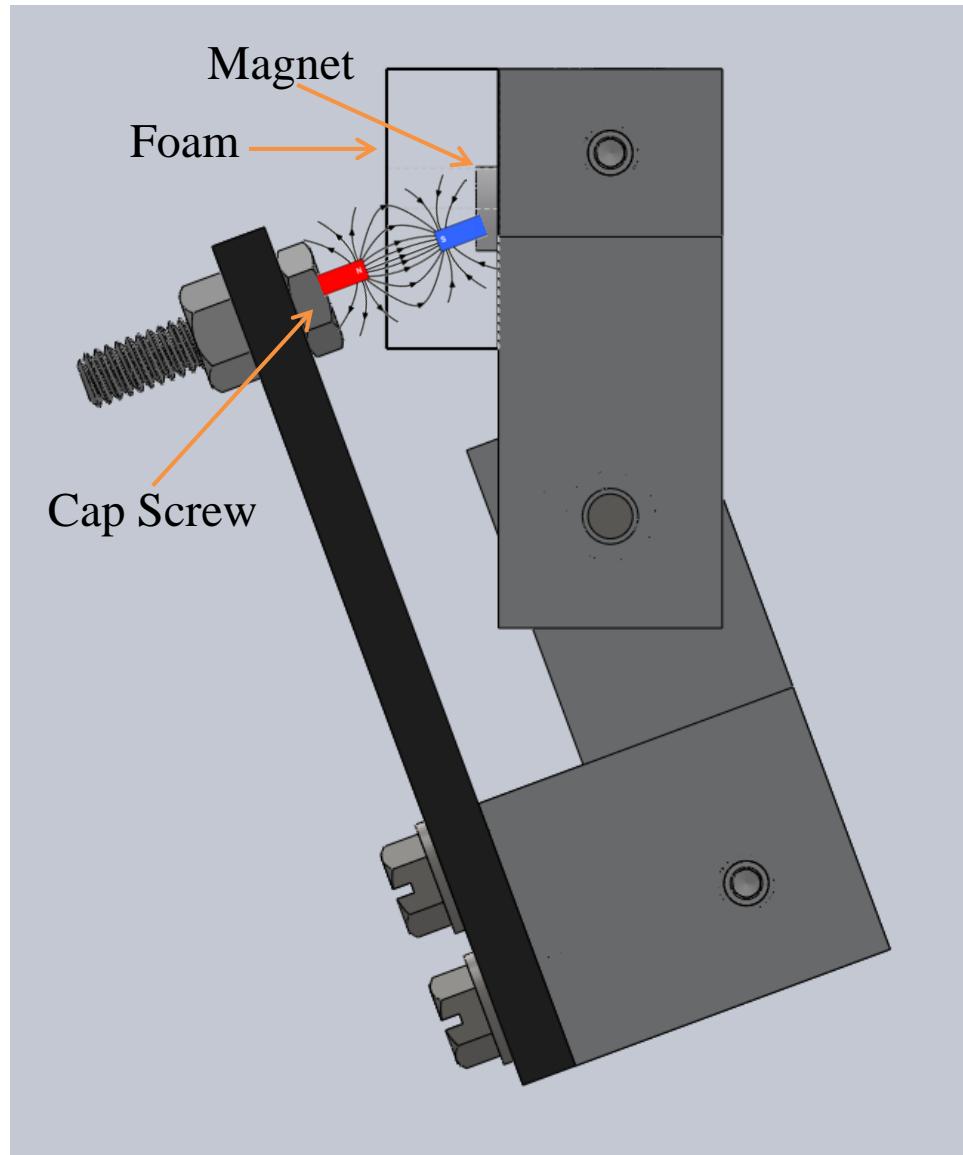


Figure 3.4: SolidWorks Model of the magnetic knee lock assembly. The cap screw is used as the ferromagnetic coupling to the magnet. The magnetic force between the two can be altered by adjusting the cap screw a certain distance from the magnet at locking point.

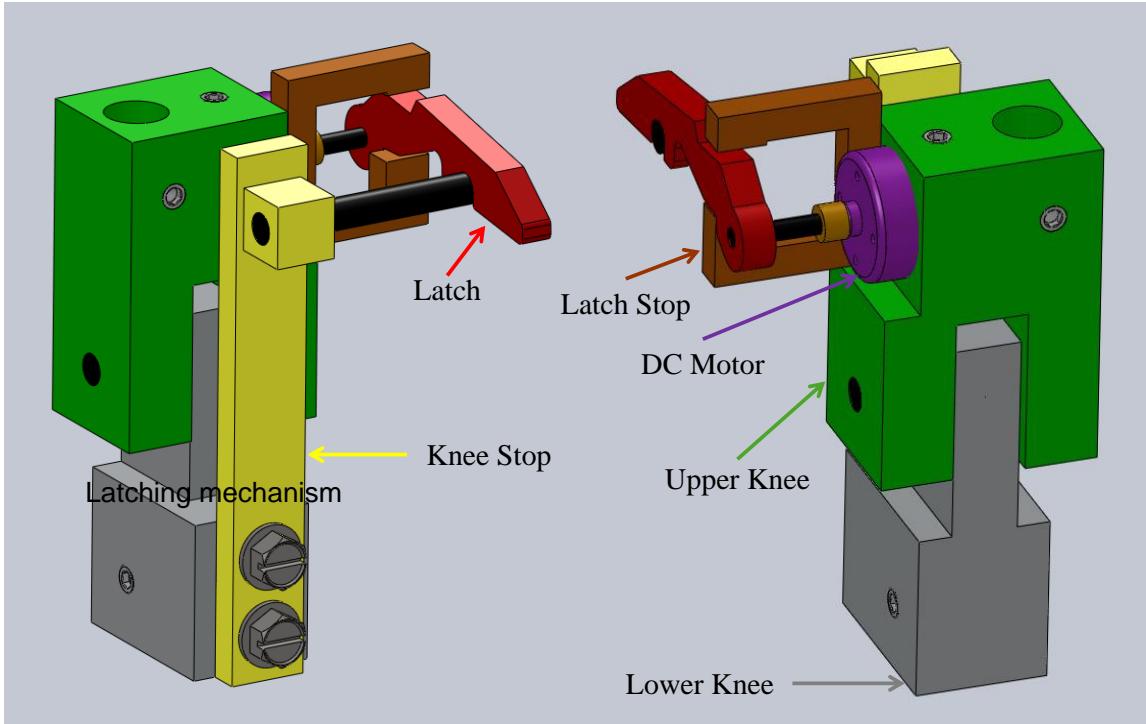


Figure 3.5: SolidWorks Model of the ratcheting knee lock mechanism.

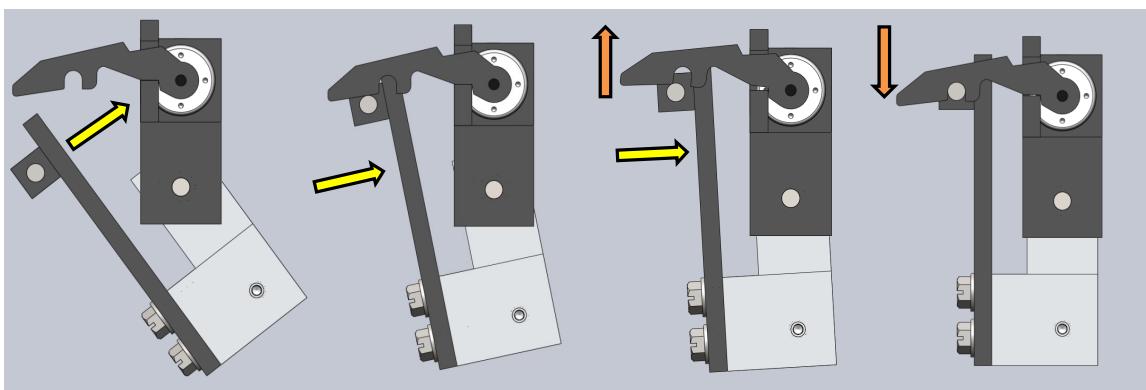


Figure 3.6: Motion of the ratcheting knee lock assembly. The latch is held down by the DC motor. As the knee stop swings and makes contact with the latch, it lifts the latch and settles into a groove, locking the knee.

pen immediately after one another, the knee latches unlock at each heel strike event. The pressure sensors at each foot are given a threshold value to act as a filter. Once a value of pressure is sensed higher than the threshold, the opposite coupled knees are unlatched. It should be noted that either outer foot contacting the ramp will cause both middle knees to unlock and vice versa. This is to force the knees of the coupled legs to unlatch simultaneously. To unlock the knees, the motor voltage is reversed causing the latch to rotate in the opposite direction. Once the latch is disengaged, the physical parameters of the walker cause the knee to bend. Phidgets boards were used for their design and simplicity (<http://www.phidgets.com>). Control board (model 1064) was paired with sensor boards (model 1018) which connected to the pressure sensors at the feet (model 1131). Programming for the sensors was done in the C++ programming language.

3.3 Foot Design

4-legged walkers do not need wide feet for lateral stability and therefore thin material is usually used because of its light weight and machinability. Since the first designs of PDWs, there have been many different ways of affixing the feet to the bottom of the shank. McGeer originally used a foot holder that held 1/16" thick aluminum plates which acted as feet. Trifonov et. al used the basic shape and design of McGeer's foot, but attached it directly to the shank using fasteners. This design deletes the foot holders which consequently reduces the overall complexity of the design. Reverting back to design for tunability, multiple foot design trials were desired resulting in the design of a quick change foot holder mechanism. The design consists of a foot holder milled out of aluminum with a transverse shaft with a groove cut in it. A foot shape is cut out of 3/8" delrin on a laser plotter and slid onto the shaft where it is constrained by an e-clip. An exploded view of this assembly is shown in Figure 3.8. For the foot insert to fit into the foot holder, there must be a 1/4" diameter hole located 1/4" from the top of the foot insert.

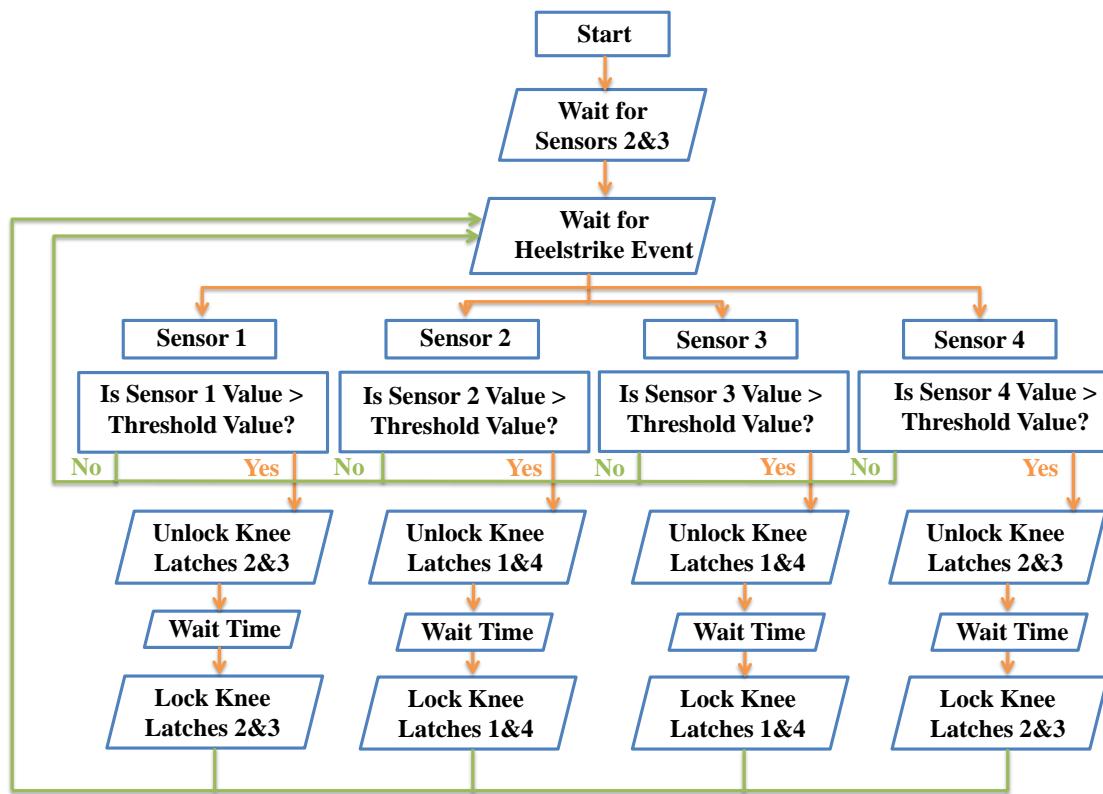
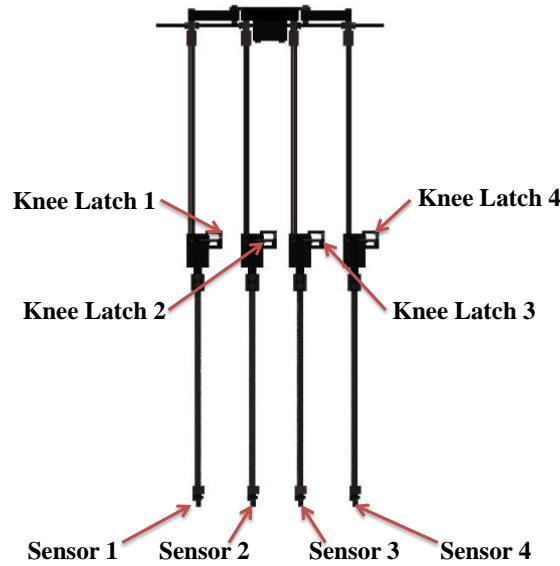


Figure 3.7: Knee latch logic. A flow chart for the knee latch programming is shown in the above diagram.

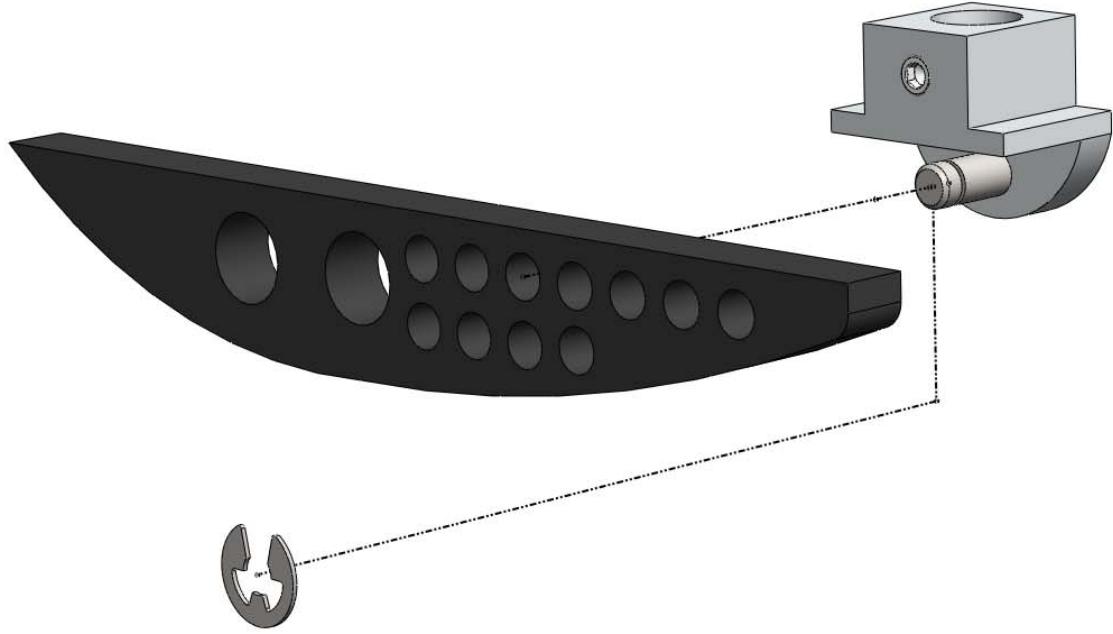


Figure 3.8: Exploded view of the quick change foot holder assembly.

The top of the insert is flat and fits securely against the foot holder eliminating rotation at foot contact. Many holes are cut into the delrin insert so that the location of the foot can be moved quickly. Overall, this design is as simple and lightweight as previous walker foot designs with the addition of quick and easy foot removal. A comparison between previous foot holder designs and the quick change foot holder is shown in Figure 3.9.

An observation from a design point of view is that there have not been significant changes to the foot shape on PDWs. The most common foot shape for PDWs emanated from McGeer's earliest designs and has since only been changed in 3-D walkers and passive robots over the years. McGeer's design for the foot is a semicircle with a radius approximately equal to one third of the total length of the leg. This simple axiom ultimately stems from the fact that anthropomorphically the length of the foot of a human is roughly one third the length of their leg. This axiom was introduced by McGeer and has ever since been the starting point for most PDW foot designs. A more simple design that eliminates many of the factors involved in foot design is the point foot. While a point

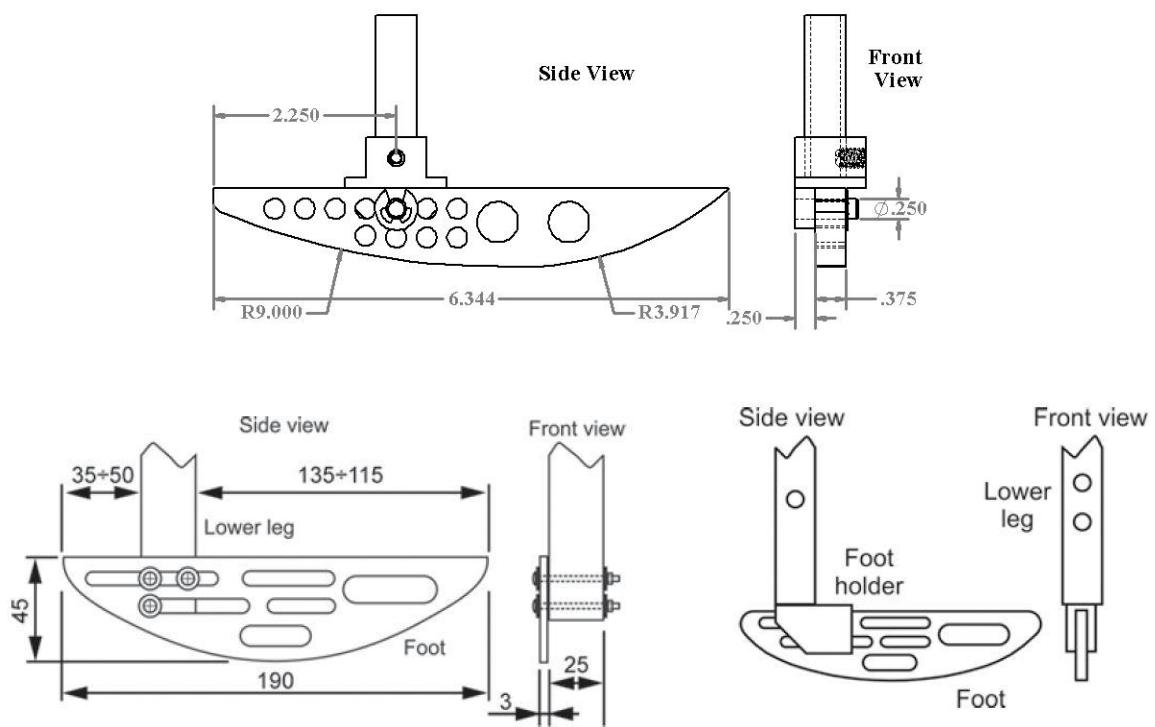


Figure 3.9: A Comparison of different PDW foot holder designs. Top: Quick change foot holder, Bottom Left: Trifonov et. al foot holder [11], Bottom Right: McGeer's original foot holder design [15]

can be accurately modeled as having a contact surface of an infinitively small point, from a practical standpoint it is beneficial to use a point with a large enough contact patch to ensure there is no slipping. Therefore, in practice a point foot is nothing more than a constant radius foot just with a radius that is small in comparison to the length of the walker leg. While from a simplicity standpoint a point foot is beneficial, it has been found that it can adversely affect the stability of the walker [15]. Since the stance leg is an inverted pendulum, the angular velocity of the stance leg is more sensitive [15]. As the foot radius decreases there is even more potential for the center of mass to move outside the stability polygon causing a divergence in stability [15]. While Chen proved that point feet can be successful in application, the increase of sensitivity to initial conditions is surely noticed.

3.3.1 Prosthetic Foot Implication

Foot shape has been studied for years in prosthesis research. Given the context of this research, it is relevant to discuss briefly a connection between PDW and prosthesis research. Rietman et. al discuss research that has been done on lower limb prosthetics and summarize many concepts, ideas and opinions brought up from over a decade of research [17]. Of the topics, the influence of the prosthesis foot designs on gait was discussed. The two main designs that have been around for some time on lower limb prosthesis are the SACH foot and the Flex-foot. While the SACH foot looks similar to a human foot, it does not behave in quite the same manner. The SACH foot acts similar to a foot of a PDW in that there is little energy absorption at heel strike. However, because the SACH foot prosthesis incorporates a pivot at the ankle joint, dorsiflexion is still possible. The Flex-foot is what is known as an energy storing foot. Because of its elastic properties, energy is absorbed by the foot at heel strike and as the foot rolls throughout its stance phase. The merit of investigating roll over shapes is the potential performance that they offer to the walking cycle [12]. Most all PDW use a curved foot and lack an ankle

pivot just as a Flex-foot, but they do not absorb as much energy upon heel strike making them actually more efficient in this sense. What a Flex-foot gains over a conventional PDW foot is energy release at toe off. As the wearer's center of mass rotates about the stance foot, the Flex-foot deforms slightly, storing energy which is then used as a spring to initiate toe off. Additionally, Flex-foot designs use a changing radius at the end of the foot which creates dorsiflexion resulting in an increased knee flexion torque [17].

The same knee flexion torque, can be applied in PDW foot design to initiate knee bend after toe off, possibly solving foot clearance issues. To create more knee torque, a changing radius foot was used, similar in shape to some Flex-foot prosthesis models. The foot was broken up into thirds. Starting at the heel, the radius for the first two-thirds of the foot was found using McGeer's axiom of $R = 1/3L$ where R is the foot radius and L is the total length of the walker leg. In the last third, closest to the front of the foot, radius decreased by fifty percent. The decrease in radius of the foot allows for greater dorsiflexion and helps initiate the knee flexion for the next step. In observing Figure 3.10, it can be seen that as the foot rolls through its stance phase the decrease in radius in the last portion of the foot creates an angular acceleration. As long as friction is present, the changing radius foot creates a ramp up which lifts the walker up higher allowing for foot clearance in the next phase. This is shown in Figure 3.11 where the heights H_1 and H_2 represent the potential for roll. Height H_1 is proportional to dimension D_1 . As shown in the figure, the time rate of change in radius promotes a time rate of change in the height of the center of mass. These dynamic characteristics yield a foot shape that overall acts more anthropomorphic as it can be related to a human foot bending at the toe line. While, a formal analysis was not performed to find the actual increases in angular acceleration on the foot and torque at the knee, it is shown conceptually in Figures 3.10 and 3.11.

For possible future work, a changing radius foot with elasticity at the front of the foot could be developed. Since energy absorbed at heel strike is not directly transferred through the rolling transition to the toe off event, elasticity at heel strike only creates a

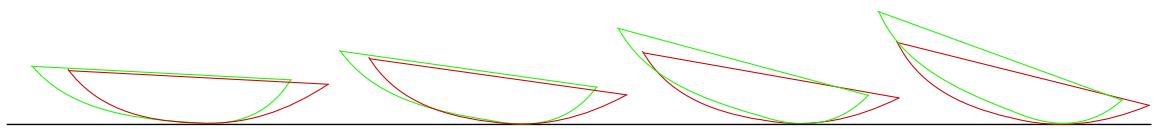


Figure 3.10: Foot motions of constant radius foot vs. changing radius foot. Displayed is the motion of a constant radius foot(Red) compared to a changing radius foot(Green) throughout a standard stance phase movement.

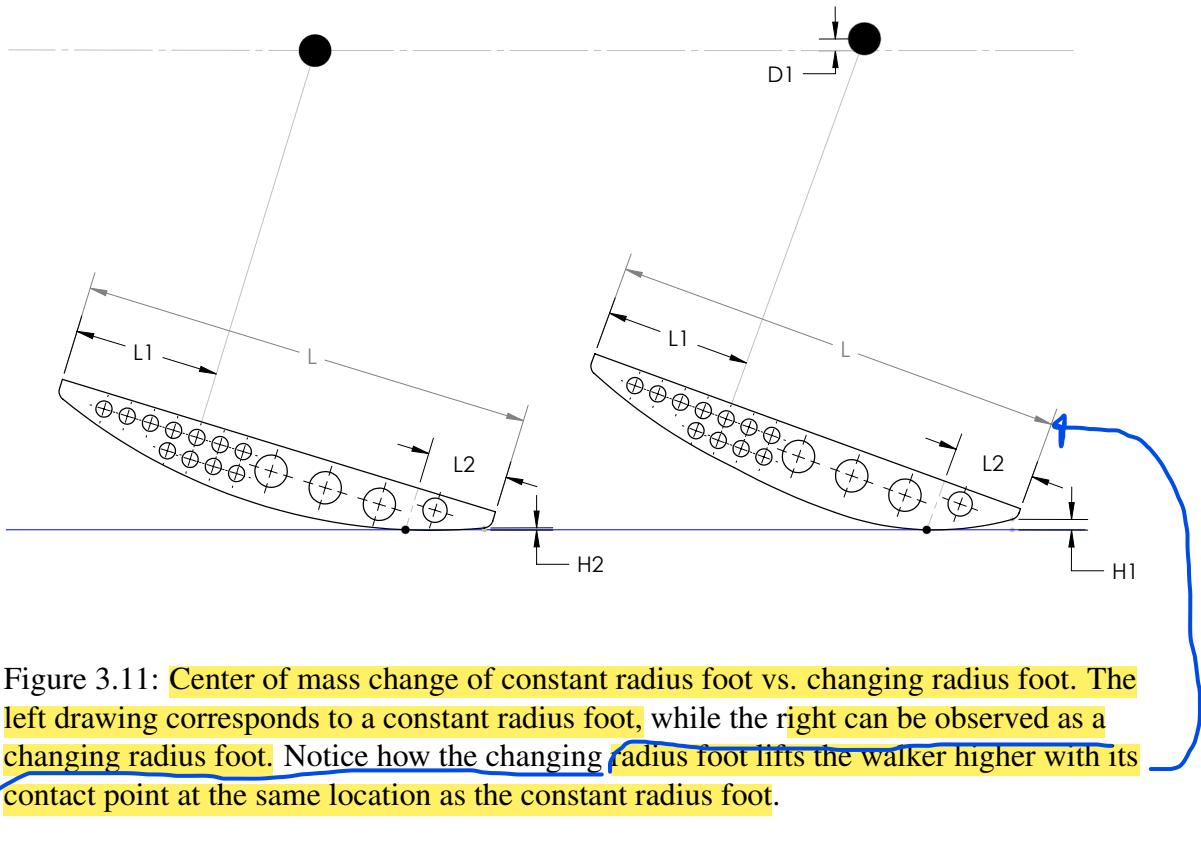


Figure 3.11: Center of mass change of constant radius foot vs. changing radius foot. The left drawing corresponds to a constant radius foot, while the right can be observed as a changing radius foot. Notice how the changing radius foot lifts the walker higher with its contact point at the same location as the constant radius foot.

loss of energy. Developing an energy storing foot for a PDW could do two things: One, it could store energy through the rolling motion and use this energy to help create knee flexion torque resulting in a successful and human-like toe off. Secondly, because of the increase in dorsiflexion, the center of mass has to be lower throughout the gait cycle creating a lesser impact at the subsequent heel strike [16]. The result of these design changes could ultimately lead to a more efficient gait for the PDW just as a Flex-foot prosthesis reduced the cost of walking in a 1993 study [18].

In summary, it is believed that foot design for PDWs has many implications in future prosthesis design. Ultimately, it is desired for a PDW to be used for testing gait rehabilitation models and devices. It is the author's opinion that a 4-legged walker makes a robust testing mechanism for foot shape due to its ample lateral stability, and by designing for tunability, these foot shapes can be quickly implemented. Changing radius feet bring about an interesting topic in PDW foot design and as far as the author knows they have never been used in this application. With their introduction, it is possible for future designs to look at better foot shapes and possibly Flex-feet which could eventually lead to a more efficient and human-like gait.

3.4 Computational Model

In order to more accurately describe a PDW, a mathematical model was used and input to MATLAB. The model started as a five-mass model similar to that derived by Chen [2]. It was developed further in our lab to differentiate between each leg of a PDW, allowing for an asymmetric model [10]. The model was then advanced by Sushko [19], where masses were added to better describe the mass distribution of a walker. This model was also used to examine the effects of changing the center of mass while the rotational inertia of a link was held constant.

Although this model was used symmetrically, it ultimately gave an accurate representation of mass distribution throughout the physical walker. Using this model, there were nine masses which needed to be defined. The hip mass, two upper thigh masses, two lower thigh masses, two upper shank masses, and two lower shank masses. The inputs to the MATLAB simulation are the following: Each of the nine masses and their locations, each joint angle and joint angular velocity (initial conditions defined by q_1 , q_2 , and q_3), and ramp angle (α). See Figure 3.12 for a representation of these variables.

To accurately describe the physical walker, each mass in the model needs to be associated with a physical mass distribution. Using SolidWorks Mass Properties Tool, components of the walker are grouped together and analyzed as if they are one rigid body. The total mass is found along with the location of the center of mass, and the values are input directly into the computational model. The total mass of a section of the walker is represented by a point mass in the model at a location identical to the location of the center of mass found from SolidWorks. Looking at Figure 3.12, each colored area of the walker on the right is grouped as a separate rigid body. Its total mass is found and its center of mass location determines the values for a_1, a_2, b_1, b_2, c_1 , and c_2 . These become the starting values for which iterations in MATLAB are based. Note that because this is a 4-legged walker and a 2-legged model, the grouped inner and outer legs are each modeled as one leg.

The values from SolidWorks are input as the starting values for the ranges of iterations in the MATLAB simulation. Calculations are carried out using Lagrangian formulation. This method is used to derive the inertia matrix, damping matrix, and gravitational matrix shown below:

$$H(q)\ddot{q} + B(q, \dot{q})\dot{q} + G(q) = 0 \quad (3.1)$$

These matrices are solved within the program for joint angles, angular velocities, and angular accelerations which are carried over into the next functions. The order in

which values flow through each function is as follows: Values start in the three-link dynamics function and are input to a knee strike collision function. The values output by the knee strike function are then input to a two-link dynamics function. To complete the step cycle, values from the two-link function are input to a heel strike collision function. At the end of each step, angular velocities and accelerations are solved for and recorded, and average step length is found from the joint angles at that specific instant. This whole process is repeated thousands of times in MATLAB, as each mass is changed with respect to the other masses. At the end of each iteration, the step length is plotted versus step number, while the general dynamics of the gait cycle are displayed on a limit cycle trajectory plot as seen in Figure 3.13. A text file of step length difference is also output at the end of each parameter run and analyzed for system stability. A step length difference of zero is desired as the gait is perfectly symmetric and stable.

Hundreds of different solutions arise and are examined using the step length plots as a rough estimate of stability. All of the text files correlating to the most uniform looking step length plots are then opened and analyzed. From the text files, the most stable solutions are found and the parameters of these solutions are applied directly to the physical walker. While this technique of modeling seems to be fairly robust, it is important to check the masses of the actual machined parts against the masses given by SolidWorks. If the materials are not specified correctly, there will sometimes be vast differences. To check these values, a table was constructed, which is shown later in the Testing Section.

3.5 Design Conclusions

It is clear to see from the previous sections that the design process for a PDW can be long and arduous. One of the focuses of this thesis is give an overview of the design process so that those in need of a PDW for a research application have a starting point to build off of. The first step in using a PDW for a specific application is to consider pos-

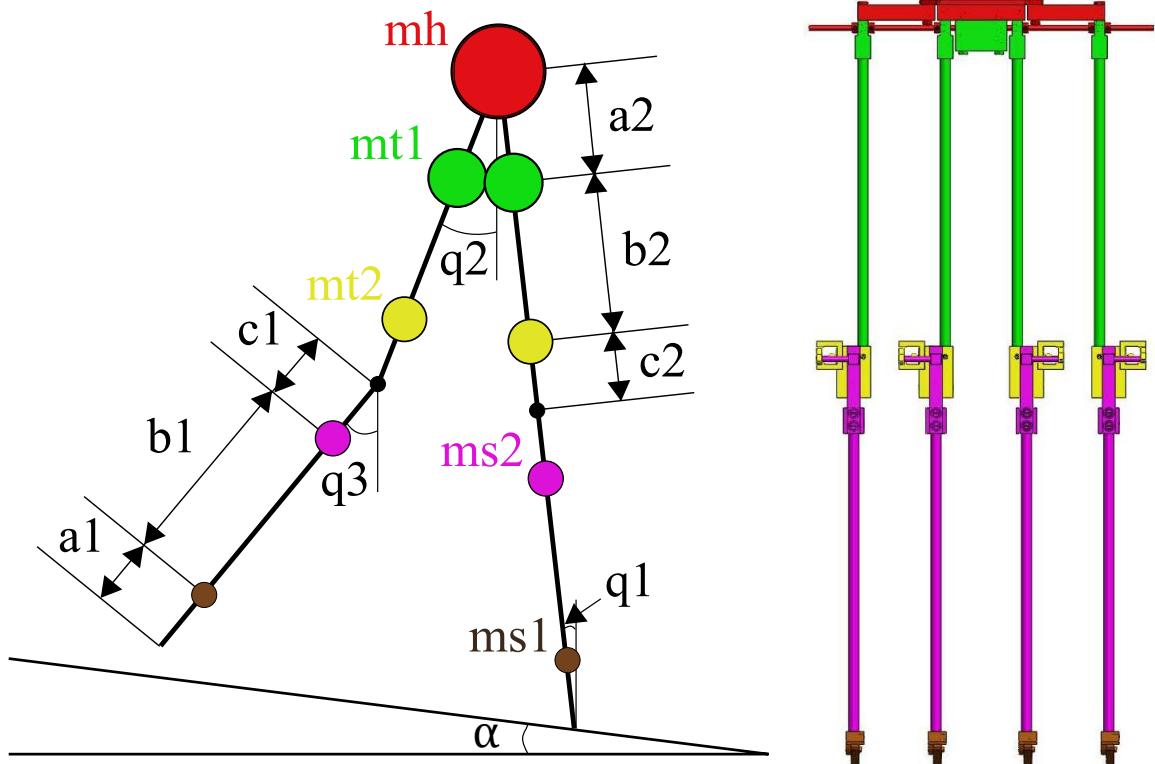


Figure 3.12: Walker mass distribution. The right figure shows a color coordination of the components which are grouped together to form the point mass on the computational model. Each point mass on the model is at the exact location of the grouped components center of mass from the physical walker.

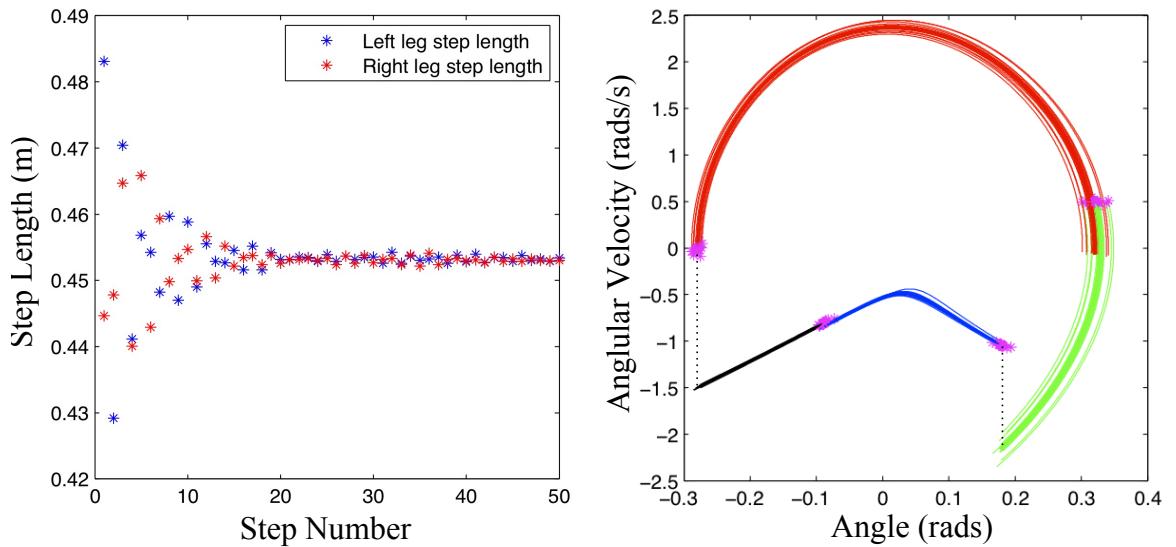


Figure 3.13: Step length and limit cycle output plots. The left figure shows the step lengths of the left and right leg over a range of 50 steps. The right plot represents the dynamics of the full gait cycle. This figure follows the right leg through a full step phase. The colors represent the following: Red - right leg in three-link swing phase, Green - right leg in two-link swing phase, Blue - right leg as left leg is in three-link swing phase, Black - right leg as left leg is in two-link swing phase. **Discontinuities in this figure at each Pink point represent a collision event.** The collisions between Green and Red and Blue and Black represent knee strikes, while the large gaps shown by the dotted lines represent heel strike events.

sible similarities in motion while also factoring in the amount of time and effort needed for design. While compass gait models can be fairly simple to design, they are not void of pitfalls. For human gait analysis, 4-legged PDWs with knees are a good starting point because they offer a human like gait which changes dynamically in only two dimensions. 3-D bipeds are of the most advanced PDWs, and while the most anthropomorphic, they can be too complex for a first design. Once a type of PDW is chosen it is important to follow an iterative process of design and check steps. As previously mentioned, the basis for design started with using basic axioms which help in selecting material and forming the basic geometry for the components of the walker. The three mentioned in the above section were the following:

1. The mass of the upper portion (hip mass and thigh mass) should be at least 10:1 [2].
2. Walking efficiency is increased as the leg spacing decreases [1].
3. The foot radius should be roughly equal to one third of the total length of the walker leg [15].

Once these axioms are established, it is beneficial to use the powerful tools offered by CAD programs such as SolidWorks. The Mass Properties Tool was used liberally throughout the entire design process first to check the total mass of each of the upper and lower components and later to assist the mass locations and magnitudes which were input into the computational model. While some have built walkers predominantly from trial and error methods, it is not advised. Because PDWs are so sensitive to inertial variations, it is very difficult to tune the gait to stability. The mathematical model consists of second order differential equations which can be input to MATLAB and solved by iteration. Once the point masses of the model are found, final tuning can be performed. In earlier design steps, it is important to recognize how the walker will be tuned before designs are finalized. Such design considerations may ease tuning procedures in the final stages of construction. The final design discussed in the above sections was designed

to be tunable and exhibit an anthropomorphic gait. Many design improvements were made over similar designs in the past such as the lightweight one-piece upper knee joints, changing radius feet, and a planar hip coupling mechanism. All three of these design improvements aid the overall gait motion of the walker. The knee joints are lightweight to enable for repeatable knee lock without lowering the center of mass of the upper leg assembly. The changing radius feet cause ramp up at the end of the stance phase creating a knee flexion torque which aids knee bend in the following step. Lastly, the planar hip coupling allows the inner and outer legs to be coupled without creating an unnecessary moment arm at the top of the walker. These features can be seen in the final constructed walker shown in Figure 3.15 and the CAD drawing with dimensions shown in Figure 3.14.

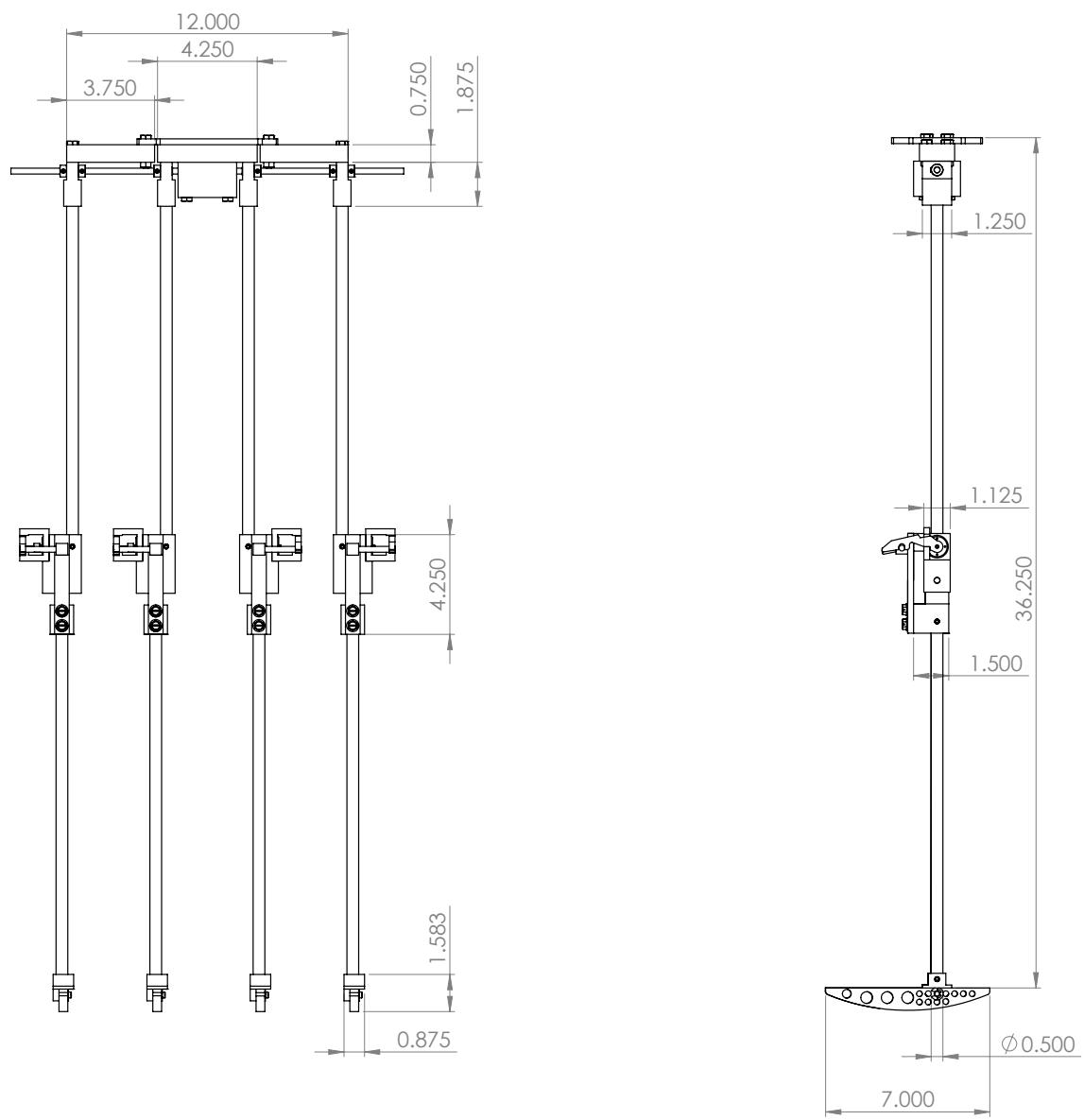


Figure 3.14: Final walker design with dimensions



Figure 3.15: Photo of final walker assembly

Chapter 4: Testing

Testing is perhaps the most frustrating process in developing a PDW. The sensitivity of the mechanism is cited as the main difficulty in tuning, but there are many other sources for failure outside the system. As accurate as it may be, it is impossible for a computational model to take into account every variable in the system. During early stages of testing, the walker was hitting the ramp so hard at heel strike that the foot bounced up off of the ramp. The vibration from this impact caused the previous stance feet to enter the swing phase prematurely, diminishing gait. This is an example of when a mathematical model might not help the physical system. There are so many other variables to the system that need attention from a practical standpoint. This section strives to give an overview of the testing process, with a focus on the more practical aspects such as building the ramp and addressing walker failures.

4.1 Parameter Tabulation

For testing to begin it is a good idea to have an easily accessible and organized spreadsheet of all components of which the walker is comprised. Testing inevitably involves changing mass locations and/or modifying parts such as the feet and knees. Reverting back to the design section, SolidWorks calculations are compared to the physical masses. Once the physical masses correlate with those in SolidWorks, the center of mass calculations can be input into the computational model. Another motivation for a spreadsheet is to keep record of any mass changes due to the addition of weights. For

instance, 1/2" shaft collars were used as weights for the shanks and thighs, and stick on weights were used for adding mass to the hips, knees, and feet. With a spreadsheet, it is easy to keep a tabulation of many designs all with different masses and mass locations. The main mass table is comprised of all parts necessary for a walker assembly, along with the masses of the different types of added weights. This table is shown below. From this table of miscellaneous parts, each design being tested is grouped into its own table. The designs group the parts into pseudo point masses which are then input directly into the mathematical model. The two designs tabulated are for the magnetic knee design and the actuated knee design located in Tables 4.2 and 4.3 respectively.

4.2 Ramp Construction

Before testing can begin, it is necessary to have a well defined slope that can be adjusted to multiple angles. There were two main concerns with the construction of the ramp. Because the computational model can assign any value to the ramp angle, it is a good idea for the ramp to have a very high resolution in terms of angle adjustment. Secondly, a smooth, level surface is desired. The adjustment mechanism on the ramp consists of a power screw that is fixed between two hinges using hex nuts. The bottom hinge attaches to the fixed part of the ramp which is locked in place and not adjusted, while the top hinge is adjusted by moving the hex nuts up and down the power screw. Once the correct angle is located using an angle finder, the hex nuts are turned in opposite directions locking the upper hinge and fixing the ramp angle. The hinges work perfectly in this application because the extra degree of freedom from the revolute joints allow the power screw to pivot as the ramp angle changes.

Early in the testing stage, there was a problem with foot clearance just after toe off on the first step. Because the walker is not settled into steady gait during the first half step, providing it with the correct initial conditions is up to the person initiating its

Table 4.1: Masses of Each Component of the Physical Walker

Masses of Walker Parts:		
Part:	Mass: (ounces)	Mass: (kilograms)
Hip Assembly	2.1	0.062
Hip Bolt	0.3	0.01
Hip Shaft	2.7	0.078
Hip Screw	0.1	0.002
1/4" Shaft Collar	0.1	0.004
1/2" Shaft Collar	1.1	0.03
3/4" outer crossbar	19.7	0.558
3/4" inner crossbar	20.5	0.582
Thigh	13.7	0.388
Upper Knee Assembly (Aluminum)	4.4	0.124
Upper Knee Assembly (Delrin)	3.6	0.102
Lower Knee Assembly	4.2	0.12
Knee Shaft	0.3	0.012
Inner Knee Stop (Magnet)	3.8	0.108
Outer Knee Stop (Magnet)	1.9	0.056
Inner Knee Stop (Latch)	3.6	0.102
Outer Knee Stop (Latch)	1	0.028
Knee Stop Bolt	0.2	0.006
Knee Latch	0.2	0.006
Magnet Bolt/Nut	0.5	0.016
Shank	2.3	0.064
Knee Magnet	0.1	0.004
Quick Change Foot Holder	0.9	0.026
Constant Radius Foot	1.2	0.036
Changing Radius Foot	1.1	0.032
Crossbar connector	12.9	0.366
Crossbar bolt	0.3	0.008
Inner crossbar weight	11.7	0.332
Weight bolt	0.5	0.016
Stick on weight	0.25	0.007

Table 4.2: Mass Table for Magnetic Knee Design

Design 1: Magnetic Knee

Mass at Hip (mh):	3.066	kg
Mass at Upper Thigh (mt1):	2.04	kg
Mass at Lower Thigh (mt2):	0.848	kg
Mass at Upper Shank (ms2):	0.784	kg
Mass at Lower Shank (ms1):	0.248	kg
Total Mass of Design 1:	6.986	kg

Table 4.3: Mass Table for Actuated Latch Knee Design

Design 2: Actuated Knee Latch

Mass at Hip (mh):	3.066	kg
Mass at Upper Thigh (mt1):	2.04	kg
Mass at Lower Thigh (mt2):	0.712	kg
Mass at Upper Shank (ms2):	0.784	kg
Mass at Lower Shank (ms1):	0.232	kg
Total Mass of Design 2:	6.834	kg

motion. Rather than dealing with the complexity involved in finding the perfect initial conditions and actually applying them to the walker, raised tiles were added to the ramp to promote foot clearance during the swing phase. Not to say that initial conditions were not investigated, rather the foremost priority was to establish any gait at all so that further analysis could be performed. Once the walker is properly tuned, the tiles can be removed and any additional gait deterring dilemmas can be dealt with. These raised tiles are simply constructed out of 1/2" thick plywood. Additionally, they are covered with rubber matting to provide a better friction surface and to help damp unwanted vibration at heel strike.

Lastly, sagging occurred after the construction of the ramp. Because of its smoother and more uniform surface properties, Medium Density Fiberboard was used for the inclined portion of the ramp instead of plywood. Its higher density created the sagging problem, but was solved by using 2"x4" lumber as bracing on either side of the ramp. Because of the thickness of these braces, the ends had to be cut on a taper to allow for the ramp to close when set to shallow angles. The fully constructed ramp has dimensions of 36"x96". The length of the ramp allows for the PDW to reach a steady gait, however a longer ramp is desired in the future along with the possibility of testing on treadmills. More on this is discussed in the future work section of the Conclusions.

4.3 Simple Friction Loss Calculation

One aspect of PDW design that is especially hard to model accurately is the losses due to friction. It has been found that the greatest losses due to friction occur on the stance foot and in the hip bearings[15]. While most PDWs use ball bearings to reduce friction at all pivoting joints, it is a good exercise to compare the natural frequencies of the physical walker to the calculated value. These calculations are a good check step to make sure unwanted damping is not introduced into the system especially by something that the



Figure 4.1: Ramp construction. Left: The ramp uses a power screw to lift the inclined portion. Hex nuts are used to lock it at a specific angle. Right: Tiles are used for extra foot clearance and to damp out unwanted vibration at foot impacts.

designer is unaware of. Such rogue damping can cause great frustration when it comes time to tune the walker.

For this calculation, a very simple relation is presented. From pendulum motion, it is found that natural frequency is directly related to the total mass moment of inertia of the system. This relation is given by the following formula:

$$\omega = \sqrt{\frac{(m_{total}gd)}{4\pi^2 I_{Total}}} \quad (4.1)$$

where ω is the natural frequency of the pendulum, m is the total mass, d is the distance from datum to the center of mass, and I is the total mass moment of inertia about the datum axis. The total mass can be found from weighing each component as performed in Table[1] of the previous section. The calculation of I can be done by approximating a general shape for each component of the walker. While the accuracy of the calculation is related to accuracy of the geometric representation of each component, basic shapes are used for simplicity. The knees and feet are approximated as cuboids while the thighs and shanks are better represented as rods. Corresponding to Figure 4.2, the following equations represent the mass moment of inertia of each component about the datum axis:

$$I_{Thigh} = \frac{1}{3}mL^2 \quad (4.2)$$

$$I_{UpperKnee} = \frac{1}{12}m(a^2 + b^2) + mD2^2 \quad (4.3)$$

$$I_{LowerKnee} = \frac{1}{12}m(a^2 + b^2) + mD3^2 \quad (4.4)$$

$$I_{Shank} = \frac{1}{3}mL^2 + mD4^2 \quad (4.5)$$

$$I_{Foot} = \frac{1}{12}m(a^2 + b^2) + mD5^2 \quad (4.6)$$

$$I_{Total} = I_{Thigh} + I_{UpperKnee} + I_{LowerKnee} + I_{Shank} + I_{Foot} \quad (4.7)$$

Applying to all equations, m is the total mass of the component, and D1, D2, D3,... is the distance from the datum axis to the centroidal axis of each component. For the equations pertaining to the thigh and shank, L is the total length of the rod. For the cuboid equations, a and b are the length and width respectively. Once the mass moment of inertia for each component is found, the center of mass location of the entire pendulum is found by the following equation:

$$x_{cm} = \frac{m_1x_1 + m_2x_2 + \dots + m_nx_n}{m_{total}} \quad (4.8)$$

Knowing the mass, the location of the center of mass, and the total inertia, the natural frequency can be found and compared with the measured data. The measurement of natural frequency was performed on each coupled pair. Because the main purpose of this calculation is to expose any unwanted damping due to friction or elasticity, the inner and outer coupled legs should be checked with the calculated value. To perform the frequency calculation, the walker was clamped to a workbench with its legs free to swing. A strip of rubber was used between the walker crossbar assembly and the bottom of the workbench table to damp out any vibration present. Each coupled pair of legs was timed for ten cycles. This test was repeated ten times and the data is as follows:

The natural frequency was then calculated using the previously mentioned equations producing a calculated natural frequency of 0.7579 cycles/s. Since this value is slightly greater than the observed values, we can conclude that damping is present in the system, but very minimal. Because these calculations are straightforward, it is recommended to step through this procedure after the final walker is constructed.

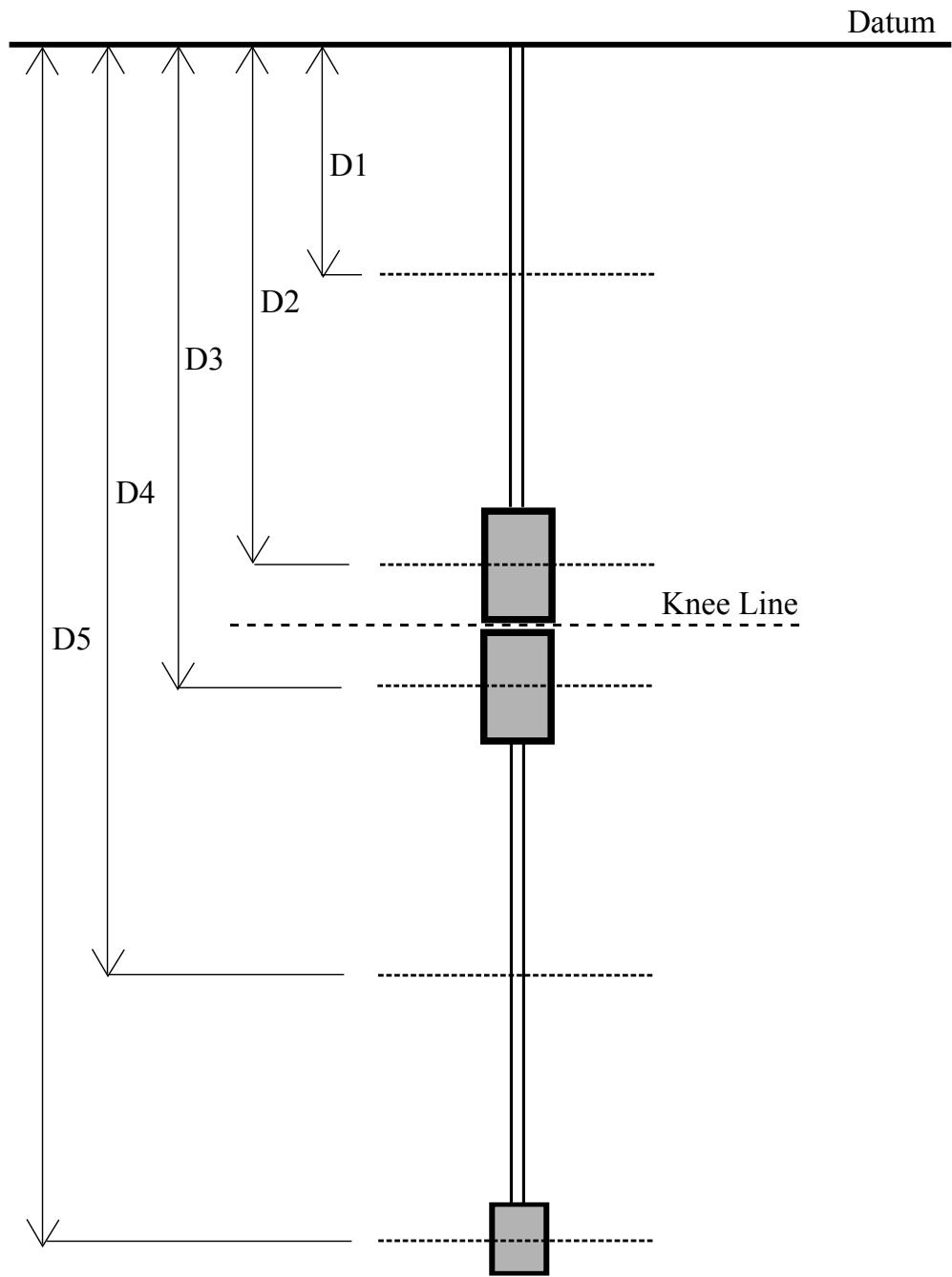


Figure 4.2: Mass moment of inertia diagram. Each distance defines the location of the centroidal axis of each part on the walker with respect the datum axis

Table 4.4: Natural Frequency Measurement

Test	Natural Frequency for Coupled Legs	
	Inner Legs	Period for 10 Cycles (s)
1	13.6	13.9
2	13.7	13.8
3	13.7	13.8
4	13.7	13.9
5	13.7	13.8
6	13.7	13.9
7	13.6	13.8
8	13.7	13.9
9	13.6	13.8
10	13.7	13.8
Avg. Inner		Avg. Outer
13.67		13.84
Inner Natural Frequency:	0.7315289	cycles/s
Outer Natural Frequency:	0.7225434	cycles/s
Calculated Natural Frequency:	0.7579005	cycles/s

4.4 Computation of Initial Conditions

Initial conditions are somewhat of an art compared to the rest of the development of a PDW. Because there has been no device developed for setting a PDW into motion, the success of each trial is largely up to the person launching the walker. Even with a robust walker such as the one built by Collins et. al, it was cited that a practiced hand was needed for a successful launch [4]. With much practice, 20 percent of trials still failed because of human error in the initial conditions [4].

While there is definitely a "feel" for setting a PDW into motion, quantifying the values of the angles and angular velocities is helpful especially in early stages of testing. To test these values, the computational model was used. With the parameters exactly equal to that of the physical walker and ramp angle set to that of the physical ramp, the optimal values for q and \dot{q} were found. These values were found by first observing each angle and angular velocity on the swing leg, just as this leg starts the three-link phase. By running the simulation a total of one hundred steps, a steady state value was found for each angle and velocity. The mathematics for this are derived from the Lagrangian formulation. From each collision event (knee strike and heel strike) angular momentum is conserved about the appropriate pivot point. Post-collision velocities are then found using the pre-collision angles and velocities from the two-link dynamics function. A more detailed explanation of the modeling of the system can be found in [19]. Figure 2.2 (far right) helps with visualizing the three joint angles and angular velocities.

From a MATLAB simulation, the following steady state conditions were found immediately after heel strike:

$$q^+ = \begin{bmatrix} 0.1987 \\ -0.2996 \\ -0.3096 \end{bmatrix} \quad (4.9)$$

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$$\dot{q}^+ = \begin{bmatrix} -1.1094 \\ 0.2877 \\ 0.2877 \end{bmatrix} \quad (4.10)$$

In the above matrices, q^+ represents the angles of each joint angle and \dot{q}^+ represents the joint angular velocities immediately after heel strike. Notice how the angular velocities for the second and third joint angle are the same. Physically this means that the knee has just unlocked and at this instance and the leg is still fully straight with no knee bend. This correlates directly with how the actual walker is launched.

With the outside feet touching the ramp and knees locked, the middle two legs are swung back and forth. This swinging motion causes the whole walker to pivot about its stance feet and can be thought of as creating a negative velocity of its first joint angle. Because the ramp uses raised tiles, it is easy to see where the first heel strike should take place. Testing was performed with both the knees of the middle legs locked and unlocked. It was found that more successful trials were completed with the knees locked, making this the preferred method. While the calculation of initial conditions is an important step from a modeling point of view, setting a walker into motion really does take a certain feel that is hard to quantify. It was observed that letting the walker swing naturally before initiating heel strike was helpful. It also helped to have a mark on the ramp where the middle feet should land initially. One important value to take from the initial condition calculations is the value of the first joint angular velocity. During testing, the walker did not have enough inertia to carry through to the next step if this value was too slow. The calculated value of -1.1099 rads/s or -63.59 deg/s seemed to be an accurate approximation. The walker can be seen set into motion in Figure 4.3.

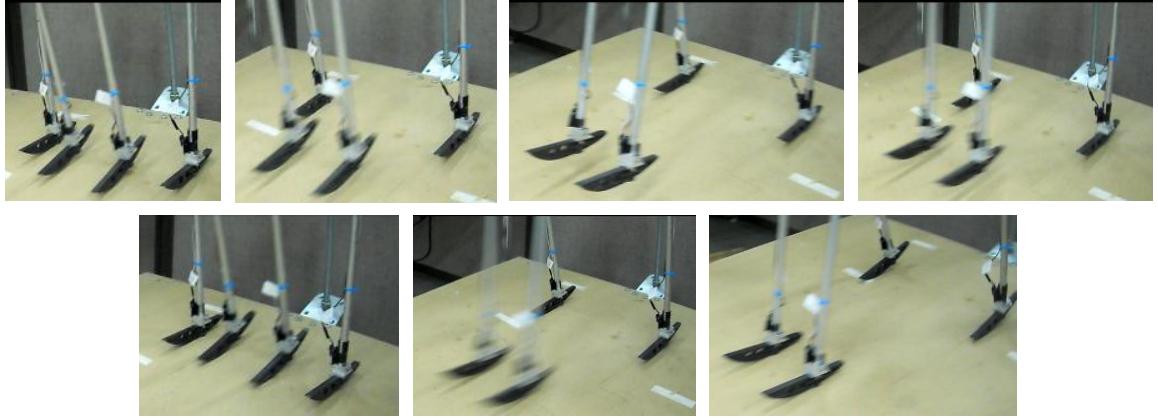


Figure 4.3: PDW launch sequence. The walker is set into motion by rocking the middle legs back and forth. This motion rotates the center of mass about joint angle one. It is necessary to keep consistency with both the joint angular velocity of joint angle one and the distance that the foot lands down ramp. The latter corresponds to the sum of joint angles one and two.

4.5 Testing Procedure

A systematic procedure was set up to test the walker. First, the walker was set to the specifications of the computational model through MATLAB simulation. Next, the walker was tried in this configuration at the following ramp angles: 10, 7.5, 7.0, 6.0, 5.5, 5.0, 4.5, 3.0, 2.5, 2.0 (all in degrees). While the MATLAB simulation was run using a ramp angle of 3.0 degrees, the walker was not stable at this ramp angle. The decision was then made to change the ramp angle while holding all other parameters constant to determine at which angle the walker would be most stable at. Completing 5 trials at each ramp angle, it was found that the walker was the most stable at 5.5 degrees. Stability in this sense was purely analytical. Video was also recorded during these trials so that trials could be re-watched and analyzed. After selecting a ramp angle of 5.5 degrees, tuning began.

From studying the motions of the walker in the film, it was clear that the main problem was foot clearance. There are many possible problems with foot clearance such as those discussed in the Foot Design Section previously. The first step was to add tiles.

The tiles helped foot clearance but because their surface was rougher, the feet now slipped.

Finally rubber was added so that the surface had friction and damped out some of the vibration due to impact. Once the ramp surface was mended, the focus was on the inertia of the PDW.

It was clear from the videos that the thighs were swinging too slow. Shaft collars located at the center of mass were taken off making the thigh swing slower. Also, a small amount of mass was added to the shank so to slow it down. With the thigh swinging faster and the shank slower this created more knee bend. At this time, the constant radius foot was tried allowing for even more foot clearance during the swing phase. It was found that with this combination, successful tests were much more common. Fine tuning was done by trial and error, but to put it into context this took about 15 trials.

Throughout the entire process there were many interesting failures. Unlike many papers, this thesis strives to highlight these failures and provide insight that can be used to resolve them. While for research sake, it is important to have a working final design, it may prove more beneficial to future research to show the problems and how they were overcome. Troubleshooting definitely is aided by video recording. In the following figures, motion shots captured during the testing process are discussed in greater detail. Perhaps in the future, motion capture equipment such as used by Chen [2]. This would give the ability for direct comparison between the computational model and the physical walker.

4.5.1 Troubleshooting

In this troubleshooting section, a few screen shots will be looked at and analyzed. As problems throughout testing arose, video was used to help solve the problem before more testing was done. Several of the most common areas in which problems arose were the feet, knees, initial conditions and problems with the ramp. It is the author's belief

that foot design will become a larger area of research in future PDW research. There seems to be a general problem of keeping feet light while also leaving enough contact area for friction. In fact, the initial foot design was designed like a common biped foot for extra friction. It was not used because of the extra weight it added to the system. This foot can be seen in the Appendix D. The knees proved to be equally hard to troubleshoot because of their rapid latching action. Several designs for the mechanical latch were developed throughout the testing phase. Early prototypes were not shaped correctly or had too much friction for the knee to unlock consistently. Lastly, as mentioned in the Ramp Construction Section, variables such as the ramp are often neglected during the initial design of a PDW. Some of these issues can be seen in the following motion shots of the walker:

The first set of screen shots shows a problem with the initial conditions. If the outer legs are not aligned properly at take off, or if the person launching the walker tilts the crossbar to one side, there is potential for the outer legs to enter the swing phase at different times. As the right outer leg comes down first, a moment is created causing a yaw motion. This motion prohibits the outer knees from locking causing the walker to collapse. A solution to this was to put marks on the ramp for a starting location for the outer legs and a landing location for the middle legs. Having these marks as guidelines greatly improved the consistency of trials.

The next motion shots show a unique condition. As with the previous set of pictures, a problem occurred during launching. However, because the feet had ample friction, the knees bent enough for the foot to regain its motion even after hitting the tile during swing phase. in the forth picture from the left you can see the difference in angle between the right an left outer legs. Before the walker made contact at heel strike, both knees locked and the walker carried out its gait cycle.

These images show the result of too much tolerance between the upper and lower knee joint. Before this particular trial, new bearings were put into the lower knee joint

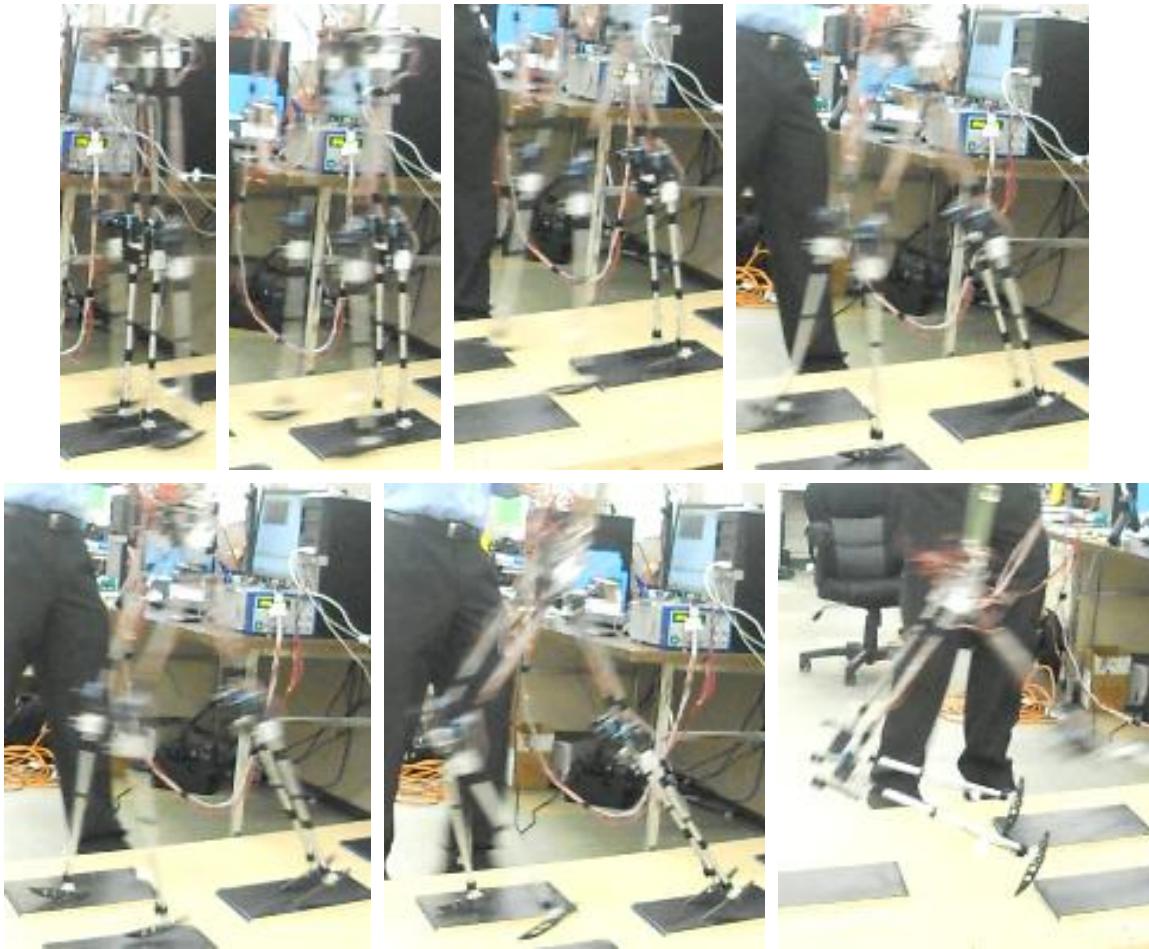


Figure 4.4: **Loss of foot friction**. As the walker made contact with the ramp tile at the second heel strike, each outer leg made contact separately. This imbalance caused the foot to bounce and skid.



Figure 4.5: **Foot clearance issue.** Looking at the figure, the far outside leg enters the swing phase too soon causing it to catch on the first raised tile. Amazingly, the leg is able to continue through the swing phase and lock the knee. Even with this collision, the walker made it down the ramp.

due to contaminants getting into the previous bearings. The new bearings were slightly thinner causing a small gap between the inner and outer joints. As the walker descended the slope, the legs bent side to side slightly causing the walker to turn by the time it got to the bottom. Teflon spacers were used after this run to limit the side to side angular displacement. Another trial had the same effect when the feet were not completely orthogonal to the body of the walker. Possibly in the future, some sort of alignment pin will be used on the round shafts to align the feet properly.

Lastly, these motion shots show the result of too much speed at launch. When the second joint angle velocity is too much at take off, it causes a large angle between inner and outer legs at the first heel strike event. Too much energy input to the system at launch will cause the step lengths to increase and the center of mass to fall out of the stability polygon. In this particular case, the feet were moving so fast that as they made contact with the ramp they bounced multiple times.

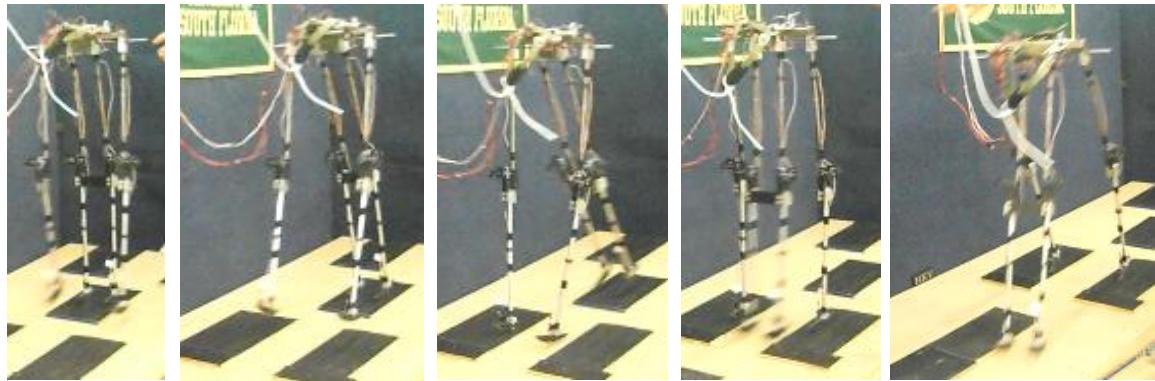


Figure 4.6: Turn due to impact. As the walker made contact with the ramp tile at the second heel strike, each outer leg made contact separately. This imbalance caused the foot to bounce and skid.

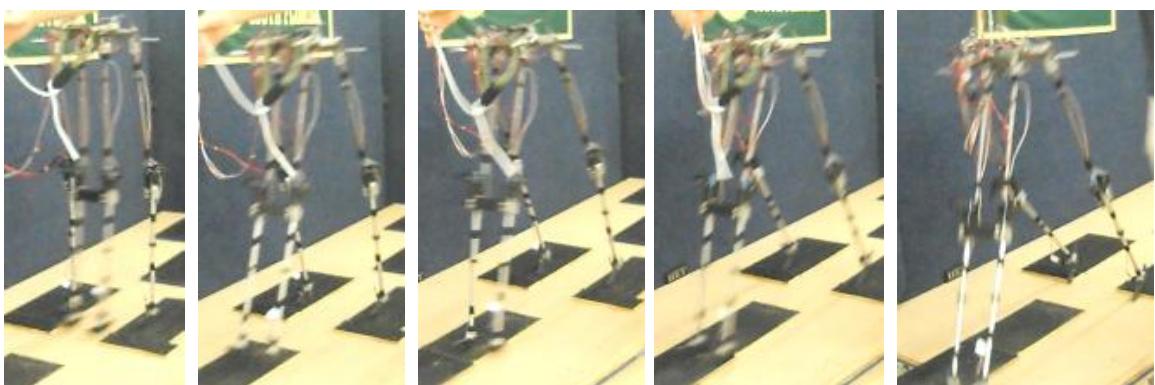


Figure 4.7: Bounce due to impact. As the walker made contact with the ramp tile at the second heel strike, each outer leg made contact separately. This imbalance caused the foot to bounce and skid.

Chapter 5: Future Works

Throughout this thesis there have been several mentions of a better design for a certain component. Often the systematic process of engineering design does not prepare us for the simple realizations that come from building and testing a finished product.

Relating back to rehabilitation applications for PDWs, future work would like to be done on prosthetic foot design using a PDW. Mentioned in the Prosthesis Foot Implication Section, a Flex-foot would be an interesting design challenge to implement on a PDW. As the foot rolls, it would store energy releasing it at toe off. This extra energy could help generate knee flexion and possibly solve some of the common problems that PDWs have with foot clearance. On the other hand, for rehabilitation research, gait motions could be observed and dorsiflexion angle differences could be looked at in a purely mechanical sense. Relating back to the Background Section, it is believed that PDWs are valuable to rehabilitation research because the dynamics of a human-like walking system can be analyzed without the corrective factors given by the control system of the human brain.

Another fascinating project that could be applied to the field of Passive Robotics is the effect of a physical asymmetric PDW. The main goal after developing this walker is to apply a physical asymmetry in the form of weight addition to one couple group of legs. It has already been proved in our earlier research that stable gait patterns could arise, but as presented in previous section, the computational model can vary from the physical walker. With a physically asymmetric walker, it might be possible to tune the inertia of the walker without changing the center of mass. This is investigated further in joint

research done by Sushko [19]. With the success of an asymmetric PDW, there is hope for rehabilitation device and methods testing in the future.

Lastly, stemming from other papers as well as this thesis, a novel launching mechanism for a PDW would be a great addition to the this research. Citing human error as the cause of unstable initial conditions, a device to set a PDW into motion could make PDWs much more reliable and therefore more feasible for other applications.

Chapter 6: Conclusions

This thesis concludes with an overview of the designs and techniques used in the development of a working 4-legged passive dynamic walker. Walking through the design process, there should be a conscious effort to abide by the simple axioms presented in the Design section. The first and most important axiom for shaping the walker is defined by a mass ratio of 10:1 between the upper mass and below knee mass.

CAD programs such as SolidWorks help the design process by calculating the expected mass of each part and outputting useful inertia data of an assembly. Used jointly with a mathematical model simulated in MATLAB, a very close representation of the model can be built. With physical parts machined and the walker assembled, it is good practice to weigh the parts and perform simple hand calculations to make sure there is no problems with assembly tolerances.

Preparing for testing, there needs to be a tabulation of data and a sufficient test area. Several problems can arise when first testing a PDW due to outside influences not described by the mathematical model. Some of the most common problems are insufficient friction between the ramp and foot, inexperience with launching the mechanism, and knee lock failure.

An investigation of a changing radius foot and planar crossbar mechanism give insight into how specific components of a walker can be improved. By linking PDWs with other facets of research such as gait rehabilitation, advancements are derived in both fields. In theory, a PDW should be able to be keep a stable gait even with physical asymmetries. This simple concept can be extended to prosthetic design or give new insight as

to how the dynamics of the human body react without human cognition. If nothing else, this thesis strives to make the design process of PDWs a little easier on those who choose to accept its frustrating challenges.

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Appendices

Appendix A: Simple Tinkertoy Walker

To get a feel for the tuning of a statically unstable robotic device, I looked to the simplest example available. This design was brought about by Coleman [3] who gave the exact design specifications in his paper. A simple ramp was made and testing was performed. The only advancement to Coleman's model was the addition of an angle finder which was laser cut out of 1/8" thick acrylic (see Figure A.2). This allows for the angle of the weights to be recorded for better repeatability in future trials. These trials were performed before the design and construction of the 4-legged PDW. While the two walkers share almost nothing in common, the Tinkertoy walker provides experience for tuning a statically unstable device. If nothing else, this was a fun exercise related to passive-dynamics.

Appendix A: (continued)

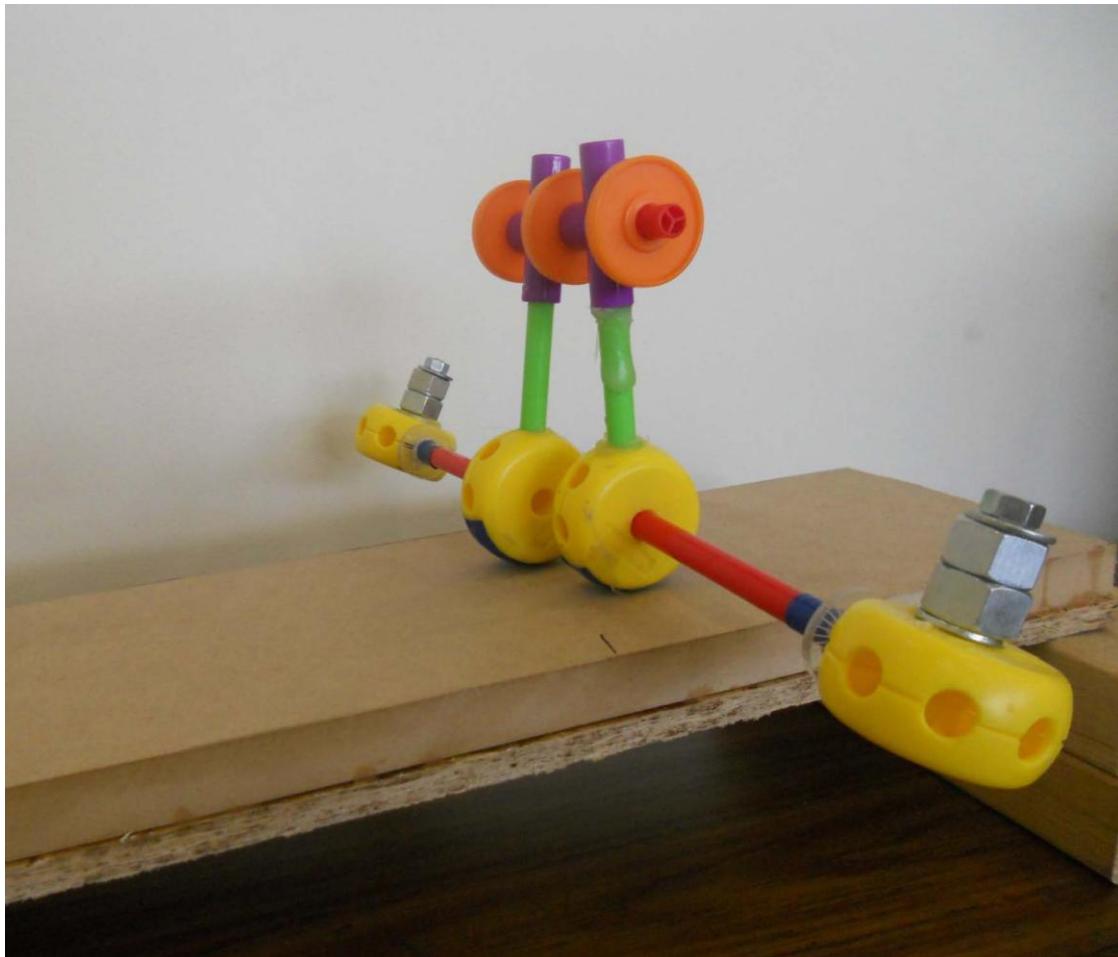


Figure A.1: Tinkertoy walker. Image of the Tinkertoy walker constructed based on original design by Coleman [3].

Appendix A: (continued)

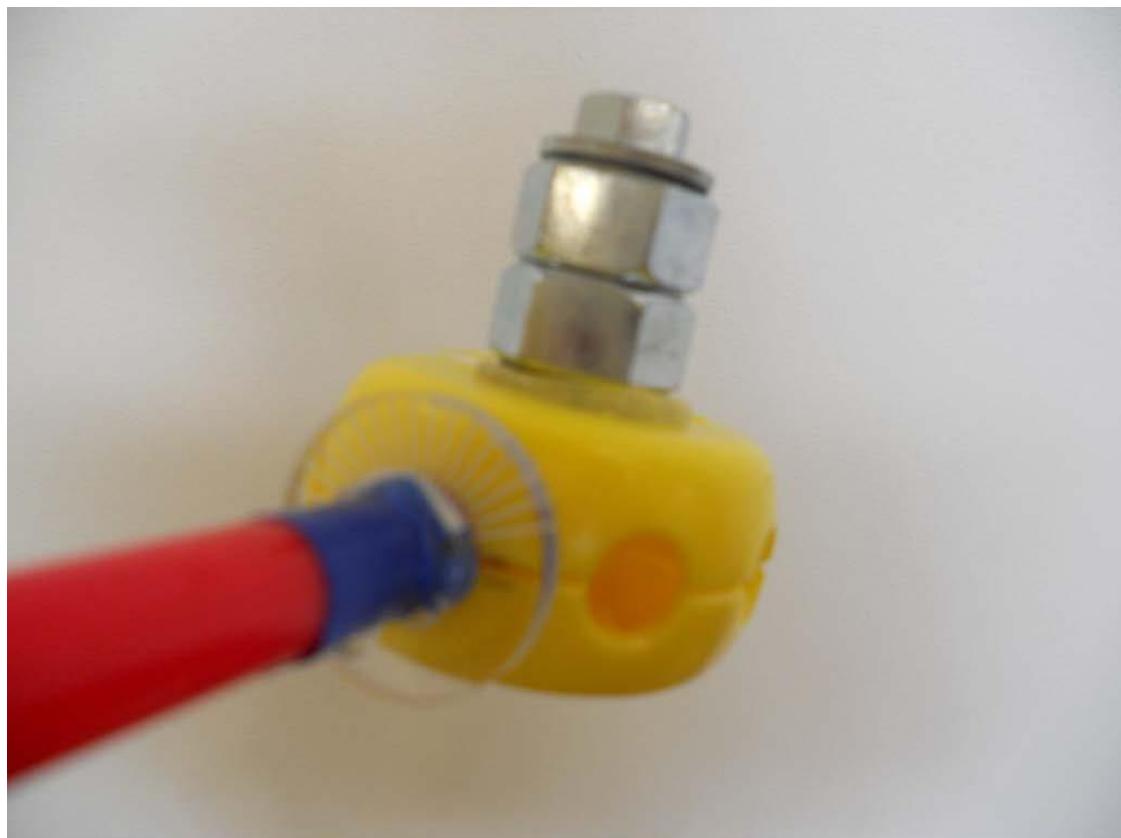


Figure A.2: Weight adjuster for Tinkertoy walker. In order to keep track of the angle of the weights on the walker, a piece of laser cut acrylic was used as an angle finder.

Appendix B: Walking Experiment

For a fun activity to get middle school children interested in engineering, a walking experiment amongst other demos were performed at the REEDLAB (<http://reedlab.eng.usf.edu>). The procedure is as follows: A tall and heavy shoe made from delrin and weighed down with stick on lead weights was strapped to each student's left foot. The student was then blindfolded and given told to walk straight across a field. To track the path walked, I followed each student dropping bright yellow Tinkertoys in their paths. After about 75ft., the students were asked to remove the blindfold and observe the path that they walked. Three different results were found from testing. First, was the expected outcome of the student traversing a left radius turn. Because of the added height and weight to the left leg, the natural tendency is for it to slow down. As one leg takes slower and shorter steps, while the other follows a normal step pattern, a turning motion should be observed.

Another pattern found was the exact opposite. Possibly due to proprioceptive feedback, the sense of body location, it may have been possible that these students overcorrected for the disturbance to their gait. The third and final result was a walking path that was nearly straight. While this could have been nothing more than luck, it would be interesting to see the paths walked by the students before the testing. It could be possible that a subject that walked in a right curved path naturally could have their gait tuned back to symmetry by the addition of weight and height to one leg. This is synonymous to testing done on a PDW model in previous research [10]. Several pictures are shown of testing on the following pages.

Appendix B: (continued)



Figure B.1: Photo of shoe worn during the walking experiment. Worn on the left leg, it made the leg 2" taller and 4lb. heavier.

Appendix B: (continued)



Figure B.2: Walking experiment picture 1. This picture shows two middle school students before participating in the walking experiment.

Appendix B: (continued)



Figure B.3: Walking experiment picture 2. Each subject was blindfolded during the experiment so that they could not correct for the physical asymmetry.

Appendix B: (continued)



Figure B.4: Walking experiment picture 3. To track the course walked by each subject, I walked behind them dropping bright yellow Tinkertoys over where they stepped.

Appendix B: (continued)



Figure B.5: Walking experiment picture 4. Here the walking path of each subject is traced with yellow Tinkertoys. The additional weight added to one side caused asymmetries in the subject's gait.

Appendix C: Novel Handle for PDW Testing

In order to keep the walker from falling and experiencing damage during testing, a flexible handle was made. The handle uses a cotton strap with a foam handle which connects to the crossbar assembly via eye-loops and metal clips. The handle needed to be flexible and fairly long in order not to disturb the walker as it descended the slope. This design can be seen in Figure C.1.

Appendix C: (continued)



Figure C.1: PDW handle for walker testing. The handle is directly bolted to the crossbar and can be removed by two metal clips. It was constructed to decrease the likelihood of walker damage due to falls

Appendix D: Preliminary Foot Design

The first foot design was done before the computational model was used. In preparation for tuning, the foot was designed so that the position of the shank with respect to the foot could be changed quickly and easily. The foot holder was milled out of aluminum and the foot was made from delrin. Because it was later found that the foot was too heavy for the design, it was not used. This design might work well with future designs if a 2-legged biped is designed. This design is shown in Figure D.1.

Appendix D: (continued)

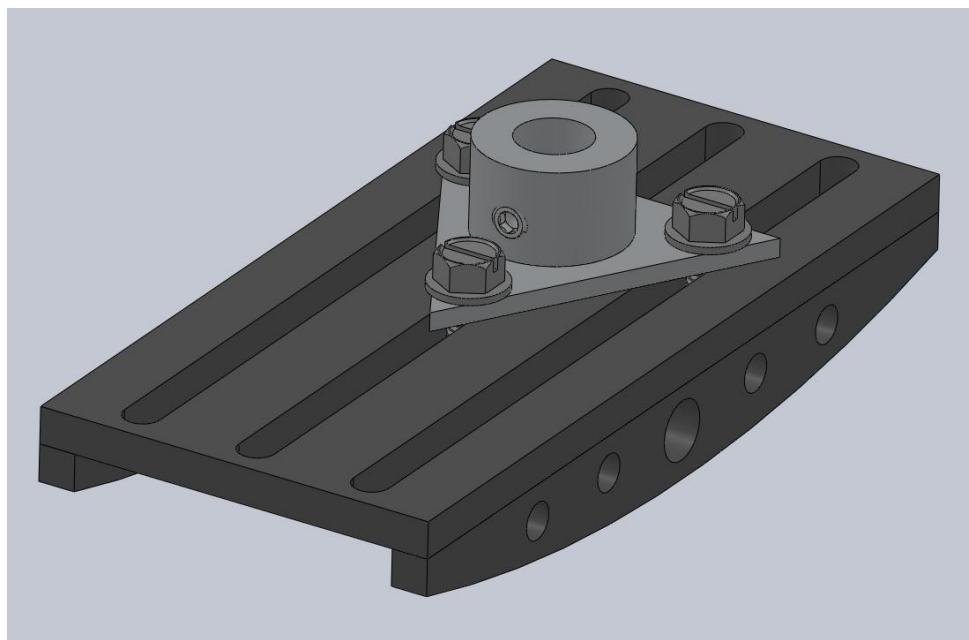


Figure D.1: SolidWorks model of the initial foot design