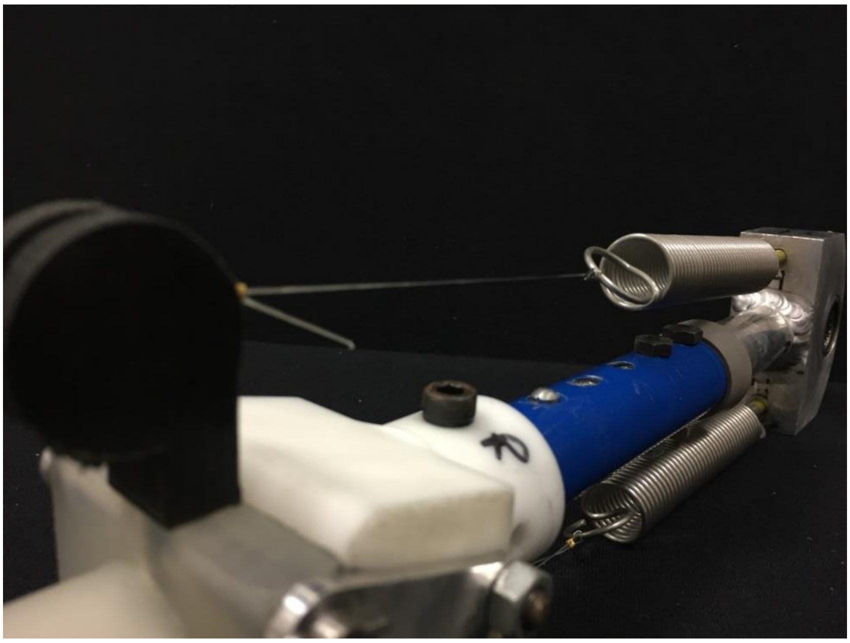
Development of a Passive Dynamic Walker with a Novel Knee Design



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List of Abbreviations

COM	Centre of Mass
PDW	Passive Dynamic Walker
C_t	Cost of Transport
UJ	Universal Joint
ICR	Instantaneous Centre of Rotation
ACL	Anterior Cruciate Ligament
PCL	Posterior Cruciate Ligament
N	Newton
S	second

Abstract

Despite of the astonishing technology developed so far, bipedal systems have seen little success in practical applications. With the advent of rapid automation the need for bipedal robots to carry out complex tasks is only a matter of time. Designing this system based on human morphology permits the easy adoption of such systems in our society. These robots could access places deemed too dangerous for humans or carry out tasks that would reduce the mechanical effort from humans.

The study of passive dynamic walkers is a field in robotics that aims to solve the problem of stability, energy efficiency, and naturalness lacking in the current robots. It aims to do this by exploiting the passive nature of human walking and hence designing an inherently stable system. A considerable research in this field has been done to analyse the effects of the shape of the feet or other variables such as the location of the centre of mass of the robot have on the walker's gait. However, so far there has been a lack of research in the effects of adopting knees on the gait of such passive walkers.

This research drew inspiration from the field of lower limb prosthetics and was able to demonstrate a stable kneed-gait, albeit for a small degree of activation. The bipedal walker with knees took an average 30.6 steps under its best configurations. An analysis of the various variables affecting the gait was successfully tested and analysed. Four different springs with various configurations were tested under three angles. The spring with a stiffness of 1430 N/m demonstrated the best performance for all three sets Moreover the most drastic improvement in the walker's performance was observed with an increase of the angle. The walker showed the most stable gait when the initial angle was set to > 2°.

It is proposed that the design of future passive dynamic walkers with knees include toes in order to resemble the human gait. Moreover, it is advised that a simple mechanism that promotes flexion should be added around the knee and ankle joint in order to achieve full flexion during the gait cycle.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other University or other institute of learning.

Acknowledgements

This project would not have been possible without the efforts of both academic and technical staff members at MACE. I would firstly like to thank Dr Lei Ren for the academic support he provided. The completion of this project would not have been possible if not for Dr Ren's infinite patience and understanding.

I am also grateful to the technicians in the Mechanical Engineering workshop for their guidance and help during the manufacturing and assembly process. Dave, Bill and Tony have been instrumental in moving the research forward in the right direction. They taught me the essentials of the manufacturing process.

Lastly, I would like to thank my parents without whom I would not have this opportunity. Their constant support allowed me to work through the difficult times.

Chapter 1 - Introduction

1.1 Background and Motivation

With the current trend in technology, humanoid robots are expected to become a major market in the future, comparable to that of the current cell-phone industry. With the advent of major automation making it easier to compute complex tasks, the need for physical machines that are able to perform such tasks is growing rapidly across many industries.

A key feature that would define such robots would be their human-like characteristics. This is deemed necessary for an easy adoption of the robots into our society since human oriented environments are not able to accommodate conventional means of locomotion. Hence an efficient mechanical design that would successfully replicate the human morphology is hugely advantageous. The study of passive dynamic walkers provides insight to the path by which this goal can be reached.

Robotic manipulators are able to out-perform humans in many precision demanding tasks such as welding, car painting, etc. This is due to the recent development of state-of-the-art biomimetic arms. However, so far we haven't seen any humanoid walking robots that can outperform human ability even while walking on the simplest of terrains. This presents a major barrier to developing advanced prosthetic legs and bipedal robots, which would have the comparable abilities and qualities as current robotic upper limbs.

This is not due to a lack of research but due to the high complexity of recreating human gait. It is a very challenging topic due to the intrinsic high-dimensionality and dynamic instability of the human locomotion. The most advanced bipedal robots nowadays still suffer high energy cost and poor dynamic stability. The study of legged locomotion is an interdisciplinary endeavour, bringing together research from biomechanics, neuroscience, control theory, mechanical design, and artificial intelligence. It includes efforts to understand and to rehabilitate human and animal locomotion, as well as to replicate human and animal locomotion in machines.

1.2 Passive Dynamic Walking

Passive Dynamic Walking (PDW) is a field of research in robotics that uses the natural dynamics of the system to achieve stable cyclic gait. The distinguishing characteristics of the PDW are the absence of any control or motors, and are usually a purely mechanical system. These robots instead use gravitational energy in order to recreate a stable gait pattern, traversing down a shallow slope. Tad McGeer (McGeer, 1990) set the foundations of this field laying the fundamental principles and models still being used for the study of PDW.

Significant research has been conducted to analyse the different variables affecting the performance of PDW. However, these studies have mostly consisted of simulation and only a few studies have conducted experimental testing in order to validate the simulation. Moreover, there is a considerable lack of research analysing the knee joint by isolating all other variables. Hence, in order to understand the human gait better and to improve its representation in the bipedal walkers the next step is to add knees to PDW. The motivation is to lay the foundation for the study of the knee joint in passive dynamic walkers.

1.3 Research Aims and Objectives

There are a few studies (Rushdi, 2014; Trifonov , 2007; Yang, 2008) in the literature that have performed experimental testing of passive-dynamic walkers with knees, however there is no notable study done to understand the specific contribution of the knee joint in achieving a stable walking pattern. This is because the aim of such studies is to demonstrate a human-like gait can be achieved by passive walkers and not to study the different parts of the walker in isolation. In most of these studies the knee is usually a simple hinge joint with the addition of a simple breaking mechanism or if complex, the knee joint will not be truly passive. In order to further the understanding of passive walkers it is vital that more research is done to find better and more robust designs for the knee joint that draw some inspiration from the human anatomy, similar to the research done for feet.

The aim of this research is to design, experimentally test, and analyse the functioning of a passive knee joint mechanism and the impact of knee joints on the walking motion of a bipedal walker. The bipedal walker comprises of a completely passive knee system on flat feet with ankle-springs system. This work aims to expand upon previous research assessing the stability of flat feet walkers by incorporating a novel knee design. It also draws inspiration from research done in the field of lower limb prosthetics where passive knee structures are being tested to replicate the human knee. The field of robotics and prosthetics derive inspiration from human morphology to recreate anthropomorphic systems; hence the adaptability of a knee system designed for prosthetics in robotics could be hugely beneficial.

The objectives of the research are as follows:

1 Design and introduce knee joints to a flat feet bipedal walker.

2 Validate the performance of the ankle-spring system with locked-knees.

3 Investigate the influence of introducing a knee joint to a flat feet bipedal walker.

4 Explore the effects of the springs at the anterior and posterior position of the knee joint on the walking motion.

5 Investigate the effects of changing the initial knee angle on the walking motion.

6 Assess the limitations of the walker and suggest designs to be followed in future work.

1.4 Thesis Overview

Chapter 1 discusses the background and motivation behind this research and briefly introduces the concept of passive dynamic walkers. The aims and objectives of the project are outlined here as well.

Chapter 2 presents the literature review going over the basics of human gait and knee anatomy. Bipedal robots are then defined and the two main areas of research are discussed along with the rationale for the research pursued. A study in the field of lower limb prosthetics concludes the chapter.

Chapter 3 explains the design process and the design specifications of the walker. The key design inspirations for the walker are noted.

Chapter 4 explains the manufacturing and the assembly stage. Issues that occurred during manufacturing and the modifications made are presented in this chapter.

Chapter 5 covers the experimental stage. The experimental protocol followed to carry out the various tests which include pilot tests, locked and unlocked kneed tests is explained.

Chapter 6 discusses the results obtained in chapter 5 and an attempt to comprehend the data is made.

Chapter 7 presents the final conclusion of the report with recommendations for future work

Chapter 2 - Literature Review

2.1 Introduction

This chapter presents a review of previous work related to the human locomotion, bipedal robots, and lower limb prosthetics.

In order to ensure the experimental protocol of this research had a strong groundwork to build upon, a thorough understanding of the current research in the field of Biomechanics was necessary.

The main features of human gait and human knee anatomy are discussed as it is not possible to study the behaviour of lower limb robotics without first understanding the basic principles from which these ideas are derived. The function and structure of the knee complex is then explored with more detail. The various knee-joint motions present during the gait cycle are also discussed. Furthermore, several terminology used in the study of robotics is derived or inspired from this field. The three planes of motion used for the study of human anatomy and motion are shown in the figure below.

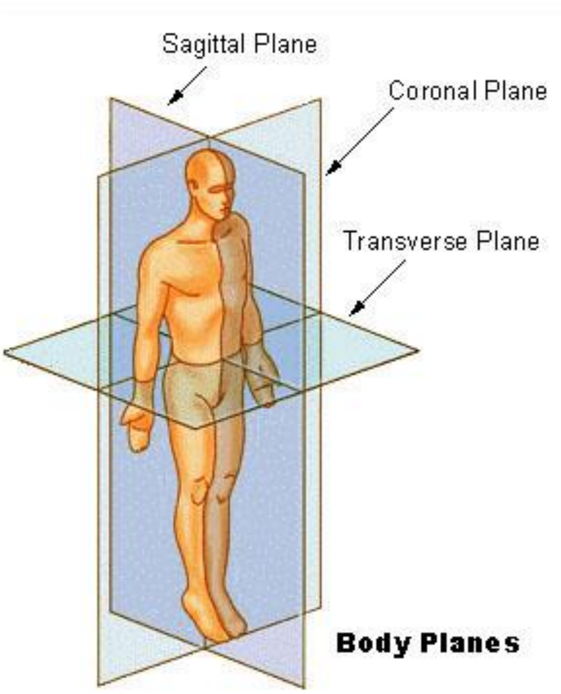

Figure 1 - Planes of motion (Torricelli, et al., 2016)

The concept of bipedal robots is then introduced, examining the various control methods being researched in the field. Actively controlled robots and PDW are the two main branches. A brief summary of a famous control method used in active robots is presented to highlight the benefits of PDW. Moreover, there are many studies in the field of PDW encouraged due to the passive nature observed in human gait.

The analysis derived from these studies has proven to be useful in the understanding of human gait (Kuo, 2007). The key functions that influence walking can be independently investigated through biologically inspired experimental machines using methods not possible within either in vivo or in vitro studies of human subjects. PDW can be further sub-divided depending on the walker's parameters such as 2D vs 3D walkers or straight-legged vs kneed-legged walkers. These are explored in more detail and the results of the various studies are analysed.

Finally, lower limb prosthetics are explored in depth classifying the different types of transfemoral prosthesis available. The various passive knee joint structures developed for above-knee amputees are explored with an analysis of their working principles. These studies serve as the inspiration for the knee joint design of this research.

2.2 Human Gait

The analysis of human gait is no modern endeavour, it is associated with Aristotle from the fourth century BC and the foundations of modern biomechanics date back to the early 17th century (Baker, 2007). Numerous studies and papers have been written discussing the biomechanical principles of human motion while walking.

The bipedal dual-phase forward movement of the COM of the human body is the key characteristic of human gait. The walking pattern is characterised by the movement patterns of the limb, forces, velocity, contact area of the foot with the floor, and kinetic and potential energy cycles (Kuo, 2007).

A single stride of human gait can be broadly divided into the stance phase and the swing phase. Moreover, the overall gait has a cyclic pattern. However it should be noted that Bernstein (1947) discovered from limb movements gathered from an analysis of multiple samples indicated almost no repetition. He named this phenomenon “repetition without repetition” (Bernstein, 1947). This implies that the trajectories of limb elements and processes of driving muscles are different when the same movements are repeated in the same conditions, despite achieving substantially the same final result (Poliakov, 2013).

Furthermore, each phase of the gait cycle is further sub-divided and it is important to understand these nuances so the subtleties of the phenomenon are not concealed. These terms are also used in the field of robotic studies, specifically for bipedal walkers. The figure below outlines the phases and the parts that comprise them.

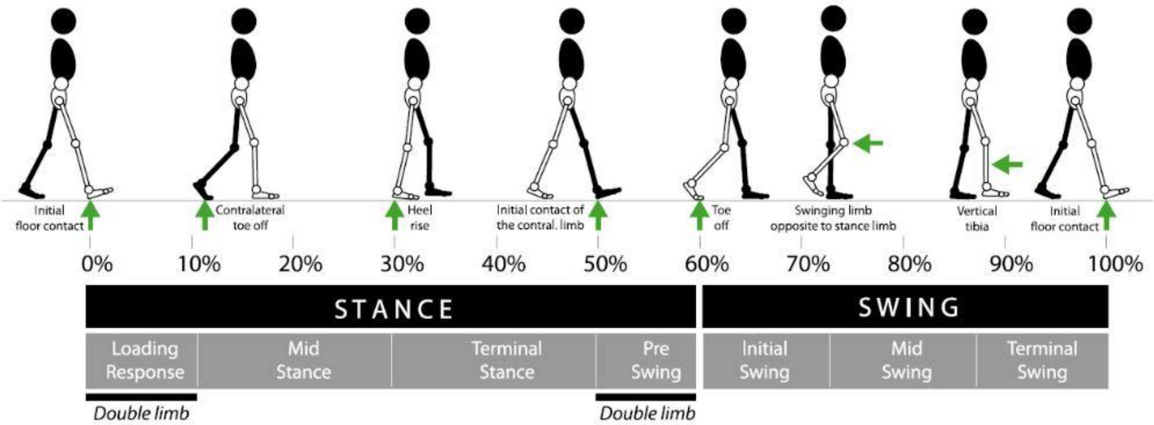

Figure 2 - Decomposition of stance and swing phases (Torricelli, et al., 2016)

A single stride consists of approximately 60% stance phase, which can be further sub-divided into 6 parts. It should be noted that each part does not represent equal proportions of the stride. These can be described as the following (Nordin & Frankel, 2001, pp. 440-441):

1. Heel strike: This point is chosen as the start of a new gait cycle and the start of stance phase. It occurs nearly instantaneously.
2. Foot-flat: After the initial contact made, the body weight is shifted to the support leg. 0 – 10 % of the stride
3. Mid-stance: The ankle joint rotates to move the body’s COM forward in the direction of motion, progressing the hip over the support leg. 10 – 30 % of the stride
4. Terminal-stance: This phase is preparing the support leg to transfer into the swing phase. The body weight is shifted from mid-foot to fore-foot. 30 – 50 %

5. Pre-swing: The support leg now shifts the body to the other leg which is now going into heel-strike. 50 – 60 % of stride
6. Toe-off: The point of contact with the ground is lost and the leg assumes free swing in the direction of locomotion. This phase occurs nearly instantaneously.

The swing phase comprises the remaining 40% of the stride and is also further sub-divided into 3 parts. Contrary to the stance phase, these parts represent nearly equal proportion of the stride and are described as the following (Nordin & Frankel, 2001):

1. Initial-swing: This phase comprises of the swinging leg moving opposite to the stance leg. 60 – 70 % of the stride
2. Mid-swing: This phase lasts until the tibia is hanging perpendicular to the ground. 70 – 85 % of the stride
3. Terminal-swing: The swing phase terminates with this stage when the heel-strike occurs at the end of this part. 85 – 100 % of the stride

The average walking speed of an adult is between 0.9 m/s to 1.8 m/s with an average step length between 0.56 m to 1.1 m (Nordin & Frankel, 2001). Throughout the gait cycle, there are different vectors of forces acting on the ankle, knee, and hip joint. And although coordinated muscle activity is key for stable gait, human walking is mostly a passive system.

Gait is often analysed quantitatively by investigating the kinematics, kinetics, and energetics. Kinematics is the study of motion of an object whereas kinetics is the study of forces and moments acting on the object in motion. Several developments have been made to investigate human walking using these methods. The figure below illustrates the convention used for knee joint angle. By observing the motion of markers placed on a body part, quantities like the joint angle can be accurately estimated. These experiments are usually conducted in a gait laboratory where reflective markers are placed on the subject which is tracked using a 3D camera set up such as VICON. Note that flexion is described as the angular displacement in the positive direction and extension is described by the angular displacement in the negative direction.

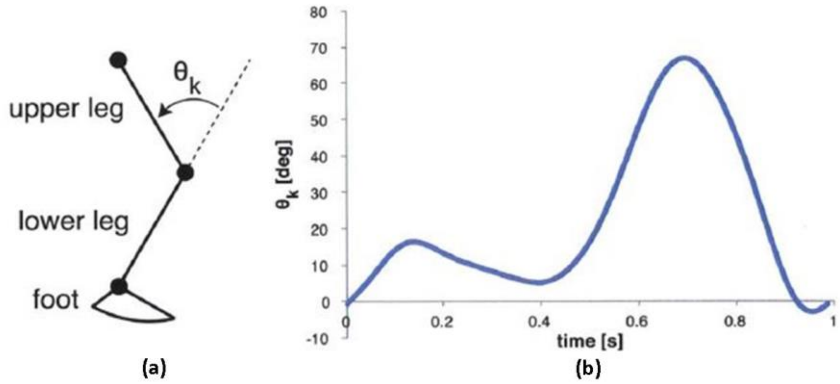

Figure 3 - (a) Convention used for knee joint angle (b) knee joint angle vs time over one git cycle (Narang, 2013)

Kinetic analysis is carried in order to estimate the forces and moments acting on a particular joint during gait. This is done by first measuring the external forces, which is the ground reaction force in the case of normal walking. This can be done using force plates and once the external forces are computed a physical model of the body is constructed based on the quantities one wants to measure. A process called inverse dynamics can then be used to compute the joint forces and moments (Narang, 2013).

A summary of the results from these studies is presented in the section for the knee joint. These are examined in order to account for the discrepancies and to conduct a comparative analysis between human gait and PDW.

2.3 The Human Knee

It is vital to understand the anatomy of the human knee and of the supporting musculature in order to understand its function in the human gait. The human knee joint is a bi-condyle synovial joint and allows for flexion-extension with a small degree of medial-lateral rotation. The knee joint complex can be broadly divided into joint passive structures and joint musculature. The figure below shows the sagittal view of the knee joint illustrating the main parts.

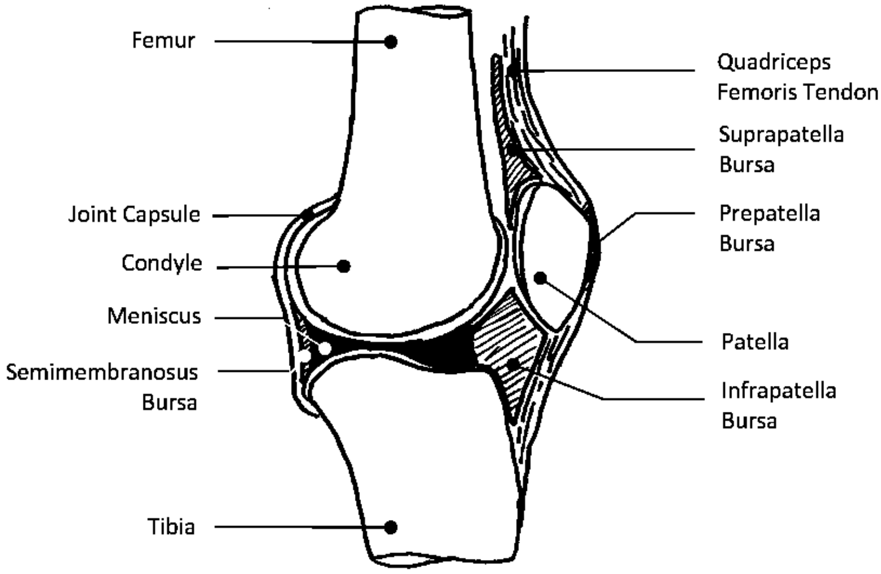

Figure 4 - Sagittal view of the Knee Joint (Narang, 2013)

2.3.1 Knee-Joint Passive Structures

The components of the knee joint that are passive in nature are classed under this category. This implies that these structures behave more like support structures than contributors of motion. These passive structures are connected between 4 bones as shown in the figure above, i.e. the femur, the tibia, the patella, and the fibular (not in the figure). The condyle (rounded protuberance) of the femur slides in the grooves of the tibia plateau. The menisci support the femur by improving stability. The Knee joint also consists of the fluid filled sacs called bursae and ligaments that help control the motion. The four main passive structures of the knee joint are presented below (Al-Turaiki, 1986, pp. 6-10).

1. Meniscus

Menisci consist of fibrocartilage structures and are further divided into lateral and medial meniscus. Structurally the lateral meniscus is O – shaped while the medial meniscus is C – shaped (Makris, et al., 2011). The two main functions of this structure are increasing the stability of the knee joint by deepening the articular surface of the tibia and to assist in load distribution. The removal of this structure could result in the increase of stress on the condyles by up to 300% (Chai, 2004). They also act as shock absorbers.

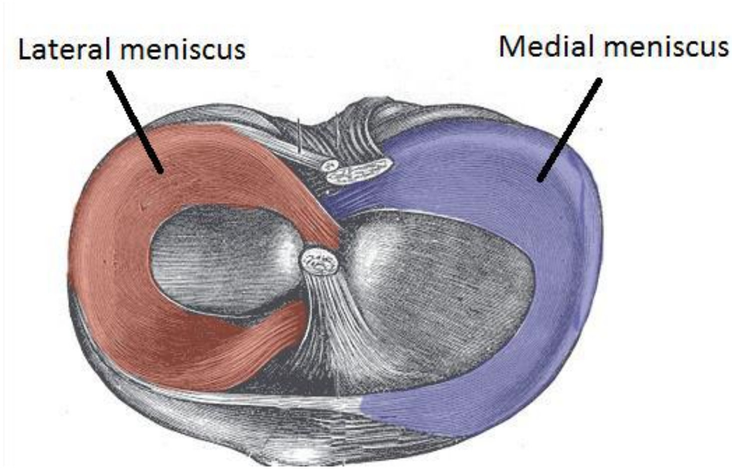

Figure 5 - Menisci on the Superior Surface of the Tibia (Netter, 2015)

2. Bursae

Synovial fluid-filled sacs found adjacent moving structures of the knee joint are termed bursae. These help reduce the wear and tear around the articulating surfaces by contributing towards shock absorption, lubrication and protection.

3. Articulating Surfaces

There are two types of articulating surfaces comprising the knee joint. Knee extension and flexion occurs with the movement of these parts.

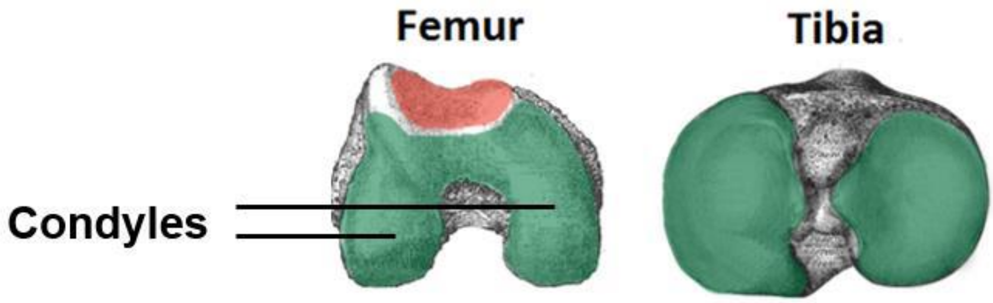

Figure 6 - Articulating Surfaces of the Knee Joint on the Inferior Surface of the Femur (Netter, 2015)

4. Ligaments

The ligaments are broadly sub-divided into three main categories. The figure below illustrates the three groups using three different colours.

- Patella Ligament (green)
- Collateral Ligaments (red)
- Cruciate Ligaments (blue)

For the purpose of this research, only the ligaments in the blue and the red colour shade are of interest. Cruciate ligaments connect the femur and tibia in the interior of the knee. These ligaments are further sub-divided into:

- Anterior Cruciate Ligament (ACL) (Dark Blue)
- Posterior Cruciate Ligament (PCL) (Light Blue)

The cruciate ligaments act to limit the extension and flexion motion around the knee joint. These ligaments assist in stabilizing the knee joint during standing, walking, or any other basic motions passively in contrast with the functioning of the muscles. An injury to the ACL or PCL can severely affect the stability of the knee joint. Athletes with ACL injuries have to undergo rehabilitation therapy. In cases of severe injury, surgical intervention is necessary in order to restore proper knee functionalities.

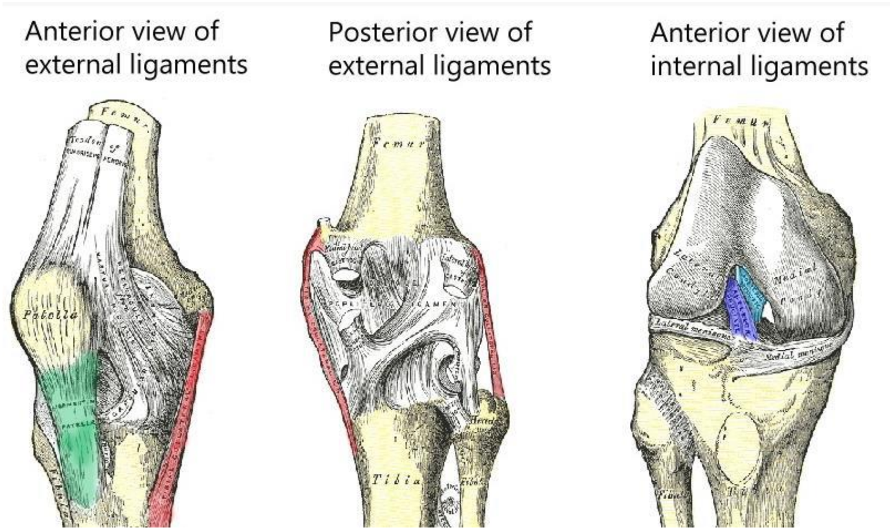

Figure 7 - Major Ligaments of the Knee Joint (Netter, 2015)

The collateral ligaments consists of two “strap-like” structures on both sides of the knee joint that aim to prevent excessive medial or lateral movement. These ligaments are also passive in nature and help stabilise the knee during extension and flexion. The collateral ligaments can be further sub-divided into:

- Tibial Collateral Ligament (TCL) – Medial
- Fibular Collateral Ligament (FCL) – Lateral

2.3.2 Knee-Joint Musculature

The muscles structures present around the knee joint primarily act in the sagittal plane. Depending on the function, they can be broadly divided into extensors or flexors (Torricelli, et al., 2016). These structures contribute to the motion of the knee joint through flexion and extension and the direction of the motion is controlled together with the passive structures.

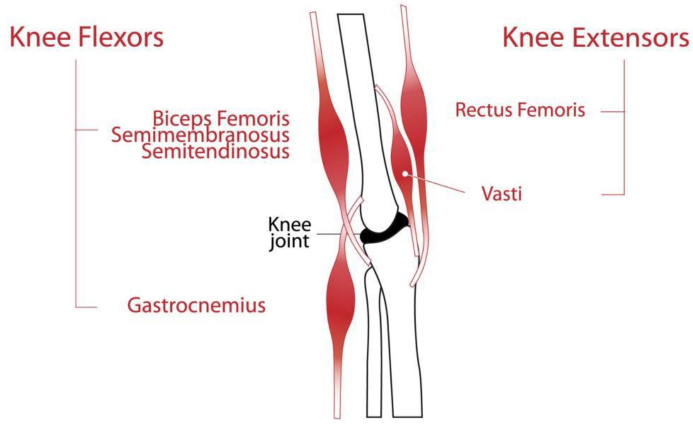

Figure 8 - Schematic breakdown of muscle groups surrounding the knee (Torricelli, et al., 2016)

The muscle structures involved in the functioning of the knee are broadly divided in two groups based on their location and hence the function. The muscle group present on the anterior region is responsible for extension and consists predominantly of the quadriceps femoris muscles (Netter, 2015). The second group present on the posterior region is responsible for flexion. The figure below highlights the different muscles present in each group.

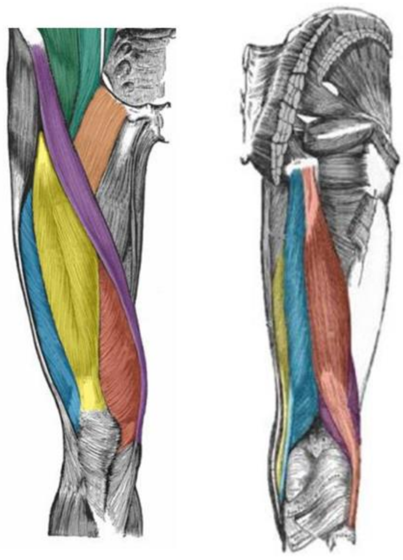

Figure 9 – Thigh muscles above the Knee Joint
Left: Anterior, Right: Posterior (Netter, 2015)

2.3.3 Knee-Joint Analysis

The knee joint is currently modelled as a polycentric joint (Guston, 1971) whereas it was traditionally seen as a simple single axis hinge joint. The new model had a significant impact on the studies of knee structures and their applications. The geometry of the joint surfaces and the constraints provided by the passive structures dictate the range of motion available in the knee joint. Many everyday activities such as walking, sitting, and standing would prove to be extremely difficult without this motion. The figure below illustrates the three main motions of the knee joint.

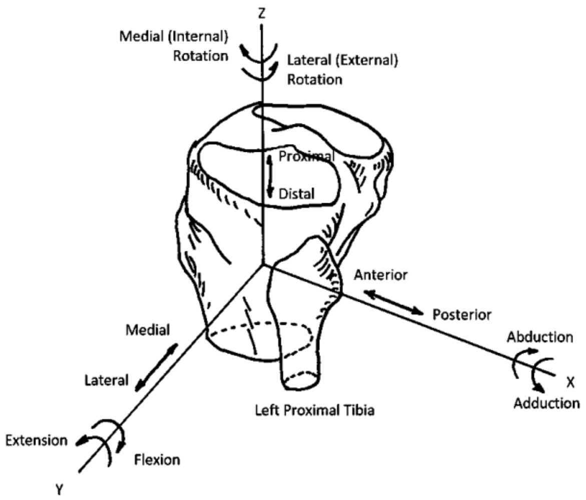

Figure 10 - Proximal Region of Tibia - Motions of the knee joint (Netter, 2015)

The two main functions of the knee joint are to allow mobility below the thigh and to transmit the upper body's load onto the lower body (Nordin & Frankel, 2001). This is the reason why the role of menisci in the knee joint is so crucial, as otherwise the solid structures might not be able to take the stresses. Without the mobility created the by the knee joint, complex motions such as climbing and jumping would not be possible (Viidik, 1966).

2.3.3.1 Motions of the knee joint

The three main motions permitted by the knee joint are:

1. Extension and flexion
2. Lateral and medial rotation
3. Abduction and adduction

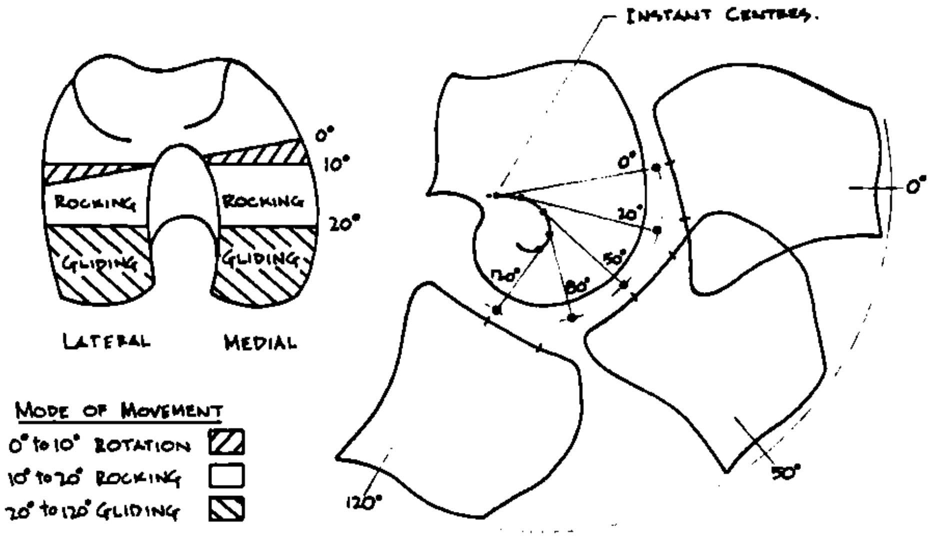

Figure 11 - Instant Centres of Rotation of the Polycentric Knee Joint during Extension and Flexion (Netter, 2015)

The figure above illustrates these motions. Extension and flexion are the main motions occurring between the tibiofemoral surfaces at the knee joint. This motion is of primary interest as the other motions largely occur within the knee complex and are irrelevant to the macroscale motions of human gait. It can be noticed from the figure below that the extension-flexion angles have a wide range between 5 to 60 degrees whereas hardly any range is observed in the frontal and transverse plane (Nordin & Frankel, 2001). Following this the study of simple planar knee designs is justified with the aim of broadly recreating human walking motion.

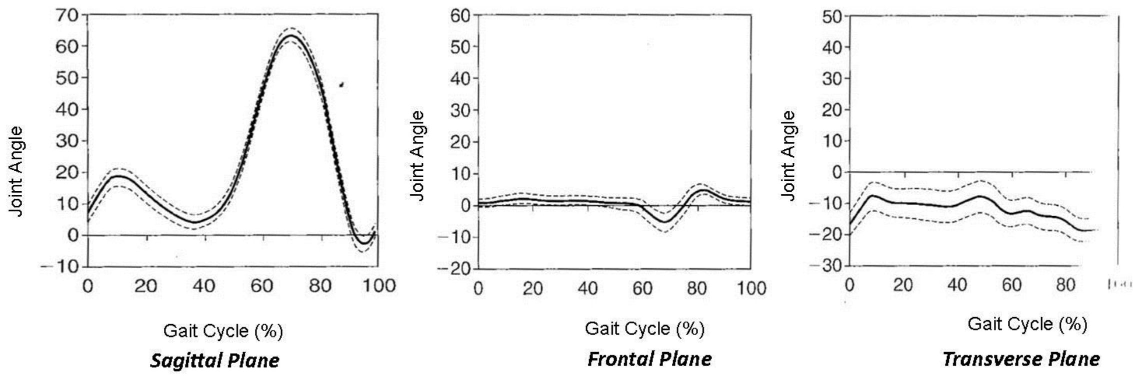

Figure 12 – (Left) Plots of sagittal (Centre) frontal (Right) and transverse angular rotations of the knee during a single stride (Nordin & Frankel, 2001)

The sagittal rotation of the knee joint occurs about a *moving polycentric axis* (Guston, 1971) which has an *instantaneous centre of rotation* (ICR). The ICR progresses through an arc-shaped path increasing the ground clearance for the foot.

Moreover, the extensor group of muscles function is to prevent premature flexion of the knee and generally subsides once the ground reaction force passes anterior of the knee joint. The flexor group of muscles control the angular position during knee flexion in order to ensure sufficient space is available for foot clearance, such functionalities are not seen in the designs of PDW which either succumb to foot scuffing and failure, or suffice with unrestrained motions. The figure below shows that the extensors are predominantly activated until around mid-stance and the flexors are predominantly activated between mid and terminal swing (Nordin & Frankel, 2001, p. 444).

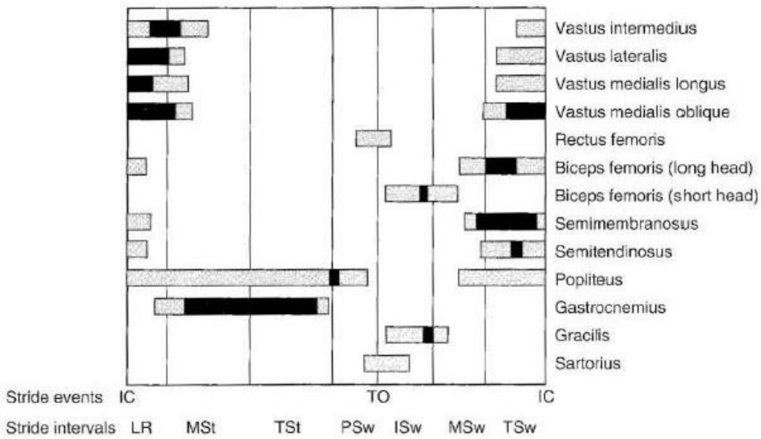

Figure 13 - Knee extensor-flexor muscle group activity during a stride (Nordin & Frankel, 2001)

Ligament motion

As discussed previously the most important ligament groups are the cruciate ligaments comprising of the ACL and PCL. They further complicate the analysis of the knee joint as these ligaments do not merely act as static constraints but deform under load preventing the knee from over extending at different stages of the gait cycle (Goldblatt & Richmond, 2003). The figure below shows the deformation of the ACL. During extension, the band B-B’ lengthens stretching the ACL to its flat profile preventing overextension. During flexion, the band A-A’ lengthens to limit the flexion of the joint the band B-B’ is folded underneath (Goldblatt & Richmond, 2003).

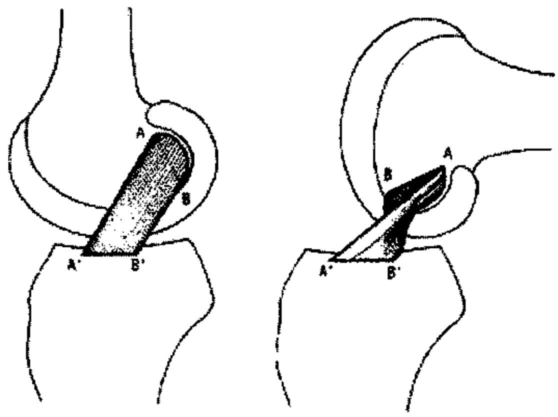

Figure 14 - Changes in the shape and tension of the ACL in extension and flexion (Goldblatt & Richmond, 2003)

A similar deformation is observed in the PCL where during extension the band A-A' lengthens in order to prevent overextension. The band B-B' lengthens during flexion, whereas the elongation of the band C-C' is negligible in both the cases. A detailed study of the stresses and forces present around these ligaments and how the ligaments respond to these loadings is out of scope of this research.

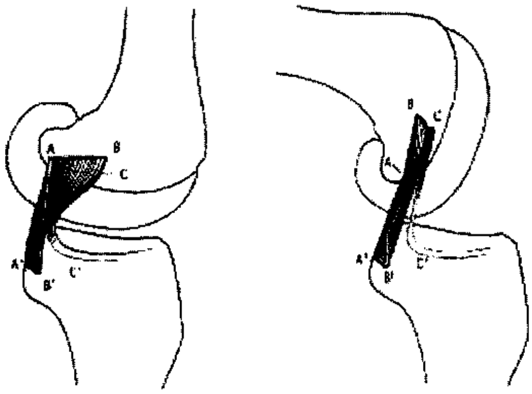

Figure 15 - Changes in the shape and tension of the PCL in extension and flexion (Goldblatt & Richmond, 2003)

2.4 Passive Dynamic Walkers

2.4.1 Bipedal Robots

Bipedal robots are developed with broadly two objectives. The first is drawing inspirations from the principles governing the human body in order to create systems that can exhibit similar agile movements. The other is using them as a scientific tool in order to investigate and experiment the various biomechanical principles. Research in this field can be broadly divided in two class; Active robots and passive-dynamic walkers (PDW).

The active robots are designed on the mainstream control paradigm, i.e. joint-angle control and sophisticated algorithms. There are many methods by which this can be achieved however the need for actuators and their precise control results in a high energy demand (Collins, 2005). In contrast, the PDW achieves *dynamically stable* gait without any active controls or power sources. These machines are usually tested down an inclined slope and the stability during the gait cycle is derived from the interplay between gravity and inertia. However the study of PDW is not restricted to only traversing slopes. Under-actuated walkers based on PDW studies are able to traverse over level-ground.

The control method employed directly affects the motion trajectory and stability of the system. Both categories of robots adopt different paradigms. For instance, control schemes for the active-robots involve Zero Moment Point (Vukobratović et al., 2014), Foot Rotation Indicator, Learning Approaches, etc. One of the most famous methods used to obtain joint trajectories is zero moment point (ZMP) method. ZMP is the point where a single force represents the influence of all the forces acting on the robot. This implies that the net ground reaction force acting on this point is zero (Vukobratović et al., 2014).

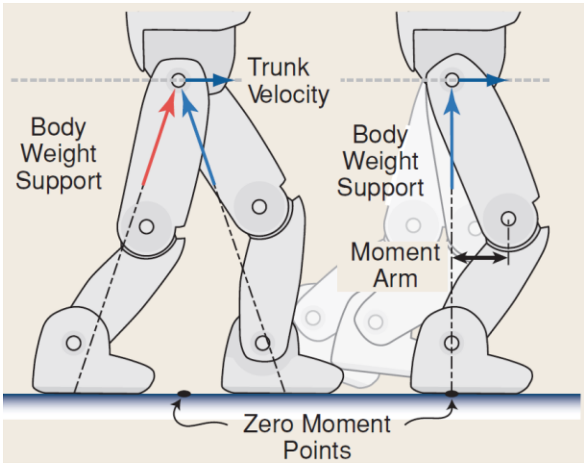

Figure 16 - Characteristic bent-legged motion of static and ZMP bipeds (Kuo, 2007)

The support polygon is defined as the area on the ground which creates a bounding box around all of the contacts between the feet and the ground (Bhounsule, 2012). The entire mass of the robot is always directly over the support polygon in a statically stable gait. In other words if the ZMP of the robot lies at the edge of the support polygon, the gait pattern may not be dynamically feasible causing the robot to fall. Prerequisites for ZMP are full flat-foot ground contact and continual control of the joints. Hence the computational and energetic costs required by robots using this method are high.

On the other hand, PDW adopts the natural dynamics scheme. The two main schemes under this control method are known as pendulum and cyclic walking. From a biomechanical point of view, the active robots greatly differ from human morphology due to the heavy reliance on precisely controlled joints. This greatly increases the energy demand of the robot and is not representative of the natural dynamics governing human walking (Ijspeert, 2014).

The term 'passive dynamic walker' was first used by McGeer during the 1980's (McGeer, 1990) who was the first to do any substantial research in this field. In fact, the foundation for most of the contemporary work being done in this field is based on McGeer's research. He was interested in this field as he believed it could shed more light on the biomechanics of human locomotion. Although his work was mostly with passive walkers his aim was to achieve groundwork for future active robots, as he mentions in several places how his passive robots could be further worked upon to make them active.

The idea to begin with passive-dynamic walkers is very similar to how the Wrights developed the first flying machine (McGeer, 1990). The Wright brothers first studied gliders in order to better understand the aerodynamics and the physical principles behind flying, after which adding a propeller was only a slight change. This type of locomotion relies on passive dynamical properties of the body such as free swinging motions when compared to the motions that are actuated at all times and hence the term 'passive'. The stability of such structures can either be dynamically stable which is the notion of stability over time or statically stable which has to do with the centre of gravity remaining over the support polygon. Since these passive walkers are dynamically stable the term 'passive-dynamic' walker is used.

The mechanical energy lost to friction and collisions, as the robot moves down a slope, is recovered by the decrease in gravitational potential energy (Bhounsule, 2012), i.e. impacts with the ground result in the exchange of the swing and stance legs, and the walker uses the potential energy to recover the kinetic energy lost through each impact to walk down a shallow slope. One method of measuring effectiveness, known as Cost of Transport, is used in order to better understand and compare these walkers to other active robots and human walking.

Cost of transport = power consumption / (weight × speed)

As power consumption is the numerator, the smaller the value of C_t the more energy-efficient is the locomotion. An often reported cost of transport for people is about 0.2 (Bhounsule, 2012). This value is the same for a typical passive dynamic robot.

A successful bipedal system should meet the following requirements (Wisse, 2004):

- Stability: The bipedal system should be able to handle small disturbances without losing balance.

- Efficiency: The bipedal should be truly autonomous in order to have high efficiency. A prerequisite for this is that the energy supply must be carried within the system.

- Naturalness: Depending on the purpose, the bipedal must be able to demonstrate morphology similar to humans.

- Versatility: Many applications would require the bipedal system to demonstrate agility in order to perform tasks such as climbing stairs and avoiding obstacles.

- Safety: An autonomous bipedal system in human environment should have a low risk of causing injury; hence it must be low powered and light weight.

Although active robots are able to demonstrate versatility with situational stability, their efficiency is still very poor. However research in the field of PDW has shown successful results in increasing the stability, efficiency, and naturalness using relatively simple mechanical systems. Albeit a lot more research has to be done in order for these walkers to have a practical application. However, efficient mechanical designs obtained through testing PDW could help accelerate the advancements in the active-robots field and shed more light on human morphology.

2.4.2 Theoretical Model

As mentioned earlier, McGeer developed and designed many passive walkers that were successful in their own right. They were however relatively simple mechanisms, i.e. constrained to two dimensions. However, it is still crucial to examine these as they serve as the foundation for modern day walkers. McGeer has built passive walkers that exhibit steady motion using a Poincaré map, which he called as a stride function, to analyze the gaits (McGeer, 1990). This method is quite useful and is independent of the biped model. The key idea that he examined is the stability of the entire step-to-step motion, and not the local stability at every instance. The resulting gait is a cyclic piecewise-continuous function which can be represented on a phase graph as shown below.

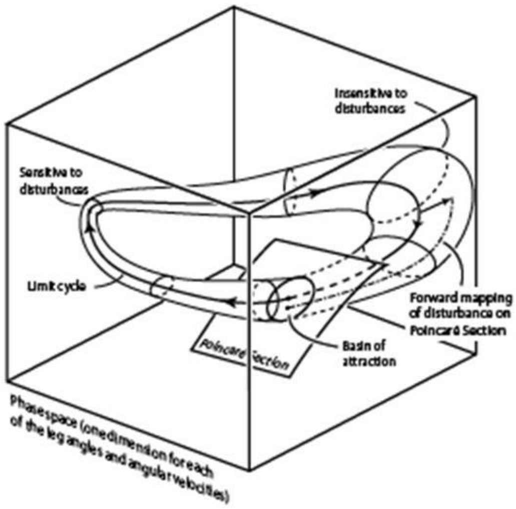

Figure 17 - Stylised phase graph with Poincare section analysis of a passive walking cycle (Wisse & Linde, 2007)

McGeer also studied two elementary passive walking models derived from a wagon wheel. One model was a rimless wheel model on a slope, and the other a synthetic wheel model on level ground. The motion of the models is constrained to the sagittal plane. Each model captures the fundamental mechanism of passive dynamic walking.

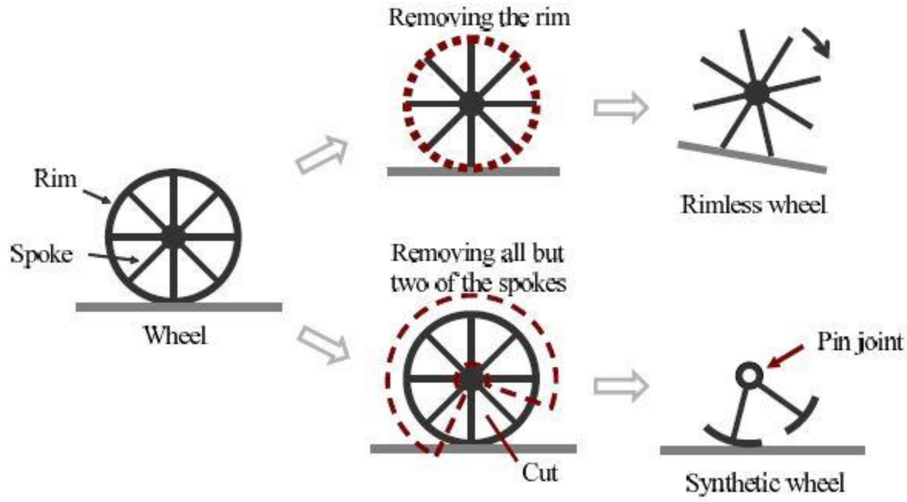

Figure 18 - Wheel, rimless wheel, and synthetic wheel (Narukawa, 2008)

Rimless Wheel

A rimless wheel can be obtained by simply removing the rim from the wheel as shown in the above figure. One of the features captured by the rimless wheel is the stance leg motion which acts as an inverted pendulum motion. The other feature is the heel strike when the swing leg touches the ground. The rimless wheel has a periodic motion for a given slope angle whose stable region is very large (McGeer, 1990). If the initial rolling speed is sufficiently large and the slope angle is large enough corresponding to the relative angle between the spokes, the rimless wheel never falls forward, and converges to the equilibrium motion (McGeer, 1990). This remarkable feature is used to strengthen the stability of passive walkers (Narukawa, 2008).

Synthetic Wheel

Passive motion of the swing leg can be explained by the synthetic wheel model (McGeer, 1990) as shown in the figure above. In this model, the rim was not removed. The rim was cut between the spokes, and all but two of the spokes were removed. A pin joint and a large point mass were put at the hip. If the leg mass is assumed to be negligible compared to the hip mass, the swing leg motion will not disturb the stance leg motion. The stance leg rolls at a constant speed on the level floor because it is part of a wheel. McGeer showed that initial conditions exist, such that the synthetic wheel exhibits periodic motion (McGeer, 1990). The step period of the synthetic wheel is determined solely by the free pendulum period of the swing leg.

A knee-less passive biped walker is similar to a synthetic wheel model (McGeer, 1990a). McGeer used four legs, with each set of two legs connected so that they moved identically, to constrain the motion of the walker to the sagittal plane (McGeer, 1990a). The physical 2D walkers without knees have a problem of foot scuffing at mid-stance.

He also researched the effects of foot radius and mass distribution. He got interesting results concerning distribution of mass in the vertical direction. The center of mass (CoM) should be near the hips, which is quite high as opposed to a statically stable system which would require the CoM to be located as low as possible. Finally, he found that friction in the hip joint is unfavorable for passive walking, but its negative effect can be compensated by moving the CoM of the legs a few millimeters backward (Wisse, 2004).

The compass model was experimentally verified through testing of the biped shown below (McGeer, 1990a). The motion of this walker is restricted to the 2-D sagittal plane by paired coupling of the outer and inner legs in order to maintain similarity to the theoretical analysis. Experimental observations were largely consistent with the modelled dynamics.

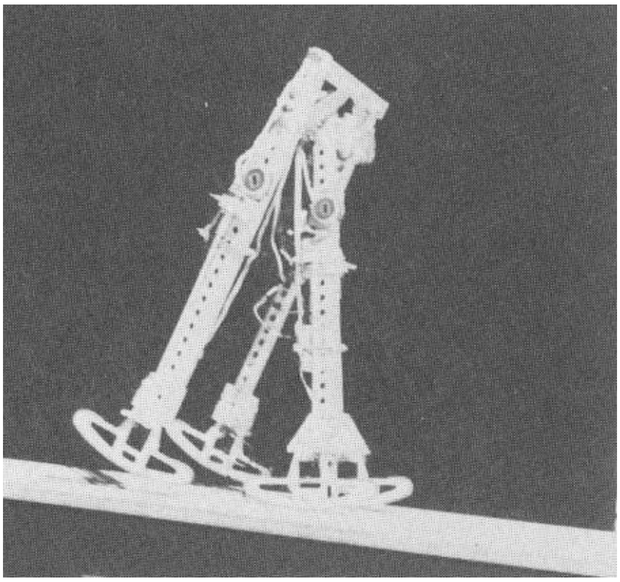

Figure 19 - Straight-legged biped with active foot clearance (McGeer, 1990a)

The additional desire to mimic human gait prompted expansion of the compass model to incorporate knee joints, as a passive alternative method of ground clearance. Passive dynamic walking with knees is a complicated problem to be solved, one that has been analysed many times but with limited success. The passive model with knees shown below is similar to the previously developed compass model; however there are key differences such as the addition of the pin knee joints, separate thigh and shank segments, and an anterior offset of the arc-foot centre of curvature. Parametric studies of this knee-jointed model produced these results (McGeer, 1990a):

- The range of parameters achieving passive cycles are more limited than those in stiff-legged walking, but are still broad.
- The stance and the swing knees are locked through the appropriate phases of the gait cycle by naturally arising torques.
- A major fraction of kinetic energy is dissipated at knee lock

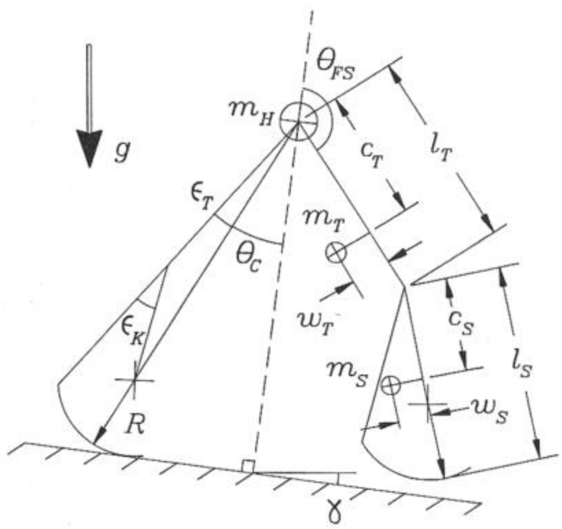

Figure 20 - Kneed model used for theoretical analysis (McGeer, 1990b)

This model was also validated by conducting simple experiments with the bipedal Dynamite shown in the figure below. An intentionally leaky suction cup used in the experiments prevents bouncing during the knee strike (McGeer, 1990b). Due to the leak, the suction cup does not resist the knee motion for the next swing phase. After the knee strike, the knee remains fully extended during the remainder of the swing phase. Then, during the heel strike impact, and during the subsequent stance phase, the knee remains extended because the ground reaction force pushes the knee in its end stop. This required the feet to be mounted in a forward position, as opposed to the straight-legged prototype which had symmetrically mounted feet. The gait of this walker looked very similar to human gait, required no controls and is extremely energy efficient (Wisse, 2004). A parameter study revealed that the mass of the shank should be high up, near the knee, and the mass of the thigh should be close to the hip joint. Hence with this, passive walking cycles were validated as worthy of further research.

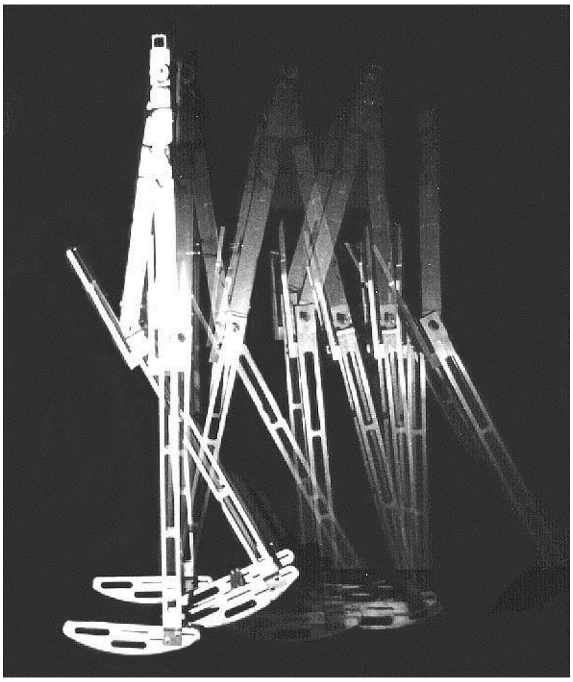

Figure 21 - Knee-legged bipedal (McGeer, 1990a)

Although it was agreed that walkers with knees are more efficient then their straight legged counterparts, many researchers have built walkers with straight legs; in-fact the most successful passive walkers are without knees. The reason for this is not just one simple explanation. Researchers decide to use fewer degrees of freedom and a simpler model in order to better understand the physical principles working to create a simple walking motion. Since the simulation of bipedal gait is a difficult task many researchers decide to experimentally tinker and test different models and test experimentally what works and what does not. Hence starting with a model with fewer parameter constraints allows the straight-legged designer to build a model with higher "fundamental" efficiency (McGeer, 1990b).

The addition of knee joints offers two main advantages. Firstly, it solves the problem of foot scuffing caused as a result of inadequate foot clearance during the recovery phase. Although humans display rocking in the walking pattern, the foot clearance is created by flexing of the knee joint. Secondly, if adapted correctly it is more stable. Knees also make the gait look more anthropomorphic, which is useful studying motion in nature and moreover is aesthetically pleasing.

2.4.3 Progression to 3-D Bipedalism

Initially passive walking was studied in two dimensions, i.e. the motion is constrained to the sagittal plane (Narukawa, 2008). In experiments, 2D passive walkers were built with four legs with each set of two legs connected to move identically in order to constrain the motion of the robots to the two-dimensional sagittal plane. Almost all of the physical 2D passive walking robots have arc-shaped feet rigidly connected to the legs.

Collins et al. (2005) from the Cornell University was the first to build a 3D passive walker which is conceptually similar to McGeer's original design. The device stands 85 cm tall. It weighs 4.8 kg, walks at about 0.51 m/s down a 3.1-degree slope, and consumes 1.3 W. To preserve fore-aft (pitch) stability, the basic design is close to what one would get by cutting the four-legged machine in half. The resulting device is no longer as constrained as the former device, creating an important difference: new degrees of freedom and new ways to fall down. Passive walking in three dimensions is still challenging due to unstable roll and yaw motions. Roll is rotation about an axis in the direction of walking whereas yaw is rotation about a vertical axis.

Figure 22 - The first 3-D passive biped with knees (Collins, et al., 2001)

The four most important ideas that distinguish Collins et al. walker from McGeer's four-legged passive walker are:

1. Foot bottoms shaped to guide lateral motion;
2. Soft heels to reduce instability at heel strike;

3. Counter-swinging arms to negate yaw induced by leg swinging;
4. Lateral-swinging arms to stabilize side-to-side lean.

The design of this walker is more anthropomorphic compared to the previous design iterations most notably due to two distinctively separate legs, knees, and counter-swinging arms. The design is relatively successful traversing down a 5 m testing ramp for 15% of its launches. Ankle springs, as showing the figure below, were also introduced in this walker in order to facilitate side-side motion of the COM. It should be noted that the transition to 3D introduces further complexities. For instance, due to the difficulty in characterizing all the factors Collins et al. abandoned theoretical simulation as a design tool and instead used a process of trial and error in order to find the walker parameters. In conclusion, although this design was relatively successful, it requires a better mechanism to prevent the bounce observed after knee collision. The methods applied during the tests were not successful at solving this issue.

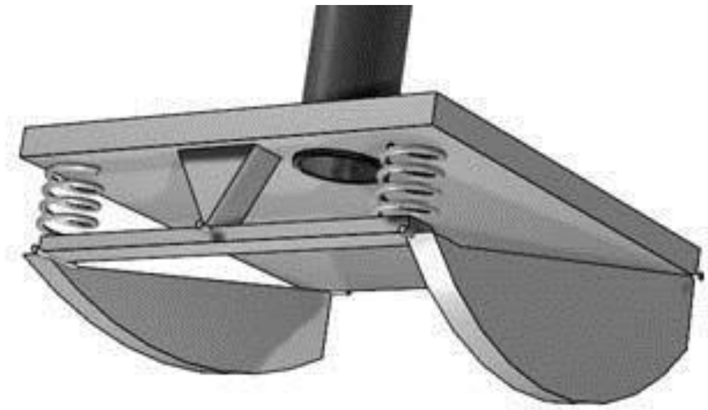

Figure 23 - Ankle springs that permit roll motion about the central pivot-point (Collins, et al., 2001)

2.4.4 Alternative 3-D Designs with Ankle Springs

Passive walkers were traditionally made with arc feet and locked ankle joints. This was a popular design trend that was inspired from old toys and Mcgeer's initial study of passive walkers and many notable passive walkers had adopted this. The feet are designed in order to provide the proper propulsion force required by the robot (Narukawa, 2008). Although this design allowed the walkers to demonstrate walking behavior, a major drawback is that it was confined to this movement and it is unstable during various behaviors such as standing, walking with different speeds, and running. These walkers especially have a drawback in three dimensions because their contact conditions with the ground would result in insufficient friction against yaw (Narukawa, 2008). Conservation of angular momentum about a vertical axis predicts unstable yaw motion when legs with arc-shaped feet pass each other.

The robot could slide and fall off due to the yaw motion. This usually occurs when only one foot is in contact with the ground and is unable to produce sufficient torque friction resulting in the yaw motion. The pitch motion makes the robot swing forward and backwards changing the point of contact between the foot and the ground. An instable pitch motion could result in the walker falling backwards or forwards.

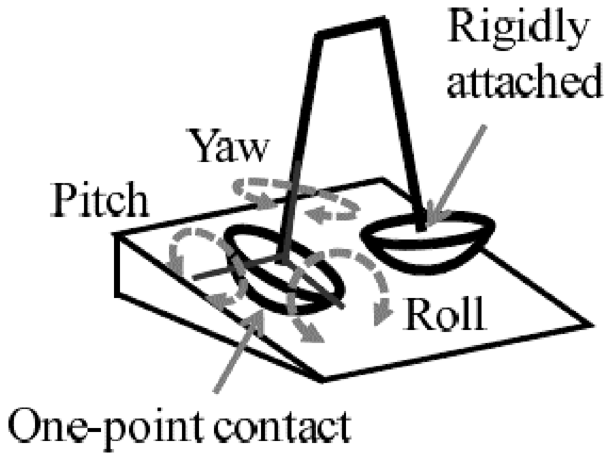

Figure 24 - Roll, Pitch and Yaw for a Passive Dynamic Walker (Collins, et al., 2001)

A study on flat feet by Narukawa et al. (2009) confirmed that the musculoskeletal structure plays a role to generate a circular roll-over shape (ROS, which is a shape of a trajectory of centre of pressure) by using a simple ankle-foot model. They used this as the groundwork to show that if ankle joints can generate a circular ROS, a robot with flat feet should have comparable performance against the robot with circular feet. In order to achieve this the flat feet are connected to the legs with springs at the ankles that produce torsional forces while the stance leg is on the ground, mimicking the motion of simple 3D passive walkers with arc-shaped feet.

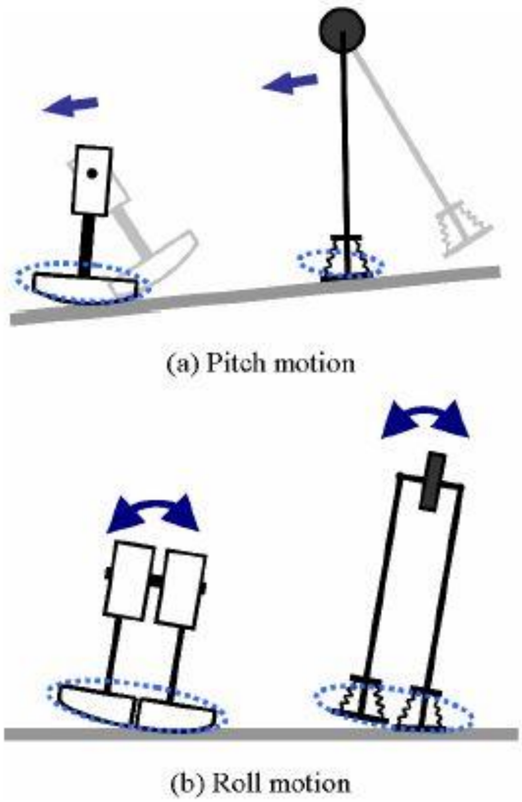

Figure 25 - Pitch and Roll motion comparison between flat foot and arc-shaped foot (Narukawa, et al., 2008)

The main focus of their study is energy efficiency and the walking speed of the bipedal. The robot consisted of one hip, two straight legs and feet. The ankles had two degrees of freedom which related to the roll and pitch of the walker. In total the walker had 5 degree of freedoms illustrated in the figure below.

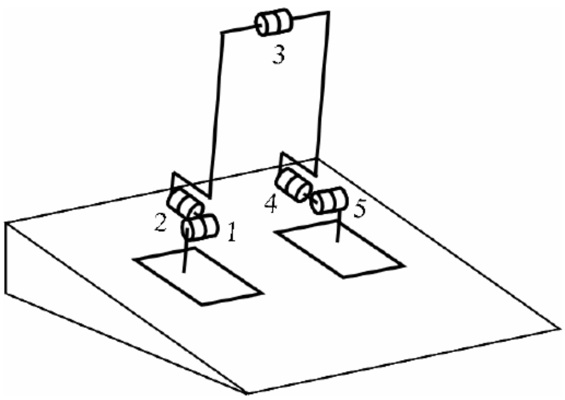

Figure 26 - Internal degrees of freedom of Nakurawa design (Narukawa, et al., 2008)

The successful performance of this walker was largely dependent on the stiffness of the springs selected. The roll motion of the walker had to create sufficient clearance that would allow the leg to swing forward. The spring constant was determined with this in mind in order to match the half period of the roll motion with the step period of the walker. Whereas the robot will fall if the spring constant is small compared to the deflection angle. Moreover, if the constant is too large the walker will start to rotate and cause unstable motion.

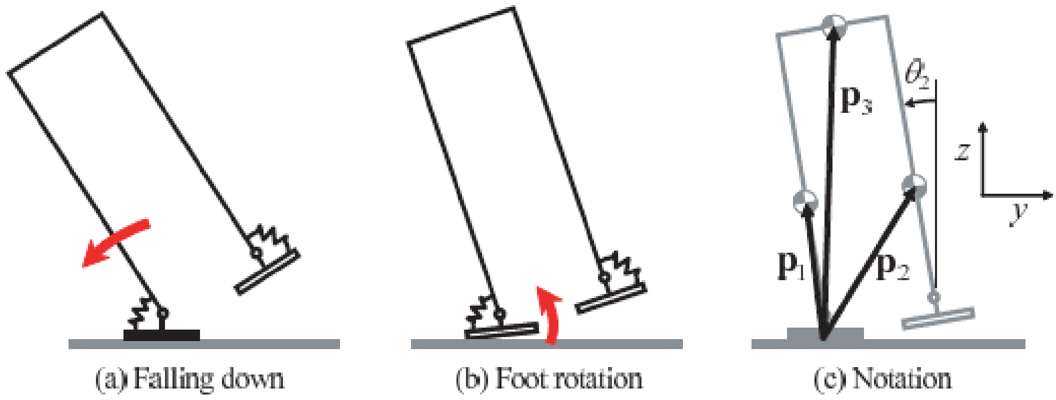

Figure 27 - Unstable Motions due to Torsional Spring Constant (Narukawa, et al., 2008)

Experimental results of this showed that flat feet with ankle springs stabilize the yaw motion, thus their 3D passive biped walker was able to take longer steps and walk faster than simple arc-footed 3D biped walkers. The stride length was about 0.44 m and the stance angle was about 0.24 rad. The walking speed was about 0.46 m/s. The non-dimensional speed was 0.15, which is slightly slower than the Cornell 3D passive walker's speed of 0.18 (Collins, 2005).

Moreover, a robust stable walking pattern was not achieved. Their robot only walked the full length of a 1.8-m slope four times out of about 100 launches by a practiced hand. This suggests that the walker needs improvement, but the cause of bipedal walking failure seems to be different than that of simple 3D walkers with arc-shaped feet (Narukawa, 2008). The main cause of unsuccessful results was not unstable motion caused by roll or yaw. Rather, the failure was caused by the scuffing of the swing leg which occurred when the legs passed each other. The scuffing of the swing leg immediately stopped the walker. This occurred when the roll motion was insufficient during swing. Narukawa et al. (2008) suggest that in order to address the scuffing problem, knee-legged robots must be studied as a way to achieve sufficient ground clearance during the swing-leg motion.

Further experimental tests were performed to prove that torsional spring stiffness affects the overall motion of the walker and selecting springs with appropriate torsional spring stiffness aids in reducing the oscillating motion of the feet induced by the impact with the ground (Narukawa, 2008). Although this study included the effects of different spring stiffness at the ankle joint, the best spring configurations leading to stable gait was later researched by Tobajas (2013). The following image shows the final walker used in the study.

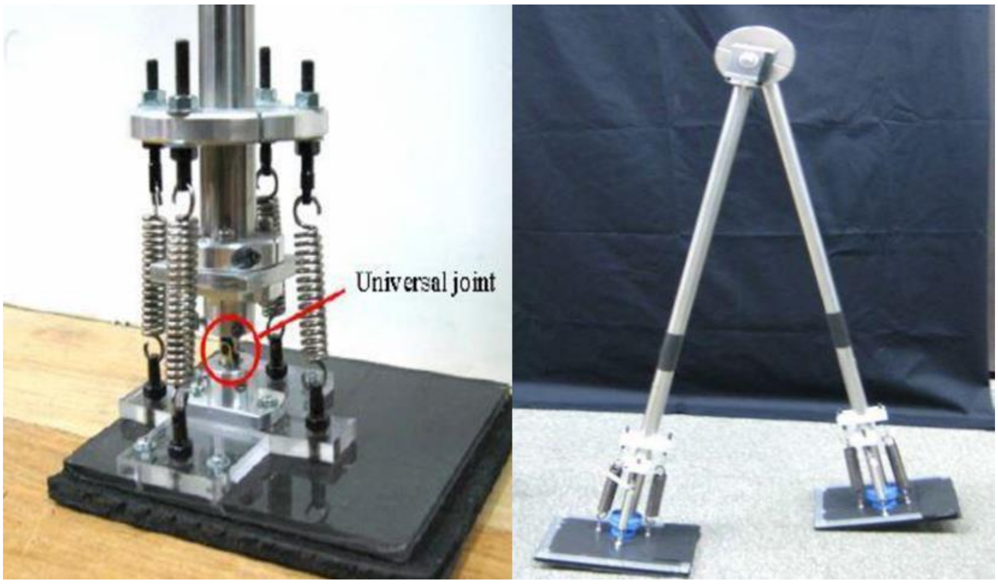

Figure 28 - Straight legs, flat feet and ankle springs (Narukawa, et al., 2008)

In the study conducted by Tobajas (2013), preliminary tests were carried out to find the walker's optimum parameters such as the height, leg separation, and slope angle. The shortest length of the robot was 422.81 mm which failed to generate a stable gait pattern due to insufficient ground clearance relative to the ground. The largest height setting also did not result in very stable gait pattern due to the exaggerated hip roll motion. The optimum height of the walker was eventually found to be at 549 mm and the angle of the ramp used while performing the tests was 5.6°.

The main features of the walker used for this study were similar to that of Narukawa (2008), i.e. flat feet with two straight legs. Three different spring stiffness were tested in various combinations across all planes. The study tested for a total of 81 different spring configurations for two different types of motion, short and long step gait. This study was successful in recreating a stable gait pattern and it was successfully able to identify the best spring configurations. The best spring configuration was able to take an average of 59.2 steps traversing the entire length of the ramp. Tobajas (2013) also drew conclusions on the relationship between the sagittal and the coronal plane.

2.4.5 Adaption of Knees in 3D Bipedalism

Although previous studies have adapted the knee design to the passive walker, there is not significant research done solely on the effects of adding a knee joint on bipedalism. The earlier walkers that incorporated knees were 2D and hence even though those walkers were able to achieve a fairly stable gait cycle, it did not provide much insight to the functioning of the knee. The figure below shows a McGeer derivate that was studied to determine the effects of slope angle on *planar* kneed gait. It was observed that increasing the angle lead to an increase in the step length and the traversal speed.

Figure 29 - Dexter MK III (Rushdi, et al., 2014)

Designs to mimic muscle function have also been developed. However, these structures do not replicate the functionality of their human counterpart due to their *reactive* nature as opposed to applying force pro-actively. The figure below shows the design that was incorporated for this study. It should also be noted that the knee joint was not entirely passive.

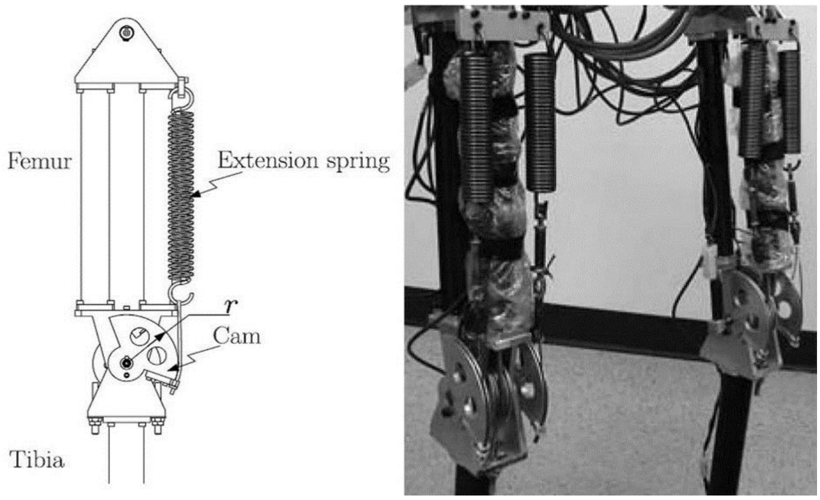

Figure 30 - Compliant spring configuration to replicate quadriceps functionality (Yang, et al., 2008)

Trifonov & Hashimoto (2007) employed an alternative knee design which was completely passive. The locking action during extension is employed through the use of magnets whose magnitude of attraction can be controlled. However experimental testing proved the tuning of these magnets to be excessively difficult and consequently the bipedal walker was "near-impossible" to launch. This locking system was eventually replaced by a locking-latch mechanism which relied on actively powered unlocking of the latch. This solution lies outside the scope of a fully passive design, it is hence dismissed.

2.4.6 Efficient Robots based on Passive-Dynamic Walkers

The stability achieved by passive walkers is not limited to slope planes and some efficient bipedal robots capable of traversing level ground have been developed drawing inspirations from this field. These robots demonstrate that stable gait can be achieved by using relatively simple control methods and hence requiring less energy. Two of the most successful robots in this field of research are briefly discussed in order to appreciate the adaptability of passive walkers.

Toddler was designed with the goal to optimize control policy during bipedal locomotion by using learning algorithms. It was based on a simple passive walker with curved feet and straight legs. The robot is 43 cm tall and weighs 2.75 kg with six internal degrees of freedom. The study successfully showed that the mechanical design of the robot made it relatively easy to create controllers which allowed the robot to walk stably on flat terrain and even up a small slope (Tedrake et al., 2004).

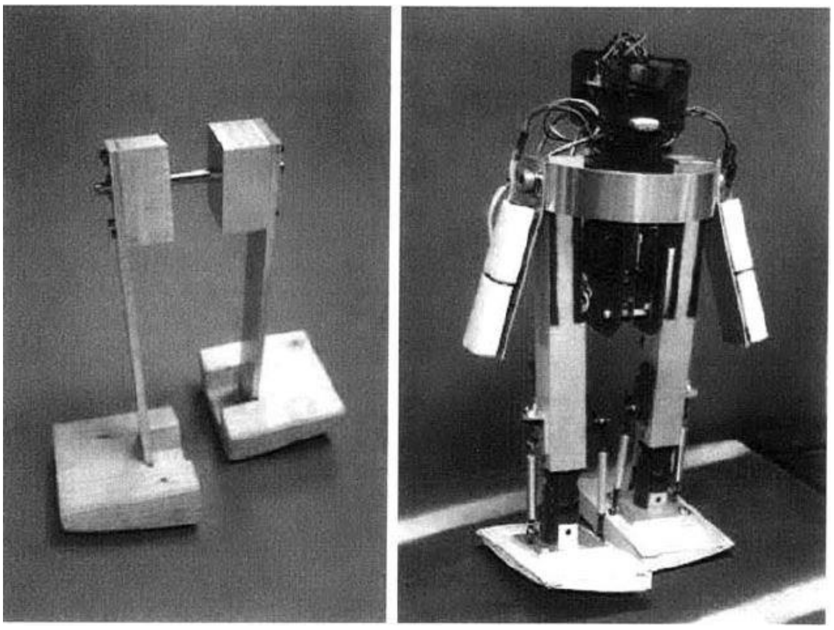

Figure 31 - Left: A simple PDW, Right: Actuated version of the simple PDW (Tedrake et al., 2004).

The figure below shows the Cornell biped based on the passive dynamic walker. Ankle push off is achieved by electric motors with springs and has 5 degrees of freedom of which 2 are the knees. The Cornell biped was specifically designed for minimal energy use and the average mechanical power consumed was 3W which is comparable to that of passive walkers. Moreover, the mechanical cost of transport for this walker was 0.055. It should be noted that these values are not reflective of the energy consumed by the actuators and other electronic components which would increase these values.

The knee joint is a simple latch mechanism with a hyperextension limit. The knee joint rotates freely when not locked. When the knee reaches full extension midway through the swing the locking mechanism engages, and the knee remains locked in full extension throughout the remainder of swing and during stance. At the beginning of leg swing, a solenoid activates to disengage the knee latch. Thus, the knee motion is largely unactuated (Collins, 2005). However the authors of this study do not investigate the effects of the knee on the stability of the walker nor highlight any specific issues faced in achieving kneed gait.

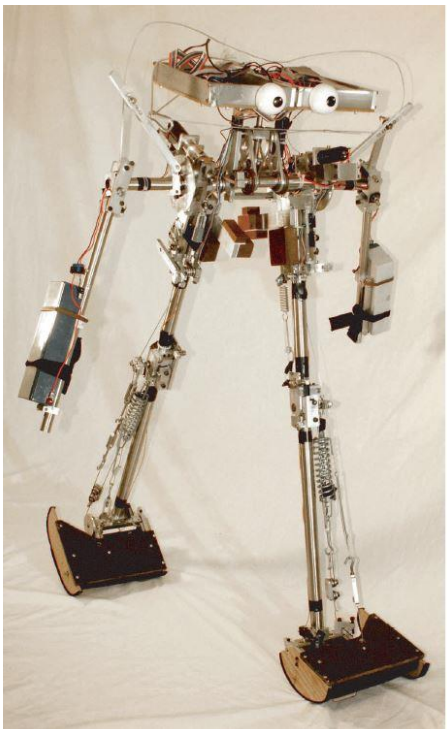

Figure 32 - Cornell bipedal robot (Collins, 2005).

2.5 Lower Limb Prosthetics

Due to an insufficient literature present for kneed walkers in the field of robotics, and also since the problems associated with the adaption of knee joints is not limited to passive walkers, a literature review of lower limb prosthetics is conducted. Many passive solutions for transfemoral prosthesis have been presented and explored in the literature. "Above-knee prosthesis" is designed for individuals who have been amputated above the knee. Research shows that individuals with transfemoral prosthesis spend around 80% more energy while walking compared to healthy individuals and experience significant discomfort (Poliakov, 2013). The cause of the discomfort is due to the functioning of the artificial knee mechanism being different from the natural functioning.

Similar to the field of robotics, two main categories exist within transfemoral prosthesis, i.e. purely mechanical and microprocessor controlled. The knee joint is one of the most constructed joints in the field of prosthesis and has been developed over the years as shown in the figure below. The design progressed from side braces, to simple single axis hinge joints, and finally multiple bar linkage system (progression is left to right in the image).

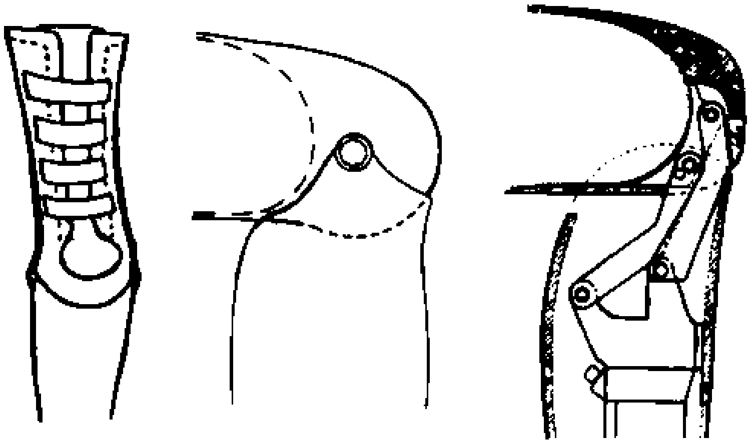

Figure 33 - Progression of the prosthetic knee joint (Radcliffe, 1977)

The effect of the ground reaction forces on prosthetic flexion must first be considered in order to examine the knee mechanisms. Oberg (1983) suggested that there are four stability characteristics of any knee joint. These include:

1. Muscular hip moment
2. Load line
3. Instantaneous centre of thing-shank rotation
4. Brake moment by knee

Such analysis is carried out with the aid of stability-zone diagrams (Radcliffe, 1977) illustrated below for simple hinge prosthesis. Although this method is a relatively simple analysis, it allows for a crude prediction of the loading response during stance on the prosthetic.

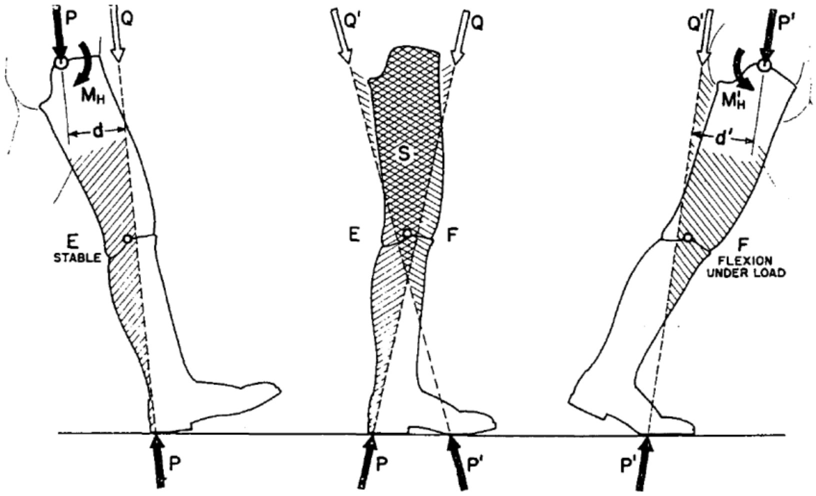

Figure 34 - Stability analysis of simple transfemoral prosthesis (Radcliffe, 1977)

By tracing lines that lie coincident to the ground reaction vectors at heel-strike and toe-off, the stability zone can be outlined. When the ground reaction vector passes posterior to both the lines passive flexion will be observed whereas if the vector is anterior to the lines, passive flexion will not be observed.

The single axis hinge joint was a standard in above knee amputees due to its low cost along with its durability and weight. However, it posed major problems in the form of loss of stability due to a lack of anterior-posterior displacement control (Dupes, 2014). Solutions to these issues are however exhibited in transfemoral prostheses which employ mechanical locking control such as that used in the study by Andrysek et al. (2011).

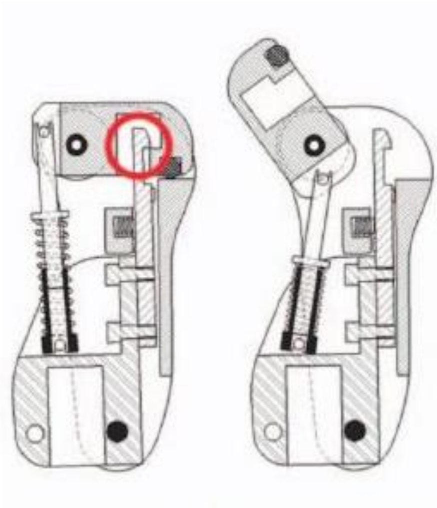

Figure 35 - Typical stance control transfemoral prosthetic with locking mechanism Andrysek et al. (2011)

A secondary control axis present within the assembly of the knee joint is the key feature of such prostheses. Many variations of the stance locking design are available in literature. Moreover, additional features which influence walking behaviour have been added to this design. Most notable is the knee joint developed by V. N. Murthy (2015) that incorporated the addition of a third axis, the *early stance flexion* (ESF) axis shown in the figure below. Although these designs accurately replicate human walking, it is not strictly for passive walkers. Moreover, a design with three axes would not be the appropriate start for a thorough understanding of the knee joint mechanism in passive walkers.

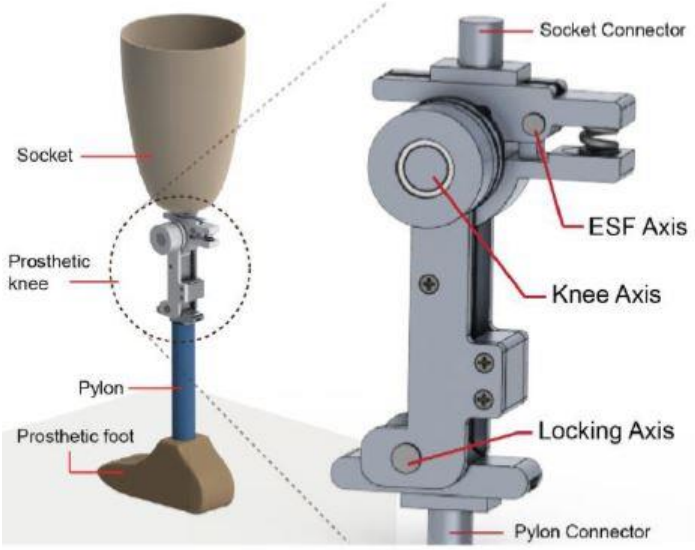

Figure 36 - Transfemoral stance locking prostheses with early stance flexion capability and adjustable thigh and shank slides (V. N. Murthy & Winter, 2015)

2.5.1 Polycentric Knee Design

Polycentric knee joints are characterized by their instantaneous centre of rotation (ICR). The position of the ICR changes with a changing knee flexion angle. This largely dictates the stability of the prosthesis while walking. The polycentric mechanism increases the range of knee flexion during gait and control mechanisms of different types can be added to further improve its stability. The versatility of these joints is the primary reason for their success and widespread adoption (Dupes, 2014).

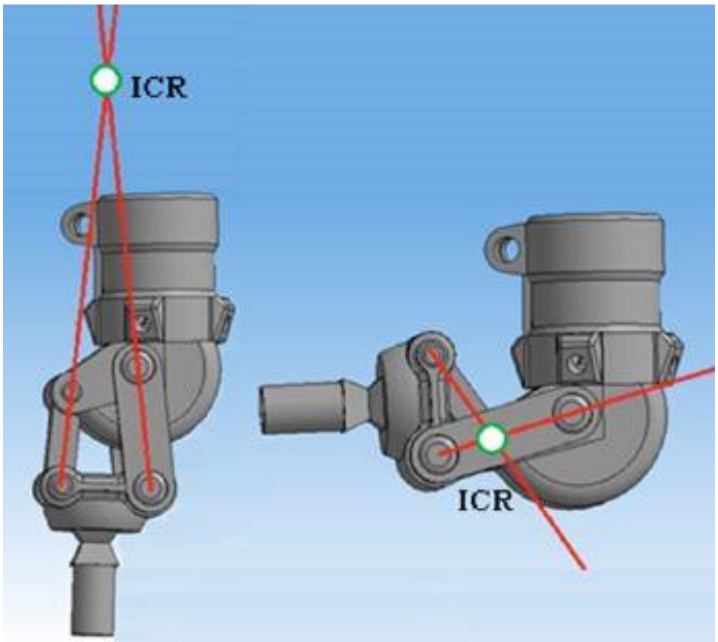

Figure 37 - 3-D model of the polycentric artificial knee joint mechanism of transfemoral prosthesis (Poliakov, 2013)

The trajectory of the ICR is dependent on the geometrical parameters of the knee joint, thus by varying these one can provide characteristics that are preferable to the different groups of amputees. The most common type of polycentric joint is the four-bar linkage polycentric knee joint. The motion of this mechanism is inspired by the deformation of the ACL presented in section 2.3.3.1. The location of the ICR can be easily located at the intersection of the two lines passing through the centre of the links, as shown in the figure below.

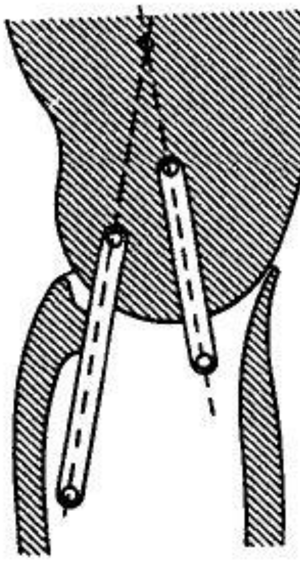

Figure 38 - The four-bar knee linkage and the instataneous center of thigh-shank rotation (Radcliffe, 1977)

One of the benefits of the polycentric knee joint is that the ICR at full extension can lie within the stability zone as shown in the figure below. These joints can be set up to having improved stance phase stability while still being able to initiate swing phase or sit down (Dupes, 2014). Moreover, the polycentric knee is also able to provide a greater foot clearance reducing the risk of stumbling. A study performed by Gard (1996) showed that the knee joint shortened beyond the standing hip elevation by about 30° to 40°, whereas the necessary angle required for toe clearance is approximately 50° for a single axis knee joint (refer to figure below). In human gait, the knee flexion angle is approximately 30°at toe off. As such, only the 4 bar link polycentric knee joint would be able to provide sufficient floor clearance.

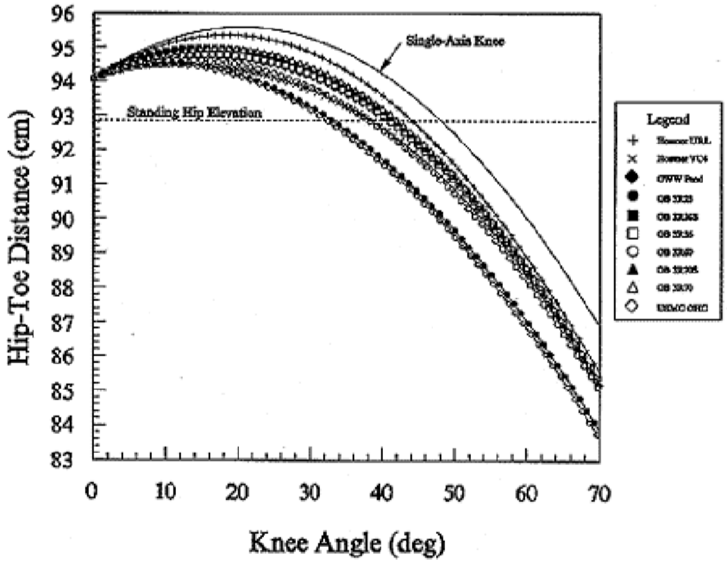

Figure 39 - Plot of Hip-Toe Distance versus Knee angle for Various Four Bar Linkage Knees and Single-Axis Knee (Radcliffe, 1977)

The Stanford-Jaipur knee is a four-bar polycentric knee joint designed in the late 2000's (Samiti, 2008) which was further improved by D-Rev (2011). It is being widely adopted in developing and under-developed countries as it offers an affordable alternative to the extremely expensive microprocessor controlled knee joints. No specialised parts are required to build this joint which offers another advantage over other more complex passive designs. Moreover, amputee patients were able to exhibit gait which was very similar to that of an able bodied person, after a few sessions of rehabilitation (Rev, 2011).

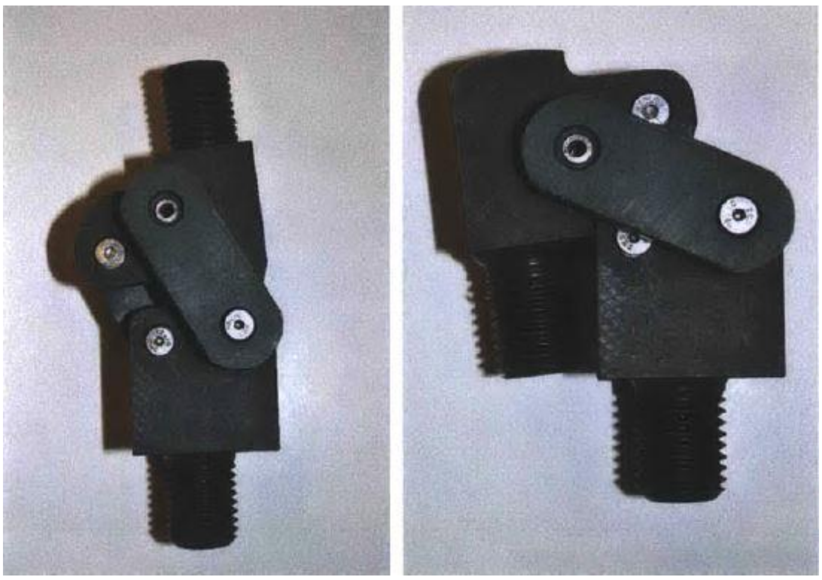

Figure 40 - Stanford-Jaipur knee joint. Left: fully extended position, right: fully flexed position (Samiti, 2008)

The 4-bar polycentric knee joint has proven to improve stability and the flexion of this joint is anthropomorphically similar to a certain degree. Moreover, the design of this joint was modelled after the human knee where the motion of its ICR represents that of the ACL. The 4 bars of the joint are also representative of the collateral ligaments that support the knee joint. Finally, the principles defining the functioning of the polycentric knee joint are basic. This is important because achieving a stable gait pattern in the experimental tests of kneed walker has been notoriously difficult. Hence this design was deemed the most appropriate and was used as the inspiration for the knee joint.

2.6 Conclusion

Human walking might seem fairly simple at first however it is a very complicated process. The goal of recreating flight has been solved for many years now however there has not been single mechanism capable of representing human gait. The synthesis of bipedal gait is difficult because of the complicated characteristics defining it and hence a thorough understanding of the underlying system characteristics must be obtained. This mandates exploration and integration of different fields in order to successfully solve the problem of recreating a bipedal system. A successful bipedal system should meet the following requirements: stability, efficiency, naturalness, versatility, and safety (Wisse, 2004).

PDW's main aim is to improve upon the first three requirements. PDW aims to solve the above problems of energy stability and naturalness by the design of mechanical systems with inherent stability. The inspirations of these designs are derived by studying human morphology and these studies in return help broaden the understanding of human functioning.

A lot of improvements have been seen in the field of active and passive robotics. The variables of the passive dynamic walker such as COM, height, shape of the feet, etc. have been isolated and analysed. However, there has been a significant lack of research in improving the design of the knee joint and it is hoped that this research would contribute to this field. Single hinge joints are susceptible to early stance flexion along with having low stability. Moreover, achieving early stance stability and offering appropriate clearance are two concerns that no single design has been able to solve. Hence in order to increase the likelihood of successful knee performance, the polycentric knee design with flat feet was deemed a suitable design strategy. This design seemed most promising due to the various benefits it offers. Moreover, it was decided to not conduct a simulative study of the kneed walker from the conclusions drawn from literature review. This is due to its inability to provide any useful data and because physical testing is better than numerical simulations when real physics is important. In many cases simulation work has shown poor agreement with experimental results. In fact, research that involved simulation and physical testing, it was the successful physical model that motivated a more careful analysis of the simulation (Rushdi, 2014).

Chapter 3 – Design Of Passive Dynamic Walker

3.1 Introduction

This chapter outlines the design of the bipedal walker used for experimental testing. The final design of the walker is shown in the figure below. Its main sections are the flat feet with ankle springs, the four-bar linkage knee system, and the hip. They are connected by extendable legs that represent the thigh and the shank. It is aimed to demonstrate that it is possible to reduce the energy consumption of active robots by providing an inherently stable system through their mechanical design. In order to develop effectively upon previous studies in this field, it was vital to select appropriate bipedal walkers that would serve as design inspirations. These are briefly discussed below along with the various design iterations.

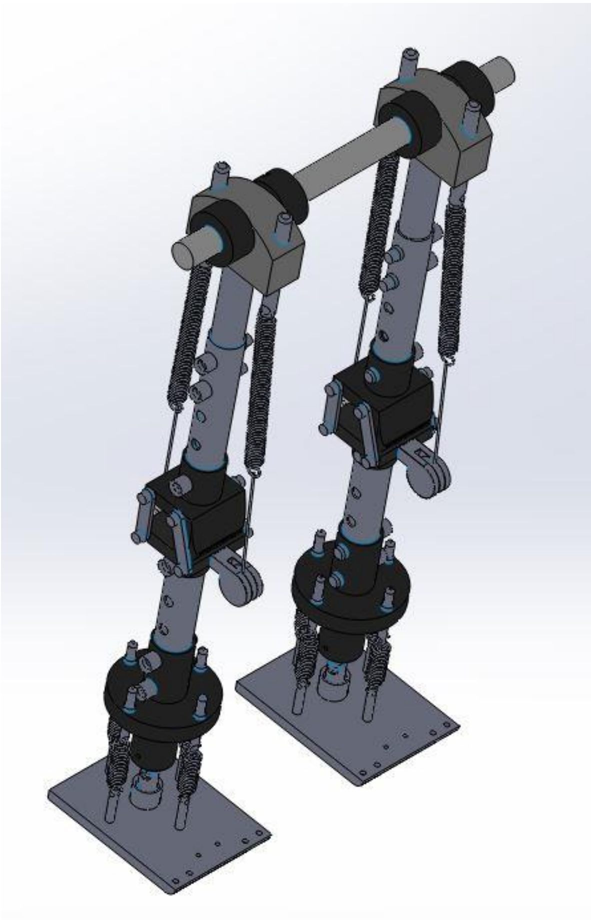

Figure 41 – 3D Passive Dynamic Walker with Knees

The key component of the walker is the knee joint as the main objective is to test its adaption to previously successful straight legged bipedal walkers and analyse its effects. Although the walker was initially designed to have interchangeable knees in order to test different knee designs, due to limited time the four-bar linkage polycentric knee joint was chosen as the sole design to be tested. Furthermore, the design specifications of the different parts are explored thoroughly.

3.2 General Overview

The bipedal walker consists of 5 major parts. These include the feet, ankle, knee, extendable legs, and the hips. The manufacturing and the assembly process were taken into consideration during the design. Each foot consists of 4 cylindrical structures in the sagittal and coronal plane with holes that allow for the attachment of steel springs via their hooks. The foot also has a housing to accommodate a universal joint which is then connected to a component made of Delrin. This component connects the universal joint with the legs and also supports 4 cylindrical structures to attach the other end of the steel springs. The universal joint along with the Delrin component and the springs make up the ankle. The legs join the ankle and the hips with the knee joint in the middle. The extendable feature of the legs makes it possible to change the step length, velocity, and dynamics of the walking motion by changing its COM. It also allows for different length ratios of the thigh and shank. The upper and lower parts of each knee are connected by 2 bars on each side. These along with a spring system attached between the lower knee and the hip makes up the knee-spring system.

Depending on the setting, the total height of the walker ranges from 596 mm to 695 mm when measured from the top most point of the hip to the ground. It should be noted that the walker was initially designed and manufactured to the height ranging from 877 mm to 724 mm. However, after further analysis and initial tests it was decided to change the height in order to better represent human proportions. For humans the leg to feet ratio is 3.6 and the average thigh to shank ratio is 1.05. With the initial design the ratio at the lowest setting was 7.3 for leg to foot but for the new design the ratio is 4.9. Although this is still not representative of human ratio, this was the minimum height required for the walker in order to accommodate the parts with an appropriate thigh to shank ratio. The thigh to shank ratio in the new design is 0.9 which is very close to average human morphology.

The total weight of the walker is 3.01 kg when fully assembled. The individual weight of the sub-assemblies is shown in the table below. The specifications for the bipedal walker is chosen to be similar to the walker Tobajas (2013) tested in order to *validate this bipedal walker's functionality without the knees*. The design was developed to allow for the adjustments of key parameters such as the height, distance between both the legs, length of the thigh in relation to the length of the shank, initial elongation of the springs, etc. in order to allow the walker to have a greater adaptability during the testing stage.

Table 1 – Measured masses of each sub-assembly

Sub-Assembly	Mass (g)
Hip and Thigh	333.5
Knee	269.9
Shank and Foot	683.8

3.2.1 Design Inspirations

In the past, a lot of research has been done in the field of passive dynamic walkers. When trying to re-create a complicated process, like human gait, it is necessary to isolate the key components of the system and simplify the model. This allows for a more comprehensive understanding of its functions. The first key component of bipedal walkers is the feet. As discussed in chapter 2, many researchers have modelled and experimented with simple 3-D bipedal walkers in order to design more efficient feet. These bipedal walkers were devoid of an upper body, consisted mostly of a simple hip joint with restricted degree of freedom, and there were no knee joints present. Their aim was to reduce the disturbances observed during the walking cycle along with understanding how much the feet alone could contribute to generating a stable walking cycle while still representing the human gait.

The design of flat-feet with ankle springs, which was first successfully tested by Narukawa (2008) and further improved by Tobajas (2013), was chosen as the basis for the walker. They successfully showed that this design was able to overcome many of the disadvantages faced by the curved feet design and achieved a stable walking pattern. It is currently the best design in literature to represent the foot/ankle-joint complex of humans for bipedal walkers. Since the effects of the knee joint in bipedal walkers have not been studied in isolation very extensively, it is important that all the variables are taken into account so that they can be controlled. It will then be possible to analyse the effects of the knee joint with a higher accuracy.

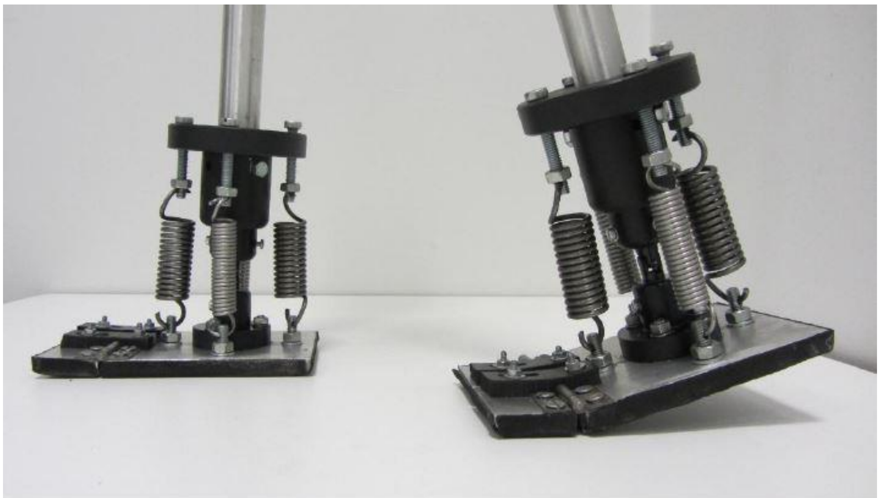

Figure 42 – Feet with ankle-spring system

A polycentric joint with a 4-bar linkage system was chosen as the knee joint. This type of joint has been studied for many years under various applications including the field of prosthetics. It has proven to be very stable and more efficient than the single hinge joint most commonly used in passive walkers and older prosthetic models. However, no research has been done to test the effectiveness of this design in passive dynamic walkers. The theoretical studies of Guston (1971), Oberg (1983), and Goldblatt & Richmond (2003) served as the design inspiration for the polycentric joint.

3.3 Parts Design

3.3.1 Feet

The main factors considered while designing the feet were strength and the weight of the material. As this is the base of the walker it needs to be durable to handle the stress produced by the ankle joint and the reaction forces acting on the walker during the walking cycle. The weight is also limited as heavy feet will lower the COM of the walker which will lead to unsuccessful walking pattern. One of the options considered was to 3-D print the part but due to the material having brittle properties it was discarded. Another option was steel but due to its weight being too high it was finally decided to go with aluminium as it provides considerable strength and has appropriate weight. The feet are 120 x 90 mm with an 8 mm thickness.

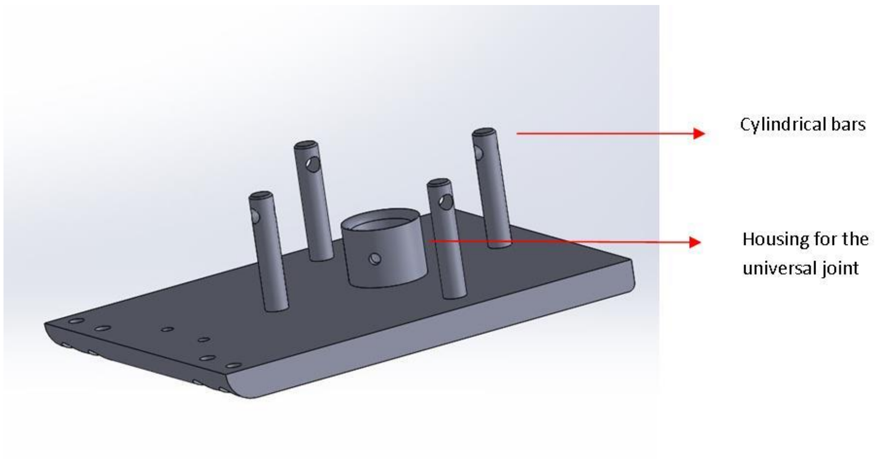

Figure 43 - CAD model of the foot

The feet have two main components, that is the 4 cylindrical bars and a housing for the universal joint welded to its top surface. It is vital that the bars have sufficient strength as they will experience high forces via the tensional springs. The bars are 30 mm high with a diameter of 8 mm. As mentioned in chapter 2, the previous iteration of this walker faced the problem of foot locking. As this was caused due to a misalignment of the force vector the design change suggested by the author was to set the ankle joint at a lower height from where the springs are fixed. A positive torque is produced in this design due to the direction of the forces which enables the leg to return to the stance position thus avoiding foot locking. Due to this the height of the bars and the location of the hole were decided based on the specifications of the universal joint.

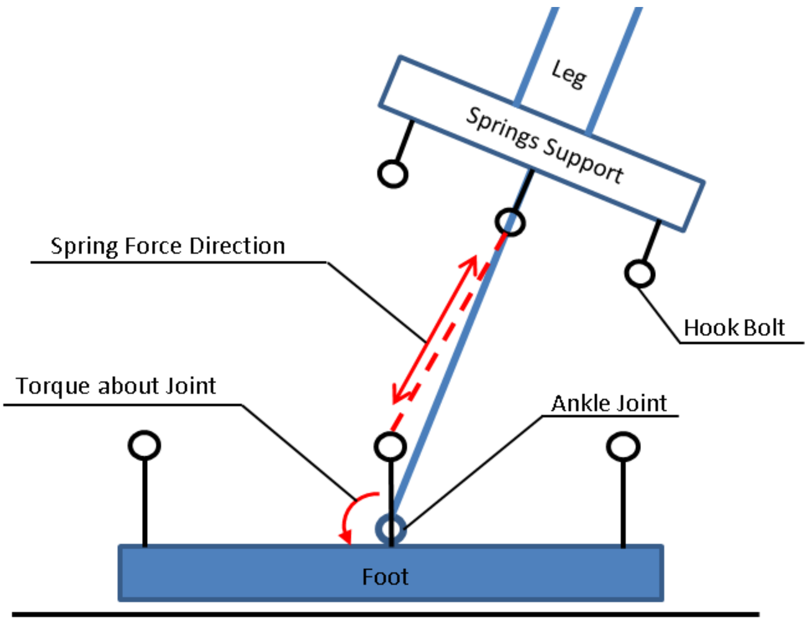

Figure 44 – New design suggestion (Tobajas, 2013)

3.3.2 Ankle Joint

The ankle joint consists of an attachment between the universal joint and the leg, and the spring system. The attachment has a hole at the bottom side where the other end of the universal joint is fixed firmly in place by using a M3 pin. This part is made of Delrin which is a thermoplastic known for its use in precision parts requiring high stiffness. It was necessary to have a light material as the ankle joint also consists of 4 steel springs contributing to the weight. The attachment is designed to accommodate the leg for two different height settings at the top end. The attachment is over 80 mm in height and has a circular component in which 4 holes are drilled in the sagittal and the coronal plane. Support bars will pass through these holes in order to serve as the other end of the attachment for the tensional springs thereby completing the ankle joint. The reason for the criticality of the circular component’s location is twofold. Firstly, the holes in the sagittal and coronal plane need to be perfectly aligned with the bars present on the feet, otherwise the ankle spring will have slight torsional force acting on it affecting the bipedal walker’s performance. Secondly, the distance between this circular component and the holes in the bars on the feet determines the maximum initial elongation of the springs. Thus the free length of the springs selected was taken into account while deciding the location of the circular component.

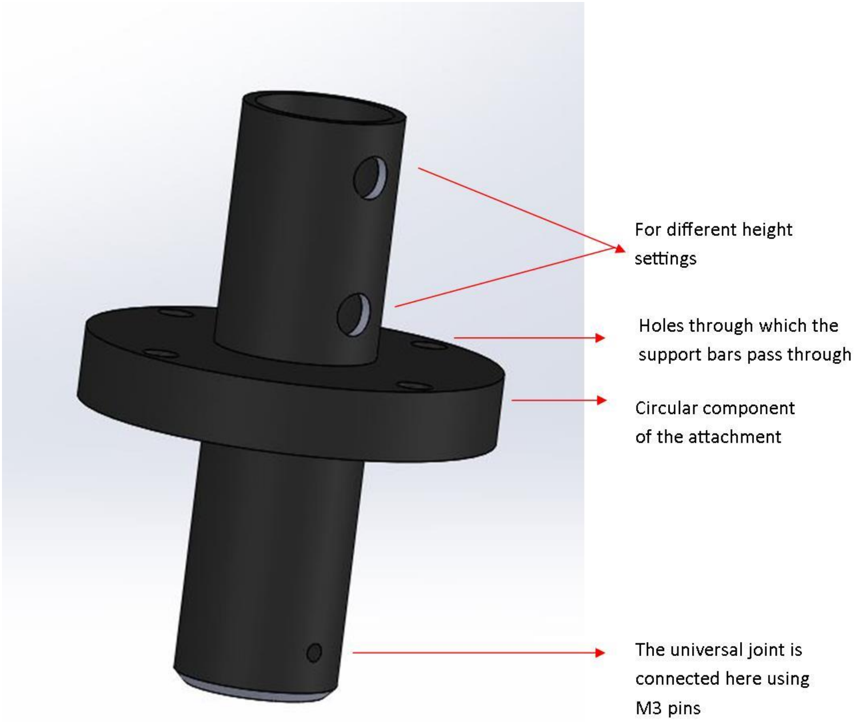

Figure 45 - Attachment between the UJ and the leg

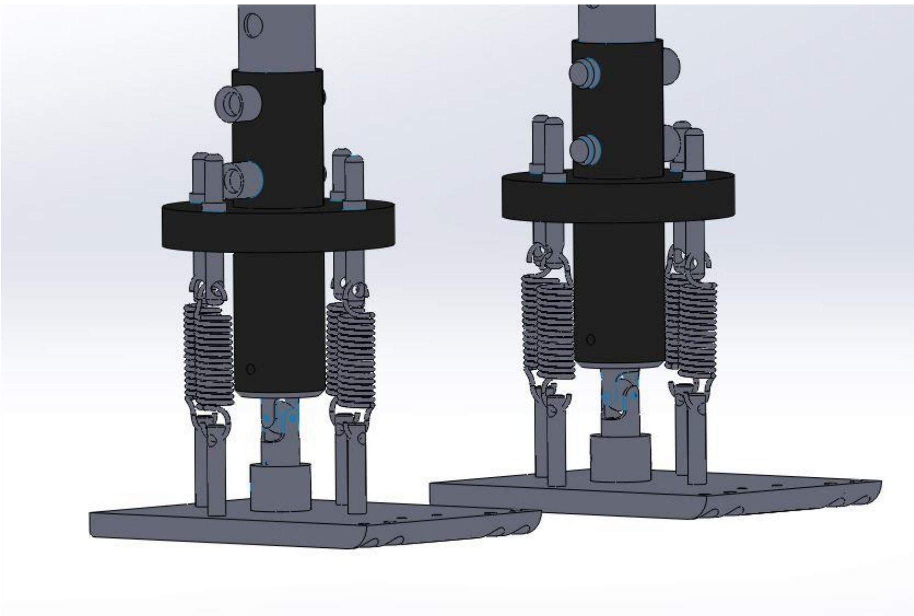

Figure 46 - CAD of ankle-spring system

Achieving a stable gait is primarily dependant on the stiffness of the ankle springs which control the roll and pitch of the walker allowing the legs to move sideward and forward. A slight change of one of the many variables would require the adjustment of the spring's stiffness. Previous iterations of this bipedal walker have established the best tensional spring stiffness for the ankle joint and tested the various combinations. The properties of the three springs selected are presented in the table below.

Table 2 – Spring selection

Spring No.	Free length (mm)	Rate (N/m)	Wire d (mm)	Outside d (mm)
1	63.5	1950	1.42	9.53
2	63.5	3260	1.83	12.7
3	63.3	6670	2.5	18

The spring system was designed to allow a large range for the initial elongation. A threaded M6 screw was chosen as the bar that would support the other end of the springs. This was decided as the screw would have sufficient strength to support the forces exerted by the springs and it can be held in place using a 6 mm nut. The initial elongation of the spring can be changed manually by turning the nut either clockwise or counter-clockwise. Another nut is threaded down on top of the spring hooks, to keep the springs in place while testing.

3.3.3 The Knee Joint

The polycentric 4-bar linkage joint consists of two – top and bottom – parts that are connected via 2 bars on each side. The bottom part of the knee has holes in the sagittal plane that accommodates the support structures which act as the spring connectors. The design of this joint was based on the criterion for voluntary stability outlined by Oberg (1983). Moreover, the criterion of stability during standing was also considered which requires the centre of rotation to move behind the load line while in stance. The figure below shows the ICR is behind the load line at stance which will follow a high order polynomial path when the angle between the two parts is changed. Link 1 represents the top part of the knee while link 4 is the bottom part. Link 2 and 3 are representative of the bars that connect the top and bottom part of the knees. These bars are free to rotate and are fixed to the Delrin parts with simple pins with threaded ends. The threaded ends allow the bars to be fastened by using nuts. The knees can be locked by completely tightening nuts or given more degree of rotation by loosening the nuts.

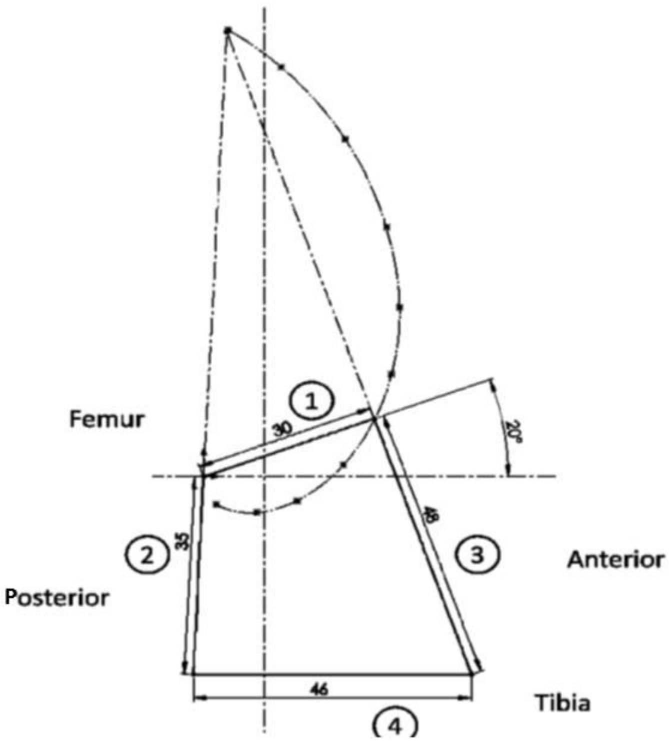

Figure 47 - Lateral view of knee joint

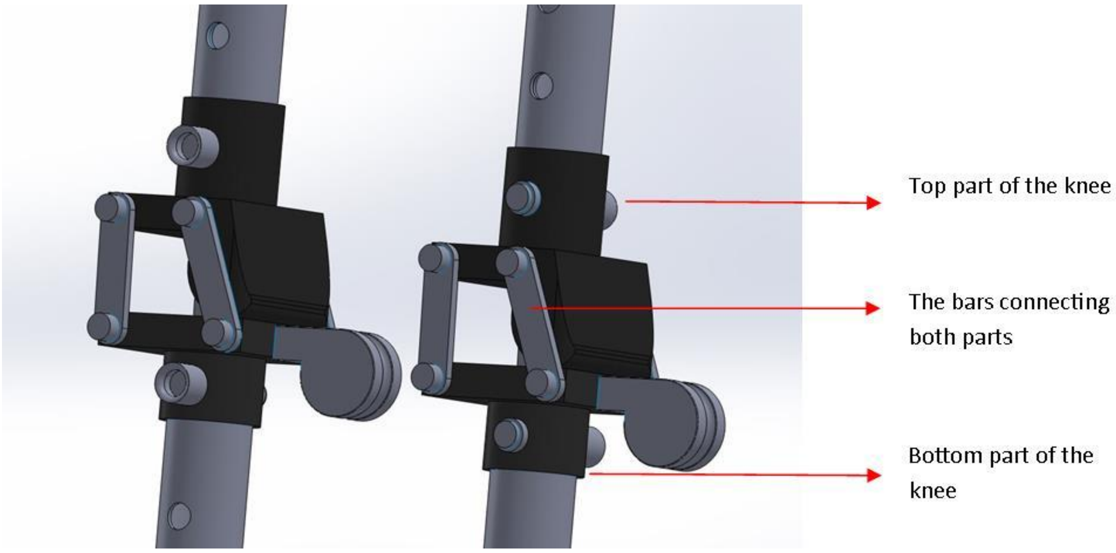

Figure 48 - CAD model of the 4 bar-linkage polycentric knee joint

The other key component of the knee joint is the spring-system. The first problem to address is the location of the springs and type of springs to select. A design completely inspired by the prosthetic joint would require placing a compression spring within the tibia zone. Although this design is proven to perform well in the field of prosthetics, it poses three main issues for this experiment. Firstly this system is not anthromorphically representative. Secondly the addition of the spring in the tibial zone would off-set the shank-thigh mass ratio which will effect the double pendulum motion of the kneed walker. Finally, the direction and the resultant forces experienced by the walker at the knee are different from those present in a prostheitc knee.

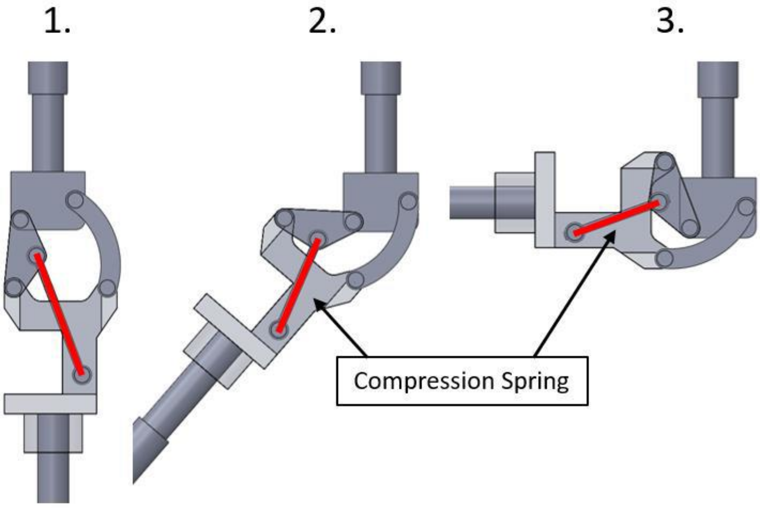

Figure 49 – Design with Single Compression Spring in Tibial Zone

Hence to appropriately balance the forces the joint would experience it was decided to place two tensional springs in the anterior and posterior position in the sagittal plane between the hip and the bottom part of the polycentric joint. Although a simple model, this is a more accurate representation of the human knee joint. The second problem that must be addressed is how the springs would be connected to the walker. It was necessary that the spring system is connected in a manner that would not hinder the motion of the knee and a relatively simple installation as the experimentation stage would require changing the springs often. Furthermore, it should still be possible to change the initial angle of the knee thus this system would need to incorporate for these features.

It was decided to use a connecting wire at one end as this would allow for the knee to flex without any obstructions (see figure below) and at the other end the spring would be attached to a solid support. The springs are connected to the bottom of the hip using a similar screw-nut system which was designed for the ankle springs. The solid pulley structure fits into the lower knee. It was decided to use soft fabric material in order to change the angle of the knee to avoid vibrations from collisions. This would be done manually by placing the cloth at the appropriate location by placing it in between the pulley structure and the lower knee. The support pulley was designed with this in mind. The angle of the knee is then dependant on the thickness of the cloth which can be easily adjusted and the right value is found through trial and error. This method was an appropriate solution to the alternative which would require changes in the knee design. Since the angle is not changed as frequently as the springs, this solution was deemed sufficient.

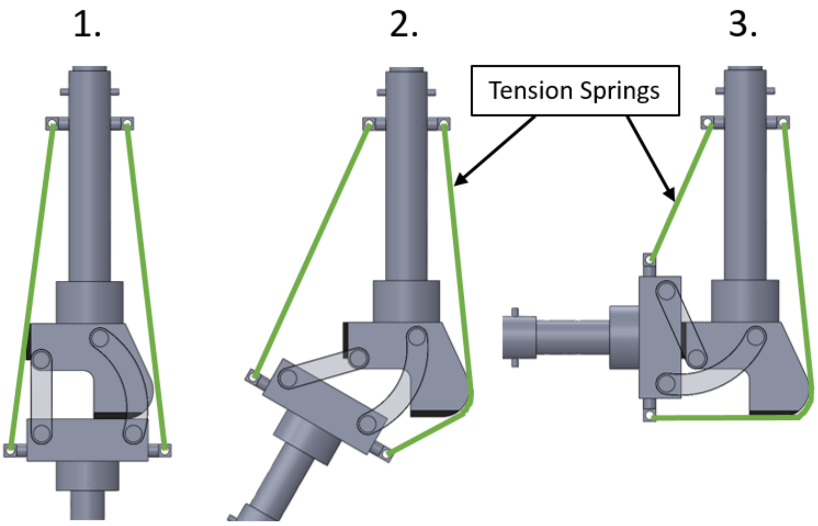

Figure 50 - Tensional springs anterior and posterior to the knee

Selecting the right material for the connecting wire was a challenge as it required a combination of different properties in order to successfully support the spring-system. The connecting wire requires high strength to handle the forces exerted by the high stiffness springs. Wires of many different materials failed here as they would snap under the force. Additionally, the wire could not be too stiff as it would not bend around the knee joint during flexion. Fishing wire, nylon braids, cloth string, circuit wires were among some of the wires which were tested however these materials either lacked the sufficient strength to support the high stiffness springs or did not have appropriate flexibility. Connecting wires used in bicycle brake mechanism along with thin metal wires were also tested with no success.

Eventually, stringing wires used for making jewellery were explored. The key properties of wires used for stringing jewellery are similar to the requirements of this project. These wires must possess adequate strength to support the heavy pieces of a jewellery set and must also be flexible in order for people to comfortably wear them. There are several options available however Beadalon bead stringing wire made from stainless steel is one of the most popular string choices for jewellery makers. Beadalon stringing wire is composed of tiny wires twisted together and nylon coated. The number of tiny wires, also known as strands, determines the flexibility of the wire. Therefore, a 19 strand is more durable than a 7 strand both of which were tested. Both the wires tested successfully and finally the 19 strand wire was chosen.

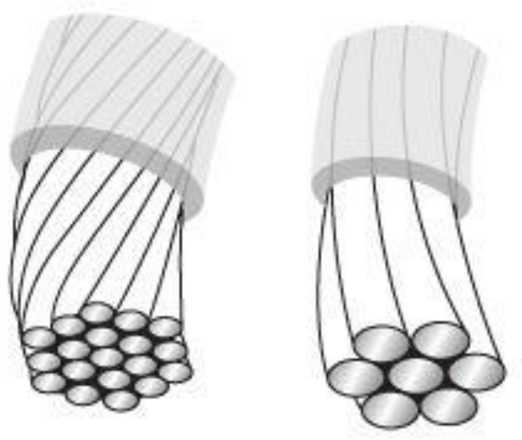

Figure 51 - Beadalon beading wire, Left: 19 strand, Right: 7 strand

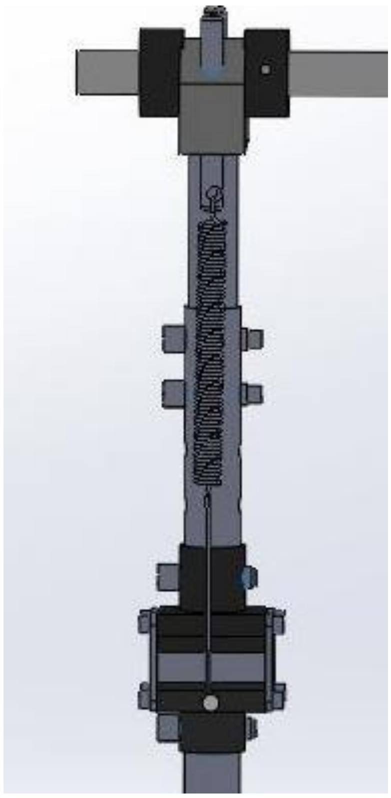

Figure 52 - Knee spring system

An initial elongation is necessitated as tensional springs cannot be compressed from free length. Hence to allow a minimum flexion angle the tensional springs are given an initial elongation. Moreover, the initial elongation of the springs dictates the various forces present in the knee joint and changing this variable by a few millimetres affects the behaviour of the walker.

Springs of four varying stiffnesses were chosen to be tested. Since this design has not been tested in the past, there was no reference to base upon the range of the spring stiffness that should be used. Hence an effort was made to cover a range of springs. The table below outlines the stiffness of the selected springs.

Table 3 – Stiffness of the knee springs

Spring Number	Spring Stiffness (N/m)
1	1030
2	1430
3	1770
4	1950

Similarly, since no previous study has adapted the 4-bar design on passive walkers, the three angles to be tested was based on changing the position of the ICR of the knee from the anterior to the posterior of the ground reaction force. The angles chosen were 0, 2, and 5 degrees.

3.3.4 Extendable Legs

The extendable legs are made using a section of crutches as these have very stable telescopic legs with various height settings. This feature provides the ability to change the bipedal walker’s height with relative ease during the experiment. They are also made with light weight strong aluminium hence fitting the design specifications of the legs. Additionally, this would reduce the total manufacturing time required.

The extendable legs are fixed to the rest of the walker using M5 bolts. These bolts are also used to lock the legs in the chosen height settings to provide further stability by reducing the vibrations induced during the testing.

3.3.5 The Hips

The hips are made of aluminium and it is designed to accommodate a shaft that connects both the legs, and the screw-nut supporting the spring-system. The size of the hips is designed to be bigger in order to increase the mass in this region. At the bottom of the hip, the top end of the leg is fitted by welding them together. A bushing is placed inside the hole through which the shaft passes to allow for frictionless rotation.

The hips are locked in place using two retainers made of Delrin. The distance between the legs can be easily changed by unlocking the retainers and moving them to the desired location. The shaft is 300 mm long hence many different configurations can be tested.

3.4 Conclusion

The design of this bipedal takes inspiration from previously successfull studies in hopes of building upon and furthering the understanding of passive walkers. The functionality of each part was thoroughly assessed during the design process and a lot of effort was made to make a robust walker with flexibility to adapt to any change in the experimental protocol.

Several design iterations were made before and some during the manufacturing process in order to improve upon the faults discovered after the initial design. This was critical as any new part that required to be manufactured would delay the experimentation stage. The two key components of the design are the ankle-spring and knee-spring system. The remaining parts are designed around these two components. The working of these systems is further explored in the later chapters.

Chapter 4 - Manufacturing and Assembly Of Passive Dynamic Walker

4.1 Introduction

The 3-D Bipedal walker designed was manufactured in the Mechanical workshop at the University of Manchester. This stage was carried out in collaboration with several technicians. During the manufacturing process there were further iterations and changes made to the design in order to reduce the total manufacturing time and the materials required. Most of the material required was available at the workshop while some of the parts such as the universal joint and the springs had to be purchased.

The success of the walker largely depends on the symmetry between the two legs. If there are slight anatomical differences between the left and the right leg in humans, the gait is considerably altered. Humans are able to make adjustments in order to recreate a stable gait pattern. However, if the bipedal walker is influenced by such variables it will not be able to recover. Hence the manufacturing and the assembly process is crucial to the success of the walker.

Great attention must be paid to each leg while assembling the different parts together to ensure every part is connected in the specified manner. Figure below shows the bipedal walker completely manufactured and assembled.

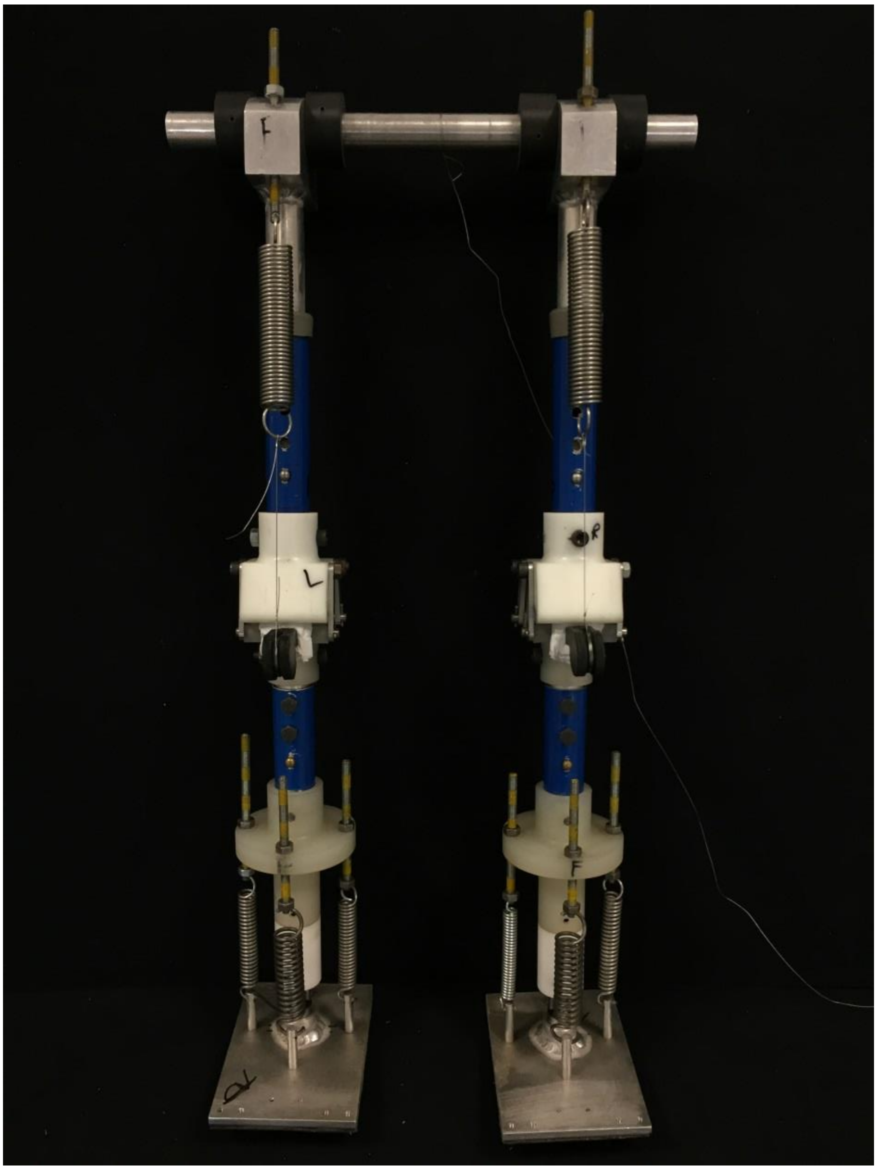

Figure 53 - 3D Bipedal walker with Knee and Ankle spring systems

4.2 Manufacturing Issues

Various mistakes occurred during the manufacturing period. This delayed the testing stage by some time as it was essential to correct these before moving to the next stage. Some of the issues are highlighted here.

Some problems were created due to using an inferior method of manufacturing for some of the parts. For instance, it was initially decided to manufacture some of the parts, such as the base of the foot with all the components or the hip with the top part of the leg, as one unit through CNC milling to increase accuracy and strength of the unit; the alternative had to be settled upon due to lack of material and time in the workshop. This caused some of the structures to have low structural integrity. For instance, the bars on the foot were manufactured separately and then fit into the foot. When the walker was fitted with the stiffest springs to analyse any problems that could arise, the joint between the bar and the foot failed. Further reinforcements were required in order to make sure these parts don’t break while testing.

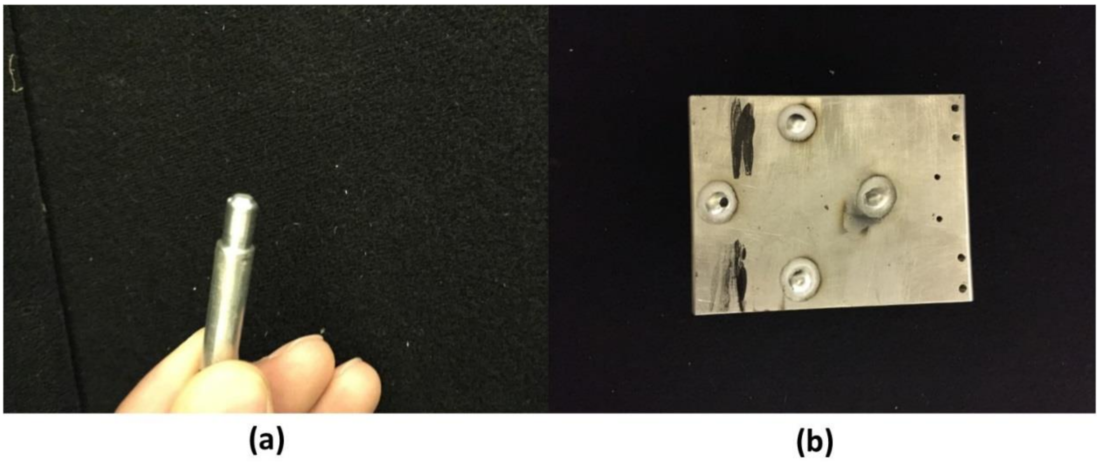

Figure 54 – (a) Broken bar (b) Bars are welded from the bottom part of the foot

However, the posterior support structure of the right leg failed during the kneed-leg testing. In order to reattach the support structure the sole of the foot had to be removed using a sanding machine in order to weld the bottom of the structure to the base of the foot. An error was made in this stage as the structure was not set completely parallel to the foot. Due to this there was a slight inclination of the structure that caused the walker to fail. Due to the inclination of the structure towards the right, shown in the figure below, the leg was not able to recover after the roll motion leading to an increase in instability and eventual failure. Once this issue was noted, it was rectified by interchanging the left foot with the right. This was done as the alternative of re-welding would further delay the experimental stage.

Results from locked knee walker demonstrated that the lateral position was the primary influencer of stability in the coronal plane (see chapter 6 for more details). Hence interchanging the feet would now entail the erroneous inclination is towards the medial plane, with the appropriate adjustment of the spring stiffness the walker was able to display normal gait patterns again.

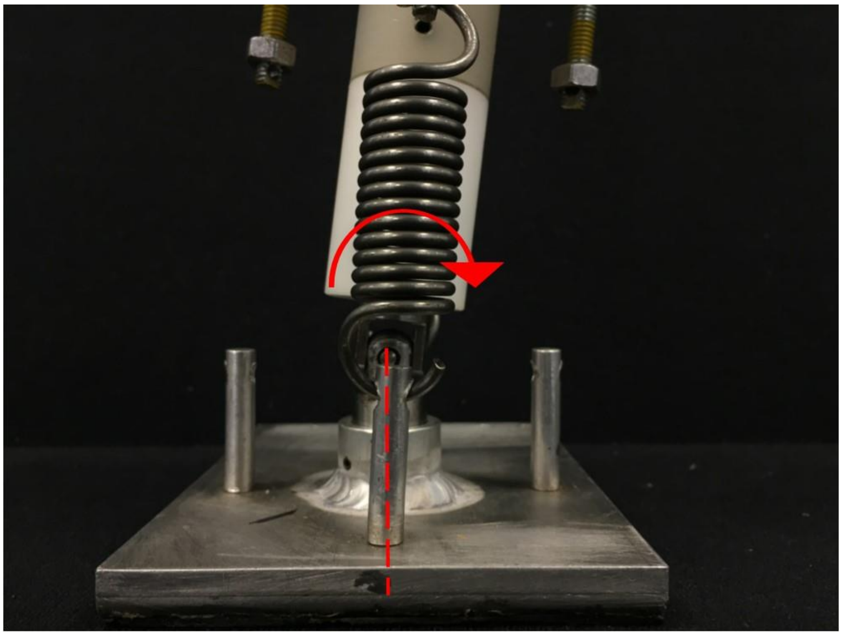

Figure 55 - Support bar not set properly before welding

Bushings in the hips were replaced with bearings. The bushing was not properly fit in creating dents on the inner surface resulting in friction.

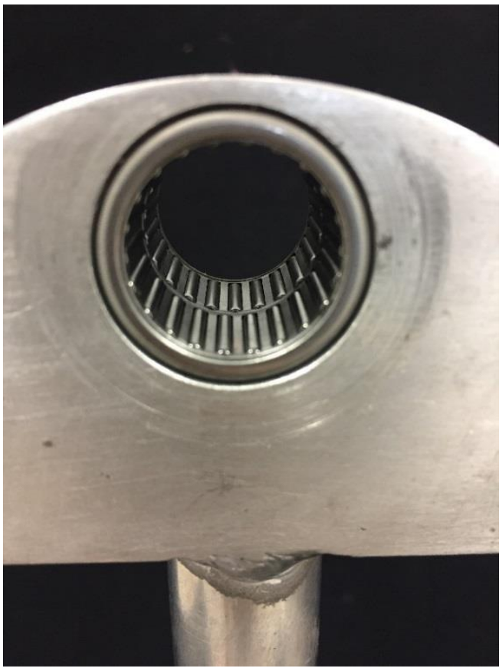

Figure 56 – New roller bearings installed

The parts of the crutches selected as the telescopic legs faced a lot of issues as well. Contrary to the initial assumption, the crutches did not have a good fit leading to vibrations. The joint between the lower knee and the leg was a point that suffered the most hence it was decided to use Araldite to fix the parts together firmly. This greatly reduced the oscillation of the legs.

For the other parts of the legs, bolts were used to fix them in place firmly.

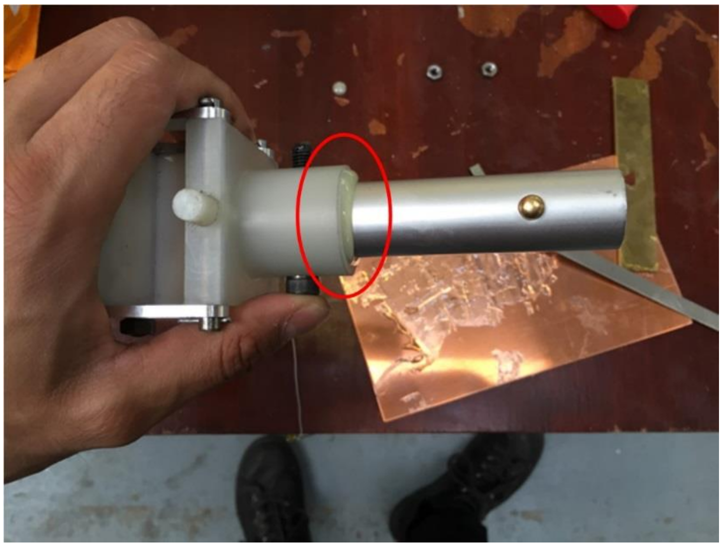

Figure 57 – Leg fixed with the lower knee with Araldite

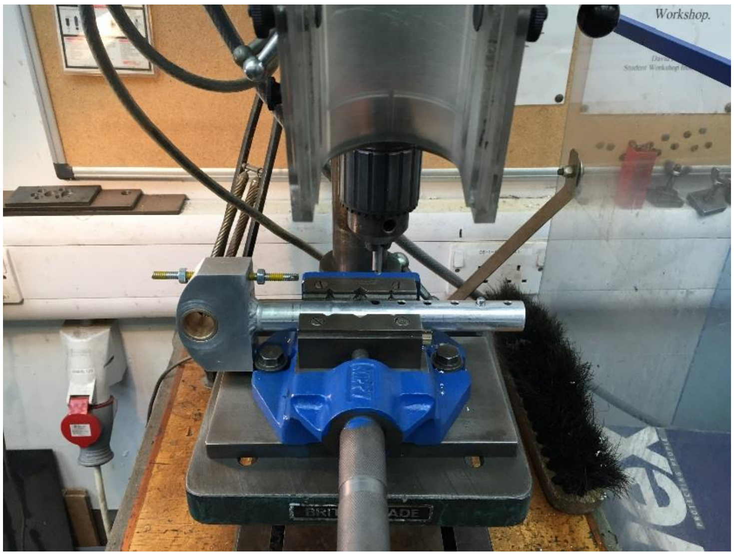

Figure 58 – Drilling holes in the leg to accommodate the bolts

There was a mistake in dimensioning the legs of the walker leading to legs of different height. The difference in height was very little and not apparent at first look. However due to this the walker was unable to walk. This was fixed by manufacturing new parts.

4.3 Modifications

The co-efficient of friction between the base of the foot and the surface of the ramp was very low leading to extreme slipping.

Hence it was decided to fix a thin rubber material with a thickness of 2 mm that would be able to increase the friction to the desired value. Multipurpose “impact” adhesive was used to fix both the parts together.

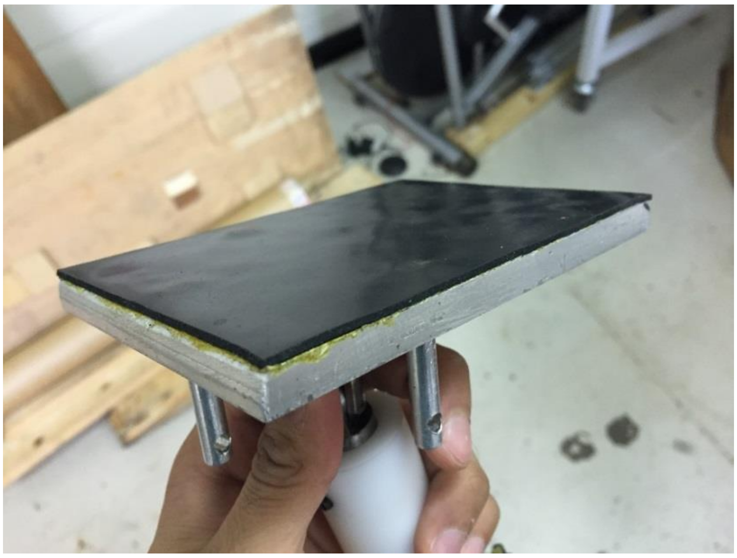

Figure 59 – Soles of the foot fixed with a rubber sheet

Preliminary test results reflected a high sensitivity towards the initial elongation of the springs. In order to change and note down the initial elongations with higher precision, it was decided to spray paint the support screws every 1 cm. This would provide a quick visual guide to estimate the initial elongation of the various springs.

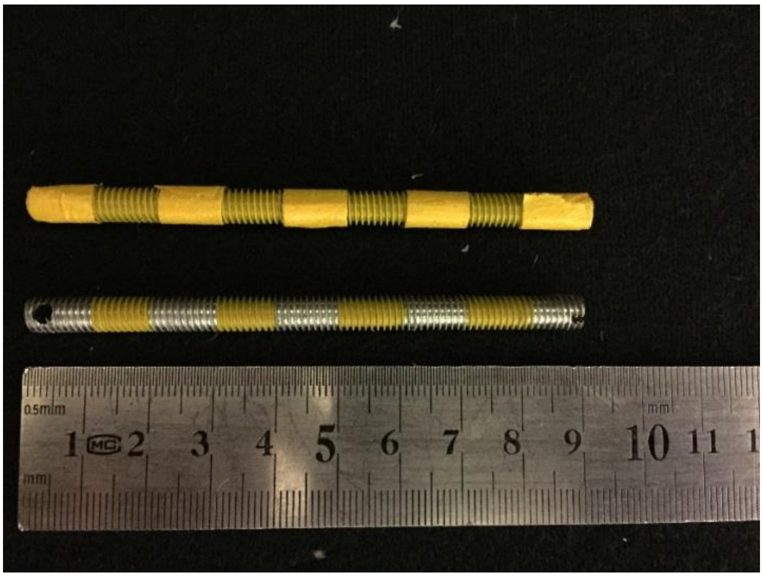

Figure 60 Support screws are spray painted

4.4 Conclusion

The manufacturing of the walker was carried out with various workshop staff members. A lot of delay and problems occurred due to manufacturing issues, however all problems were rectified before the tests began. Design considerations that were not initially accounted for were improved upon and eventually a robust kneed walker ready for experimental analysis was built. During the assembly stage, it was crucial to check for parts symmetry as any small changes could lead to disturbances. Furthermore, a few modifications were made in order to improve the testing stage.

Chapter 5 - Experimental Testing

5.1 Introduction

This chapter covers the experimental set-up and methodology used for creating and assessing the gait of the bipedal walker. The experimental set-up is simple as it consists of only four key elements; the bipedal walker outlined in the previous chapter, a ramp with an adjustable inclination angle, equipment for data gathering, and a PC to process and analyse the data. The key points defining the criteria used for measuring the results of the tests are outlined as well.

Figure 61 - Experimental testing of the bipedal walker

The parameters chosen for the bipedal were not determined using simulation but it was done experimentally and by referencing the previous iterations of this walker due to simulation being highly complex for such a system. Moreover, even if the scope of the project permitted time for simulation, it has been proven to not accurately represent experimental results. Therefore, preliminary tests were carried out and studied through a trial and error process. The results of the different configurations were analysed to finalise the walker's parameters. The different variables affecting the walker are explained in detail below.

The most crucial issues encountered during pilot tests and the modifications made in order to resolve these issues are also discussed. Furthermore, the two parts that are being tested are the ankle joint and the knee joint. The effect of the ankle joint on the walker is first tested separately by locking the knees. A kneed-walker has more degrees of freedom compared to a straight legged walker; hence the validation tests are first run to verify the walker is able to achieve a stable gait without the knees as this would reduce the errors from being compounded. Once the results of these tests are analysed and validated with previous studies, the final tests of the kneed bipedal walker are carried out. This would also allow for a comparative analysis between the performance of the straight-legged walker and the walker with knees.

5.2 Equipment and Data Acquisition

5.2.1 The Ramp

The main equipment required apart from the walker is a ramp. The slope, friction, and damping of the ramp are key variables that affect the performance of the walker. The friction of the ramp surface can be altered at a later stage by using sanding equipment. However, the ability to change the ramp angle and the ramp's sturdiness need to be considered during the set up. The length of the ramp is the maximum distance the walker can traverse hence it was decided the minimum length of the ramp needed to be 200 cm.

Several iterations of the ramp set-up were tested. The first ramp was built using three pieces of plywood. However, it was very difficult to build an even surface using three different boards. A slight variation between one of the three boards would affect the walker drastically. Thus it was decided to use one full piece of wood. But one of the drawbacks of using big continuous piece of plywood for the entire ramp is that when set-up at an angle bending of the ramp is observed, shown in figure 65. This will affect the reaction forces experienced by the walker leading to failure.

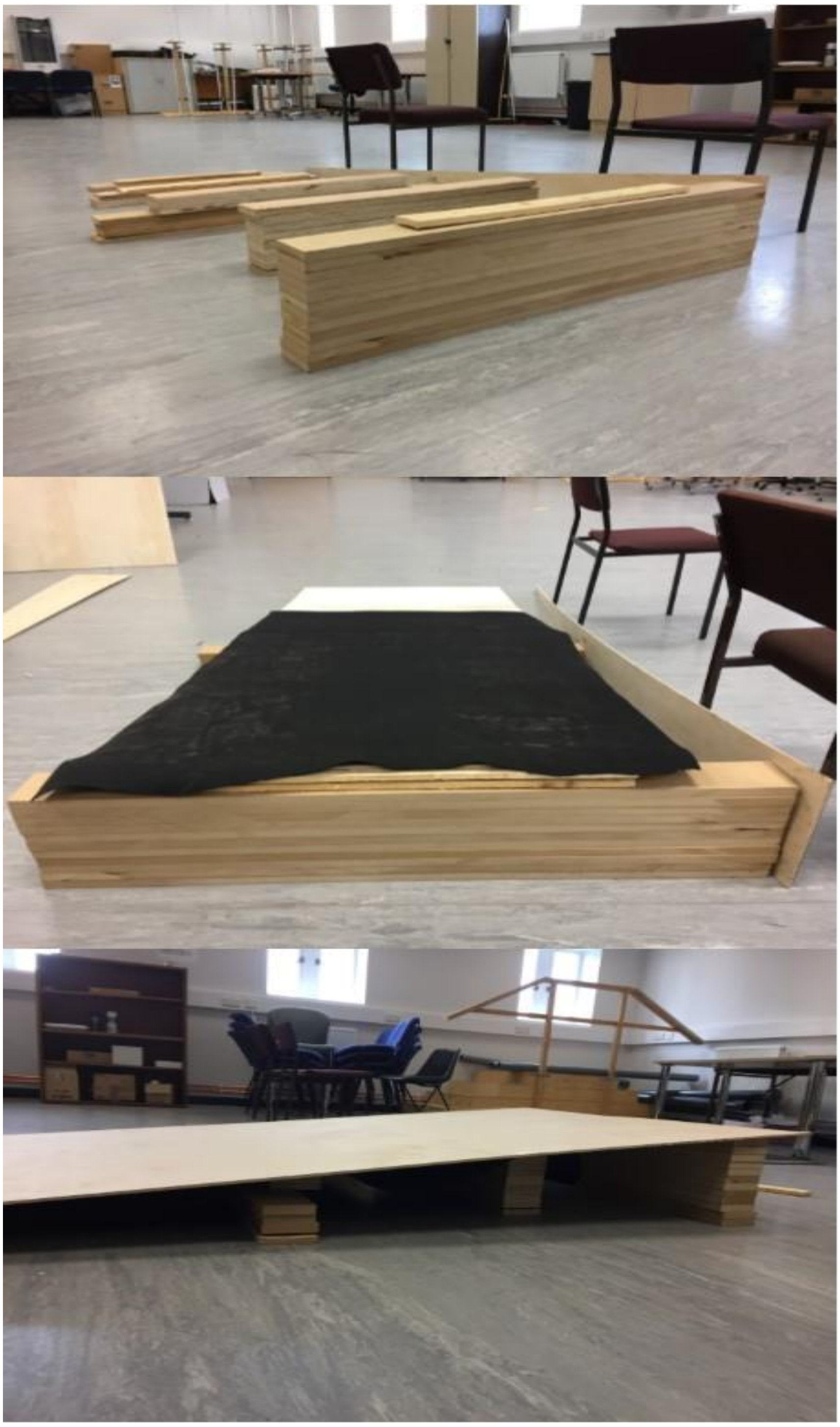

Figure 62 – Ramp set-up used for the experiments (note the rubber sheet in the second picture)

To reduce the bending, support structures need to be placed at the appropriate locations and the ramp must have a sufficient thickness. The figure below shows the ramp used for the experiments being set up. It is strong plywood, measuring 244 x 122 cm with a thickness of 0.6 cm. The ramp provides sufficient surface area for testing the walker and the thickness ensures there is no bending of the ramp at points without support. The ramp is supported at four points and a rubber sheet is placed between the ramp and the support structures. This is done to reduce any vibrations created by the walker as this would lead to collisional indeterminacy. The angle of the ramp can be easily changed by adding or removing parts of the support structure.

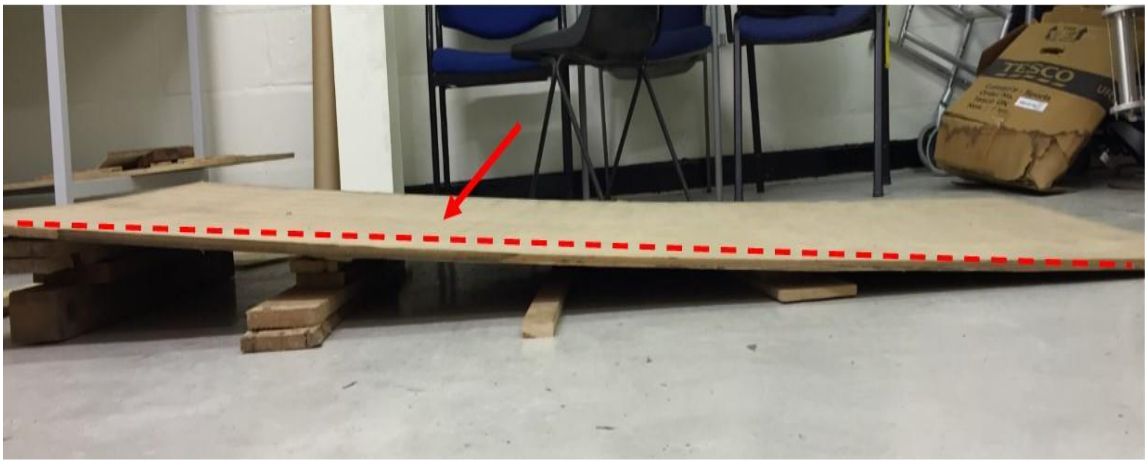

Figure 63 – Bending of the ramp

5.2.2 Data Gathering

Video recording was used for all the experiments to analyse individual trials. This was deemed to have sufficient accuracy due to the ability to study the video recording frame by frame. More sophisticated equipment could have been used to improve the accuracy of certain measurements such as velocity and step length. However these systems are relatively more complex to set-up while offering little benefit towards the aim of the project. This method is also considerably more accurate than using a stop watch and visual inspection.

An IPhone 5 was used for all the recordings. This was mounted on a tripod and was either set up at the side or at the front of the ramp. Due to the availability of only one recording device, multiple angles could not be recorded simultaneously. Measurements were made by markings made on the walker and a measuring tape was fixed on the side of the walker for reference.

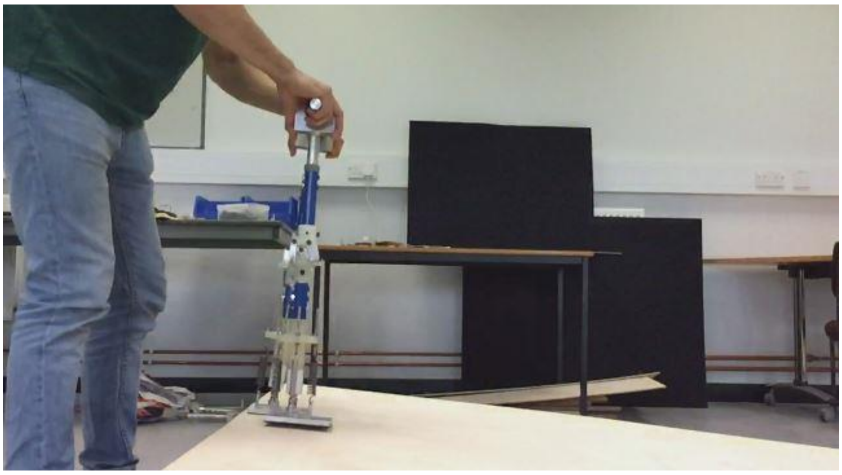

Figure 64 - Walker testing from side view

5.2.3 The Key Measurements

The following points define the criteria used for measuring the results of the tests.

1. Number of steps: This is counted from the first heel-strike produced after the walker has been launched. It is important to ensure the point of contact of the heel-strike is ahead of the stance leg. Also a successful step comprises of both the swing and stance phase. All the steps until the walker stops or falls down are counted. The walker stops due to insufficient energy and comes to a complete stop after a gradual deceleration. In some cases, the walker will take many short steps before coming to a complete stop. These steps are not counted in such instances. The walker falls down differently when the knee is locked and unlocked. But it mostly happens due to an imbalance of the forces around the springs.
2. Distance Traversed: The distance travelled is measured using the markings on the ramp and is read in relation to the position of the toe upon stationary contact of the last step. The least count of the measuring tape used is 0.1 cm and hence it is accurate for measuring the distance.
3. Time consumed: The time between the initial release until either the walker stops or loses stability is recorded as the time consumed.

5.3 Preliminary Calibration

Preliminary tests are carried out to find the best walker configurations. To achieve this, the bipedal is taken to its limits to analyse the effects of the different variables. The walking motion of the walker can be assumed as a problem that needs to be solved for each set of determined variables. Hence a change in any of the variables would require a readjustment of the walker settings. As outlined in the previous chapters, the walker is designed to accept a wide range of configurations in order to adapt to the different conditions.

There are three main sub sets of the variables present in this experiment. The first are the external variables that include the angle of the ramp, the friction of the ramp surface, and the damping capabilities. The second are the internal variables which comprises of the different walker settings, i.e. knee and ankle spring configuration, the total height of the walker, ratio between upper and lower legs, and leg separation. Finally, the third sub-set is the type of walking motion. The two main types of walking motion tested in literature are short and long step testing. The step length during the launch of the walker determines the type of motion the walker will exhibit. For this research only short step testing was considered.

Lastly, the protocol to be used for every launch was also finalised during this stage and is outlined below.

5.3.1 Variables Affecting the Walking Motion

1. Height of the Walker

All the different leg length combinations are tested in order to find the most optimal height for the walker. The total height of the walker affects the dynamics of the system as it changes the COM. While testing for the optimum height, it must be taken into account that the walker can be adjusted from above (thigh) and below (shank) the knee. Hence it is crucial that the best height setting also reflects a reasonable thigh to shank ratio. The thigh has 4 different height settings while the shank has 3. This means the walker has a total of twelve different configurations available.

The bipedal walker failed to achieve a stable walking motion when testing it under the tallest leg configuration, which makes it 695 mm. This is due to the inability of the walker to balance the forces generated at the hips. Ultimately, the most stable walking motion was achieved at a height 596 mm which is the shortest setting.

2. <u>Leg Separation</u>

A balanced separation of the legs is required to allow roll motion within a certain range of angles. If the legs are too far apart it will reduce the range of allowable roll angles. The hip retainers allowed for an easy change of this parameter. For the experiments the distance between the legs was set at 100 mm.

3. <u>Friction of the Ramp</u>

Although the soles of the walker's feet were fitted with rubber padding as the co-efficient of friction for aluminium is low, it was still not sufficient to completely eliminate slipping. Hence the surface of the ramp was sanded with increasing number of roughness to generate the right amount of friction. If the surface is too rough, the walker will lose energy faster and will hence take fewer steps.

4. <u>Angle of the Ramp</u>

The slope of the ramp has a significant impact on the performance of the walker. When the slope is too shallow, the walker will not even be able to take one step. The front moment generated when the angle of the ramp was over 8° was too high for the posterior ankle springs to balance. The angle used in the experiments was 6°.

5.3.2 Launching

The method by which the walker is launched for every test is another variable that affects the performance of the walker. Since this is done manually, it is essential the launching steps are formalised to improve consistency among every tests conducted. This does not imply that specific initial conditions for the launching can be stated. The walker must be launched in a manner such that the conditions at release are representative of the corresponding gate cycle for those specific parameters. The steps to be followed in most cases are outlined below.

1. The initial stance foot must first be positioned parallel to the ramp such that the toes are just behind the starting line.
2. The support leg is then tilted to the side while maintaining contact with the ramp.

3. The hip of the initial swing leg should then be rotated to place the foot ahead of the stance leg.
4. Some cases might require moving the shaft slightly forward to enhance the moment.
5. The robot should be released while the swing leg is still in motion.

It was not possible to determine the precise angular displacements of the hip and swing leg at every launch and hence the experience of the launcher is important for successful results.

5.4 Ankle-Spring Tests

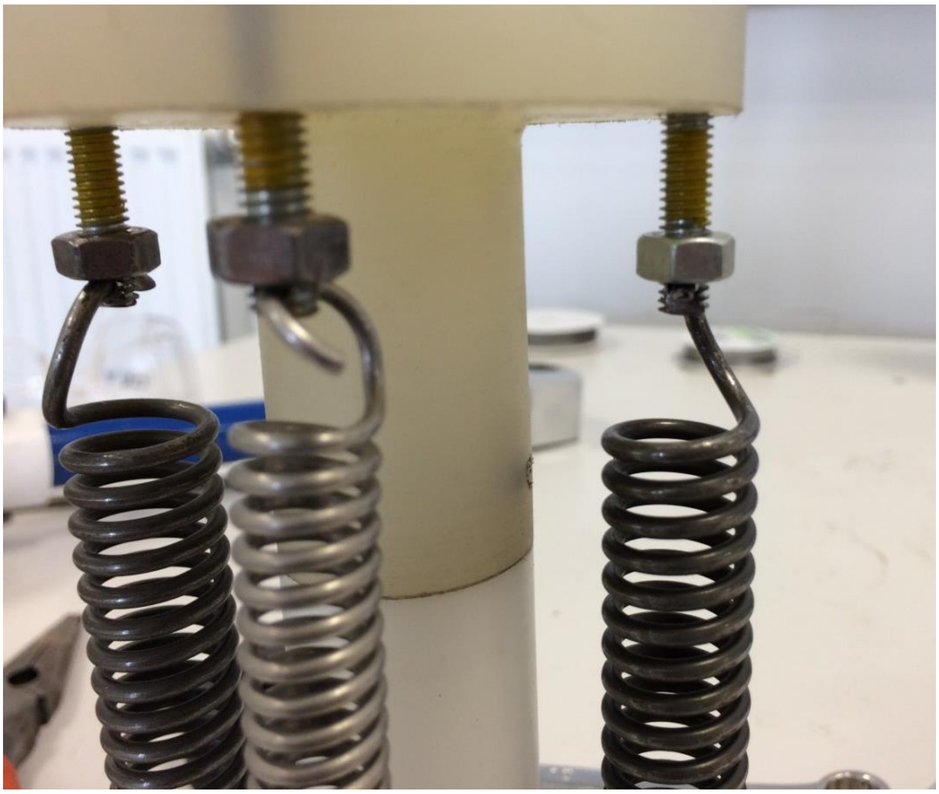

Figure 65 - Ankle joint installed with springs

Before the walker with knees is tested, it was important to find the best spring configurations for the ankle joint. In order to validate the walker with previous studies, and to analyse and experimentally observe the effects of using different spring stiffness; it was decided to test springs with 3 different stiffness. Since the three springs can be located at any 4 positions of the ankle joint, the total number of possible configurations equals to 81. The following figure shows and marks the four different spring locations.

The springs are numbered from 1 – 3 in the order of increasing stiffness. The notation used is as follows:

[Posterior, Anterior, Lateral, Medial]

The list of all possible configurations is presented in the appendix.

After installing the springs, the elongation is then adjusted using a trial and error process. Every configuration is tested several times as it is difficult to launch the walker accurately even for trained hands. Hence, only the first three right launches are recorded. The results are then averaged to get an overview of the success or failure of the particular spring configuration. The graphs on the following page have the average values for all the 81 tests.

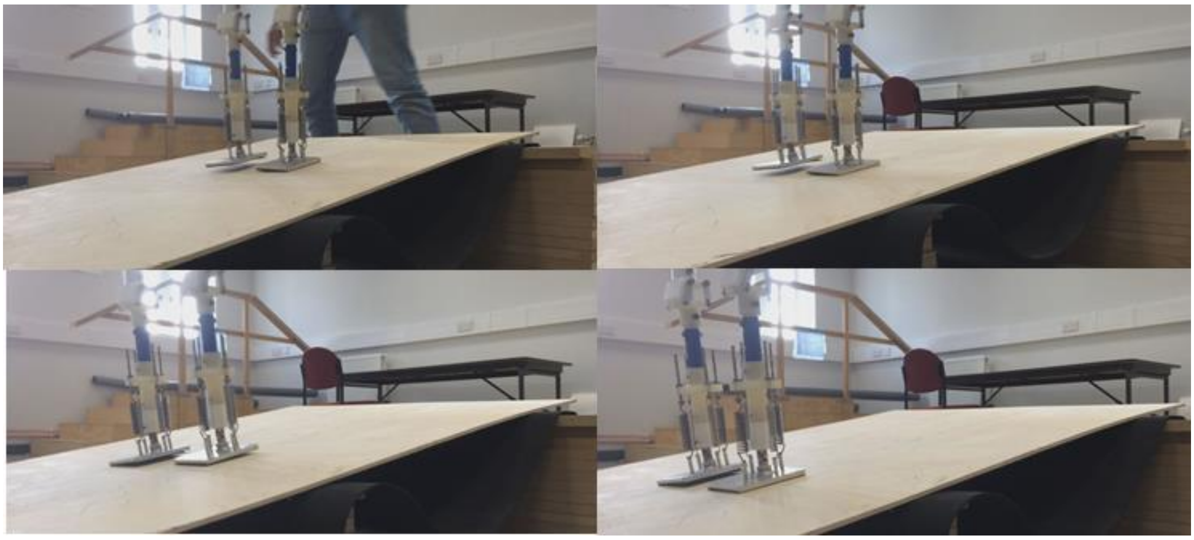

Figure 66 – Walking sequence from ankle-spring testing

It can be observed that the most successful result was obtained for testing ID 77 which is using the spring configuration [3, 3, 2, 2]. It was able to walk with a stable gait motion up to a distance of 230 cm with the average number of steps being 55.5. It is also observed that the walker starts performing more effectively after test 46 suggesting that the bipedal walker requires a minimum stiffness, especially in the sagittal plane, in order to achieve stable walking. Graphs of number steps taken and distance travelled are shown below. A further analysis of the data is done in the next chapter.

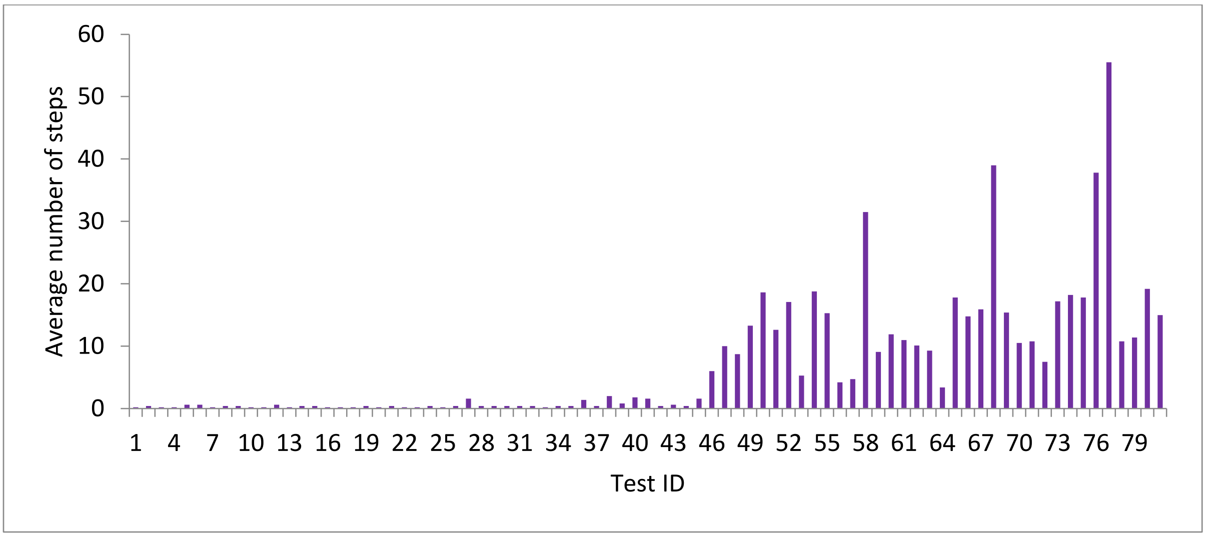

Figure 67 Ankle spring testing – Number of steps

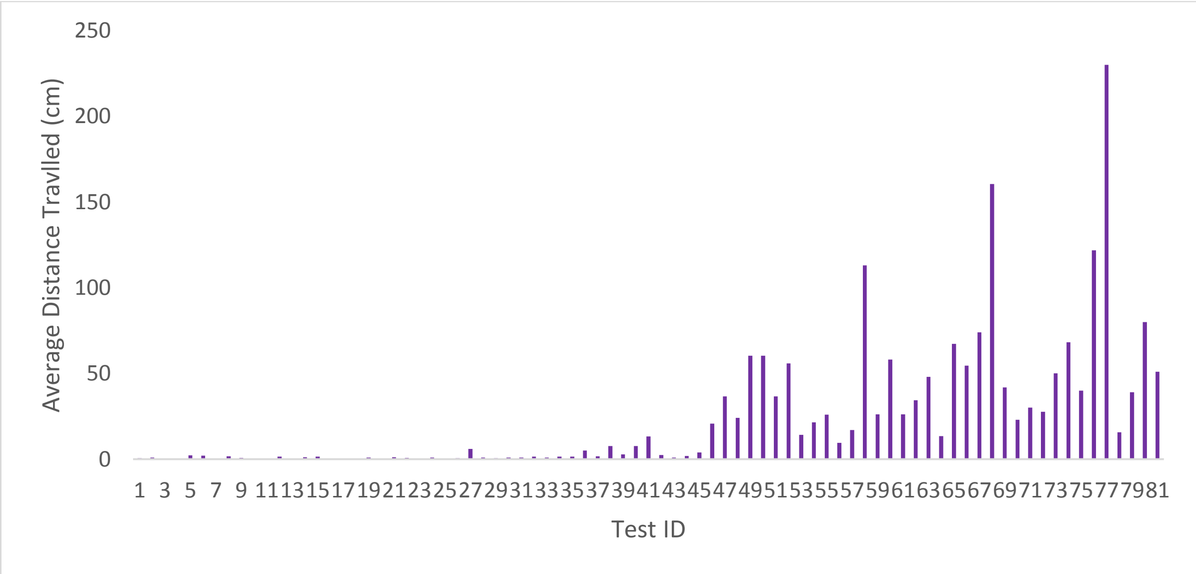

Figure 68 Ankle spring testing - Distance

These results are very similar to the results obtained by the previous iterations of the walker. The best ankle-spring configuration in the study done by Tobajas (2013) was also [3, 3, 2, 2]. Hence the performance of the locked-knee walker was validated and the next phase of the tests could begin.

5.5 Knee-Spring Tests

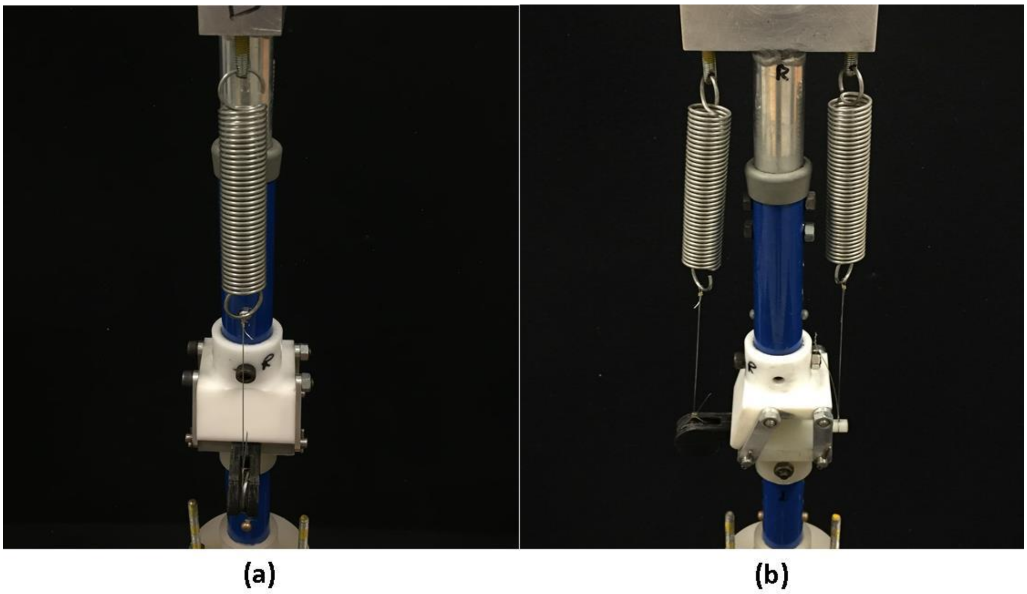

Figure 69 - Knee-Spring system (a) Front view (b) Side view

After finding the best specifications of the walker and validating the ankle spring system, the final tests focusing on the knee joint were carried out. The objective is to find the best spring configurations able to perform the most stable walking motion. Furthermore, the effect of changing the initial angle of the knee is also investigated. This part of the research was especially challenging as slight variations in any of the parameters would affect the performance of the walker. The first round of experiments was not successful as the knee joint was not able to engage. After careful analysis of the design, it was decided to make alterations to the knee-spring system, which was necessitated during this stage to enable kneed walking of the bipedal.

Initially it was decided to connect the other end of the springs to the lower part of knee at a distance of 10 mm however this lead to poor results. During the initial tests with unlocked-knees it was observed that the walker failed to take any steps with the knee engaged. The mechanism would either flex prematurely at stance or not flex at all.

When the spring system is in place, the spring in the anterior position exerts force on the connecting wire making it very stiff. Even though flexibility was considered during material selection, due to the close proximity to the knee the forces generated are not enough to push the stiff wire around and flex the knee. Hence another part was designed to attach the wire. The new design allows the spring to be positioned at a distance of 20 mm or 25 mm. The original design can be seen next to the proposed solution in the figure below.

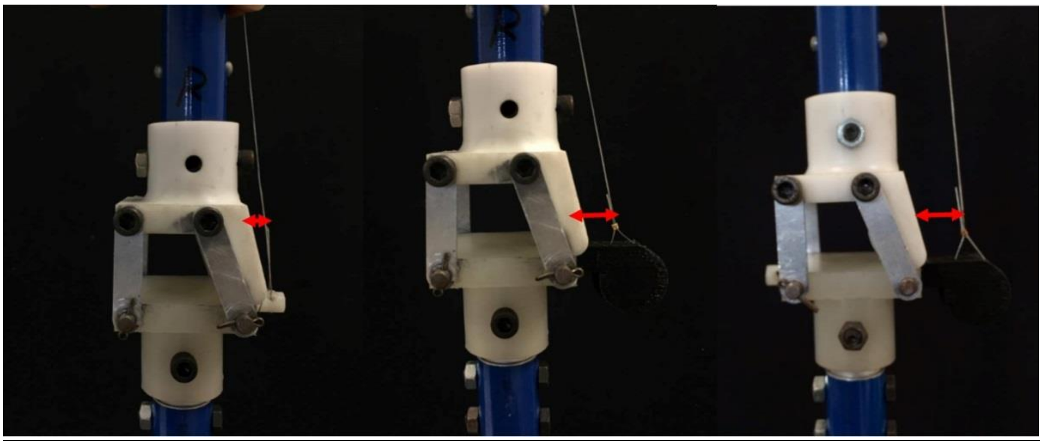

Figure 70 – The three different distances tested

The data obtained from testing the new designs is presented below along with the data from the original design. As it can be seen there is a significant improvement when the distance is increase from 10 mm to 20 mm. However, when the distance is further increased there is a drop in the improvement observed earlier. Hence a distance of 20 mm was finally chosen.

Table 4 – Data obtained from pilot tests

Testing ID	Distance Of Spring System from Knee (mm)	Number of Steps
1	10	0.8
2	20	3.2
3	25	1.2

Hence it was decided to adopt this new design with the distance of 20 mm for the main experiments. Four springs of different stiffness were selected for this stage. The fifth option was to test it without any spring. This would help highlight the role of the anterior and posterior positions of the spring. Each spring can either be located anterior or posterior to the knee. In addition, to study the effects of changing the initial angle of the knee on the walking motion, three different angles of the knee were tested under all spring configurations. Thus a total of

72 tests were carried out, 24 tests per angle for all spring configurations.

Table 5 - Initial angle of the knees tested

Set Number	Initial Angle of Knee
1	0°
2	>2°
3	>5°

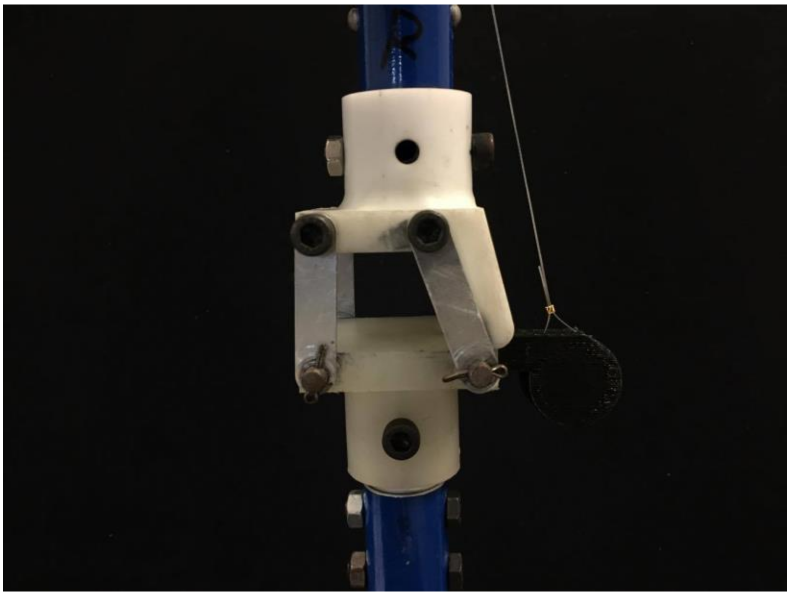

Figure 71 - Knee with initial angle 0°

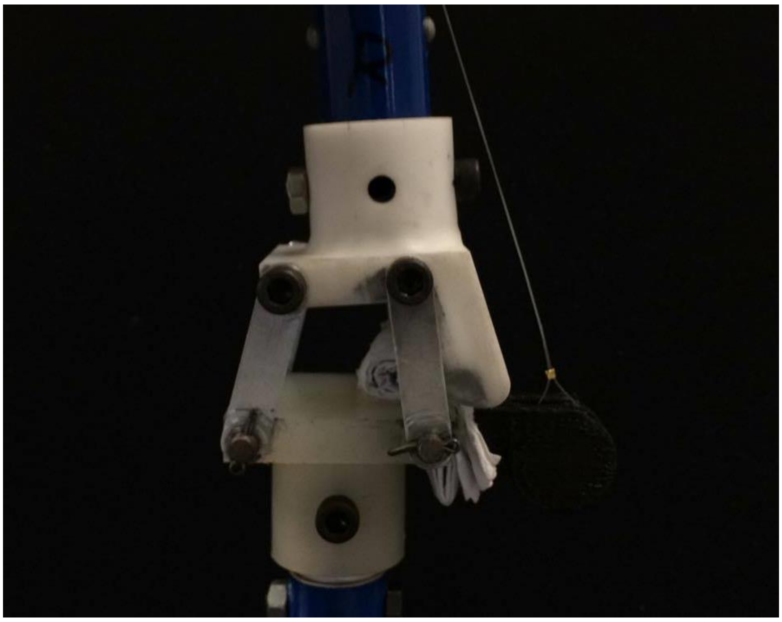

Figure 72 - Knee with initial angle > 2°

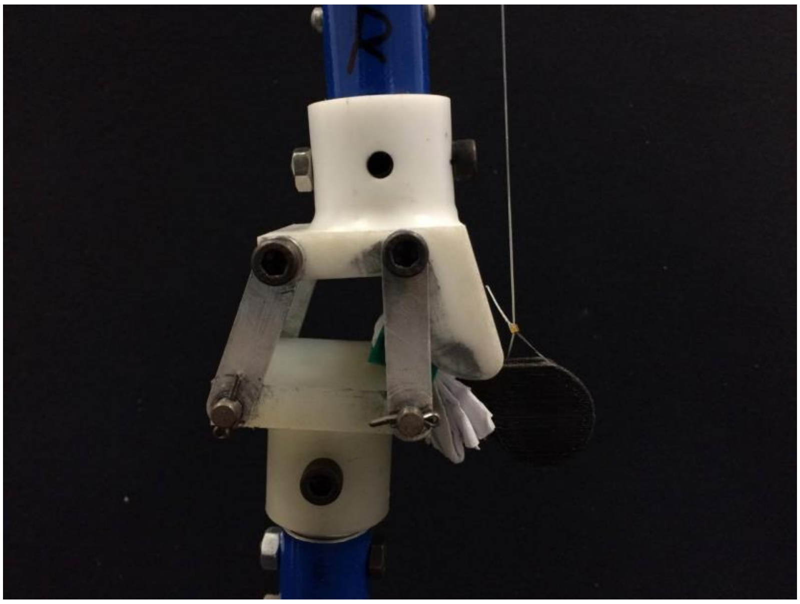

Figure 73 - Knee with initial angle > 5°

The table below shows the stiffness of the springs selected:

Table 6 - Stiffness of knee springs

Spring Number	Spring Stiffness (N/m)
1	1030
2	1430
3	1770
4	1950

Notation used is as follows:

Set Number – [Anterior, Posterior] / [Test Number]

The following steps outline the testing procedure:

1. Set the angle of the knee and install the springs
2. Ensure both the legs are symmetrical in all aspects and the feet are parallel to the ground
3. Place the walker at the starting position on the ramp making sure the stance foot is parallel to the starting line.
4. Test the walker through a trial and error process, threading the springs up or down until the best configuration is found

5. After the right elongation of the springs is found, record the first 5 launches.
6. Change for new spring configuration
7. After testing all the configurations, repeat the entire procedure for the other angles.

It must be noted that the walker is tested with the process of trial and error; also due to the sensitivity of the walker to the different variables it is very difficult to accurately launch the walker every time. Moreover, the distribution of forces between the ankle and the knee joint are crucial in order to activate the knee. This is largely dependent on the correct launching of the walker. Considering this the walker was tested several times for each case as a sustainable walking pattern was not found. The five readings were taken from the tests in which the walker was correctly released and the knees were activated to a satisfactory level. The results are then averaged to get an overview of the success or failure of the particular spring configuration. The following table has the average values of the number of steps taken for all the 72 tests.

Table 7 - Tests results showing number of steps for the knee springs

Test ID	Anterior	Posterior	Set 1	Set 2	Set 3
1	0	1	0.2	0	0
2	0	2	0.2	0	0
3	0	3	0	0	0
4	0	4	0	0	0
5	1	0	0.4	13.4	11.6
6	1	1	0.6	12	9.8
7	1	2	1.4	8.6	6
8	1	3	1.8	2	0
9	1	4	0.8	0	0
10	2	0	0.2	16.4	14.6
11	2	1	0.4	30.6	15
12	2	2	2.2	22	12.6
13	2	3	4	18.4	6.8

14	2	4	3.6	6	0
15	3	0	0	19	16
16	3	1	0.2	23.2	17.4
17	3	2	0.6	26.8	8
18	3	3	1.2	12	2
19	3	4	1	8.2	0.6
20	4	0	0	12	15.2
21	4	1	0	14	17
22	4	2	0.8	18.8	13.6
23	4	3	2	8.6	4.4
24	4	4	0	7	0.8

The following table shows the results of test 2 – [10].

Launch	Number of Steps	Time (sec)	Distance (cm)
1	21	9	108
2	15	7	95
3	11	4	60.5
4	19	9	104
5	16	7	93
Average	**16.4**	**7.2**	**92.1**

It can be observed that test 2 – [11] has the best spring configuration as it took an average of 30.6 steps. There is also a considerable difference between the different sets. The second set shows a significant improvement compared to the first suggesting the need for an initial angle while performing kneed gait. However, a further increase of the angle did not lead to better results in these tests. This could be due to the springs not having sufficient stiffness to accommodate for the higher degree of engagement of the knee. The following graph represents the number of steps taken for all the tests, where test number 1-24 represents set 1, 25 – 49 represents set 2, and 50 – 72 represents set 3.

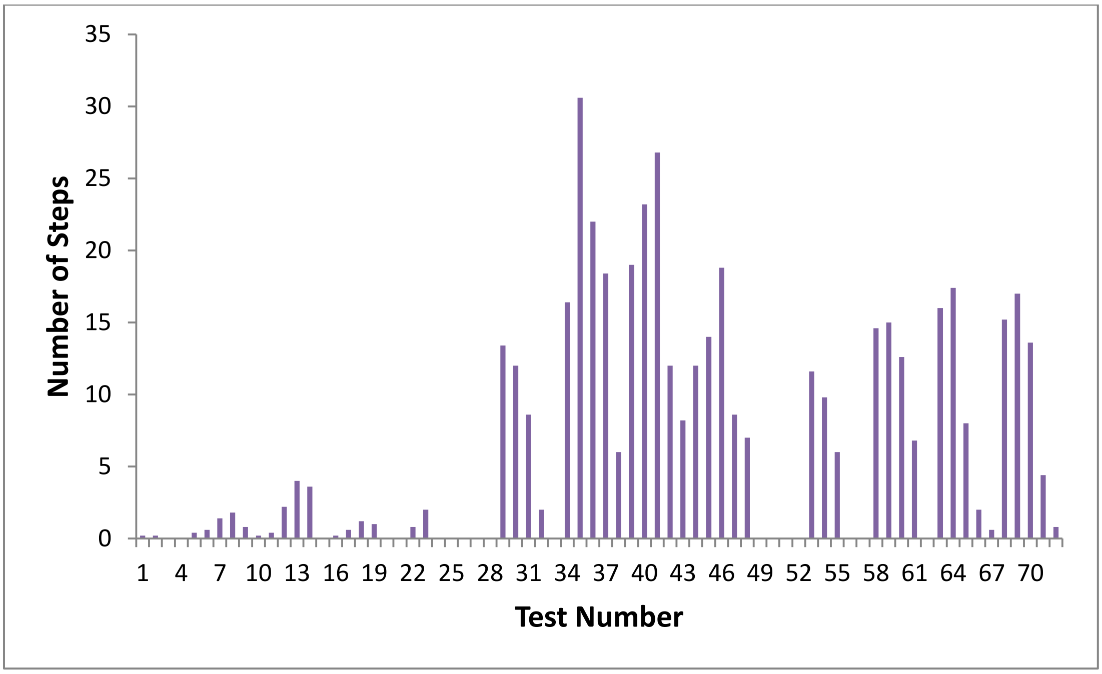

Figure 74 - Number of steps for all the tests

Chapter 6 - Analysis and Discussion

6.1 Introduction

This chapter presents and discusses the results of ankle and knee spring tests. The straight legged walker's knees were locked while conducting the tests and the effects of the different spring configurations on the different positions is analysed. For kneed walking the effects of the different springs on each position for the three angles is discussed along with an attempt at analysing the mechanics of the joint. Furthermore, a comparative analysis is performed between the different angles comparing the best results for each case. This provides the opportunity to determine the variables affecting kneed gait. The results from ankle spring and knee spring tests are also compared. It should be noted that in both instances the walker was unable to traverse the entire length of the ramp.

6.2 Analysis of Ankle-Spring Tests

The best spring configuration is test ID 77 with an average number of steps taken at 55.5 covering a distance of 230 cm which was the furthest distance covered. The next best configuration was test ID 68 with an average number of 39 steps covering a distance of 160.4 cm.

The graph below highlights the importance of the ankle stiffness in achieving stable gait. It can be seen that till testing ID 46 the walker barely takes a step; however once stiffer springs are introduced it becomes possible for the walker to achieve gait. Although a stable gait pattern can be observed in most cases, the walker only takes an average of 10 steps in most cases. There are a few configurations that perform much better, however these cases are the outliers.

Looking at data from test ID 47 onwards shows that in most cases a similar stability in gait pattern is achieved. Moreover, the four outlying cases i.e. Test ID 58, 68, 76, and 77 have spring number 3 in the posterior position. The walker was able to walk for at least 30 steps in only these four cases.

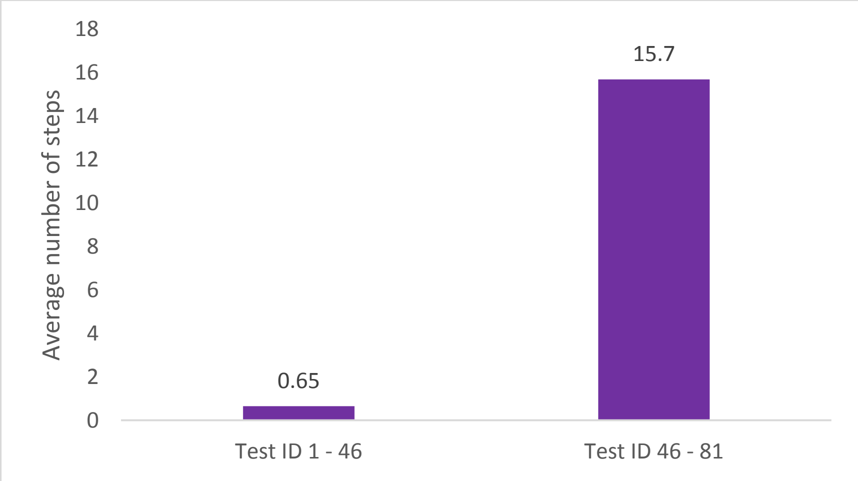

Figure 75 - Results comparison

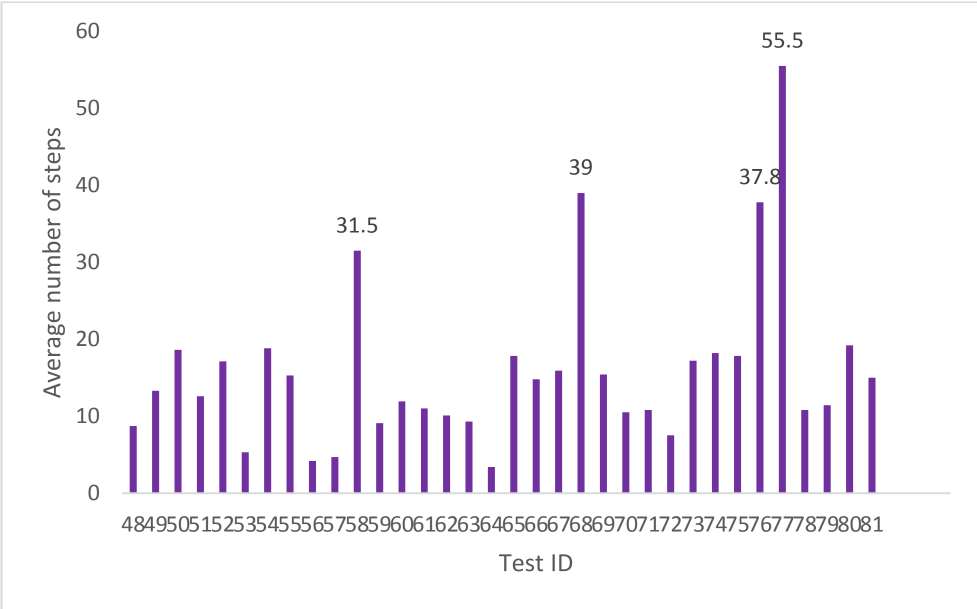

Figure 76 - Number of steps for Test ID 47-81

The ankle-spring system is further analysed in terms of its effect on the sagittal and the coronal planes. The sagittal plane comprises of the anterior and the posterior springs which control the pitch of the walker, i.e. the forward motion. The coronal plane consists of the lateral and medial springs which control the roll of the walker. The roll angle is crucial as it dictates the step length.

6.2.1 Sagittal Plane

The springs in the sagittal plane are responsible for controlling the pitch of the walker. Hence it is responsible for keeping the walker upright during the gait cycle, so the first step is to ensure the spring at this position has sufficient stiffness. The main reason for the significant improvement noticed from set

46 onwards is due to the placement of springs with higher stiffness in the sagittal plane. The heavy hips of the walker were designed to provide forward motion by enhancing the pendulum motion and the walker falls without the present of sufficient support. Furthermore, within the sagittal plane it can be clearly observed the posterior position has the main impact on the stability of the walker. For instance, Test ID 19 with the spring configuration [1, 3, 1, 1] takes an average of 0.4 steps whereas test ID 55 with the configuration [3, 1, 1, 1] is able to take an average of 15.3 steps. This implies a significant improvement in performance. However by placing a spring of higher stiffness in the anterior plane, the forces are better balanced which improves the performance of the walker. For example the number of steps taken for test ID 73 [3, 3, 1, 1] is 50. This is one of the outlying cases and a great improvement can be noticed by the addition of a stiffer spring in the anterior position.

This is however fairly intuitive, as the posterior spring produces a torque around the ankle joint while traversing down the slope by trying to return to its free length preventing the walker from falling down. Furthermore, the maximum pitch angle depends on the stiffness of the springs at the sagittal plane. The pitch angle affects the step length and velocity the walker takes. In stance, the pitch angle is zero. Successful pitch angles must be close to zero. If there is a positive pitch angle, the walker will tend to move faster however it will lose stability. Whereas negative angles make the robot walk with shorter steps. In conclusion, spring 3 performed the best in this plane.

6.2.2 Coronal Plane

The roll motion of the walker is dictated by the springs in the coronal plane. The maximum roll angle of the walker depends on the stiffness of the springs placed in these locations. The roll angle can be set by either compressing the lateral spring or extending the medial spring. The roll cycle of the walker must be the same as the swing cycle of the leg if stable gait is to be achieved.

Note the difference between test ID 77 [3, 3, 2, 2] and 81 [3, 3, 3, 3]. The average number of steps taken in each of the cases is 55.5 and 15 respectively. Such discrepancies in results are observed for any configuration containing the spring 3 in its coronal plane. This is because the stiffness of the spring 3 is too high and it blocks the walker from setting into a stable gait pattern.

Similar to the sagittal plane, the lateral position in the coronal plane has the main impact on the stability of the walker. For example, in test ID 74 [3, 3, 1, 2] the walker is able to take an average of 18.2 steps whereas in test ID 76 [3, 3, 2, 1] the walker is able to take 32.8 steps on an average. As observed while performing the experiments and from the data, the roll angle is dependent on the stiffness of the lateral spring. This is because the walker does not bend in the direction of the medial spring; hence the spring at this position is mostly balancing the force exerted by the spring in the lateral position. The best spring configurations for this plane was spring number 2 for lateral plane and spring number 1 in the medial position.

6.3 Analysis of Knee-Spring Tests

Results for the knee spring system are analysed in order to gain a comprehensive understanding of the different variables affecting the gait of the walker. The effect of spring stiffness on the anterior and posterior plane of the walker is analysed for every angle. The spring stiffness that performs the best in each set is also compared to gain an understanding of how this variable affects the gait. Finally, the effect of changing the initial angle of the knee at launch is analysed.

The spring in the anterior position of the knee helps to restore the knee back to the stance position. During flexion, the anterior spring is extended. The energy in the anterior spring allows the spring to return to its initial elongation causing an extension moment about the knee joint. The spring in the posterior position is responsible for knee flexion and the initial elongation of this spring dictates the maximum flexing angle. This is because the spring can only compress till its free length. The graph below compares the performance of all the sets. It should be noted that although the maximum number of steps taken in set 3 is less than that taken in set 2, the walker is still able to demonstrate a stable gait pattern albeit for a fewer number of steps. The results of each set is analysed in further detail below.

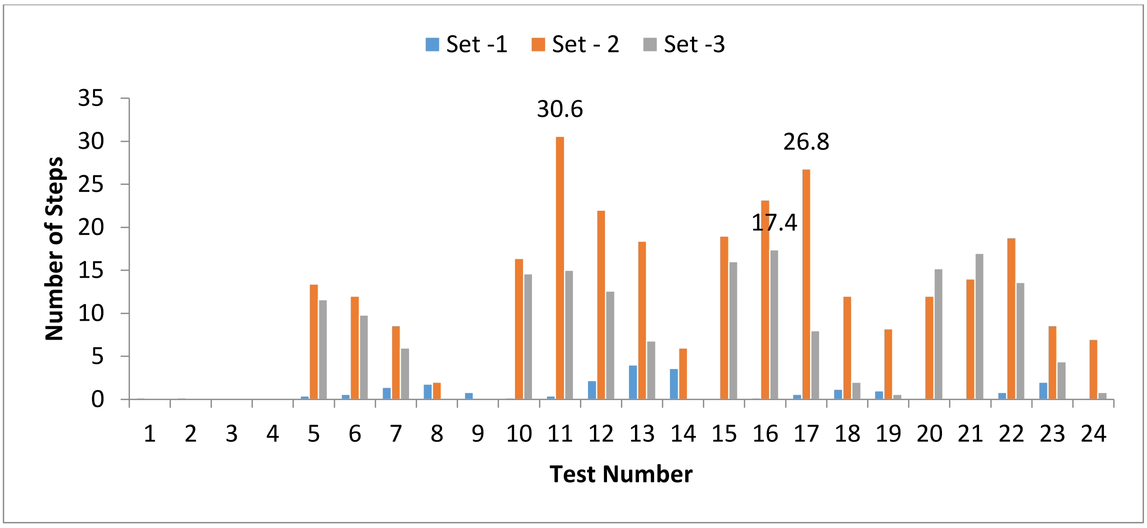

Figure 77 - Graph comparing number of steps taken between each set

6.3.1 Knee Engagement

During the knee tests it was vital to ensure that there was minimum level of knee engagement observed. Although the aim was to achieve complete flexion of the knee joint, this was not observed in the experiments. It is important to understand this before further analysis of the test data.

The ankle spring system contributes to the pitch and the roll of the ankle and although it was hypothesized that the kneed walker would not exhibit roll motion due to the clearance created by the knee joint. However, the contrary was observed during the tests, due to this the knee was not able to achieve complete flexion due to the direction of the forces acting on the system. In order to better appreciate this, a qualitative analysis is carried out. It would not be possible to make accurate measurements while performing the tests to make a quantitative analysis and this is out of the scope of this research. However, such an analysis will definitely broaden the understanding of the underlying mechanical principles.

The figure below illustrates the direction of the main forces acting on the springs. The tendency of tensional springs is to return to its original free length and hence it exerts an upward force on the walker. When the force vector in the posterior of the knee is more than that of the anterior, flexion is observed and vice versa for extension. This imbalance of force can be a result of moment acting on the knee during the swing phase or during another phase of the walking cycle.

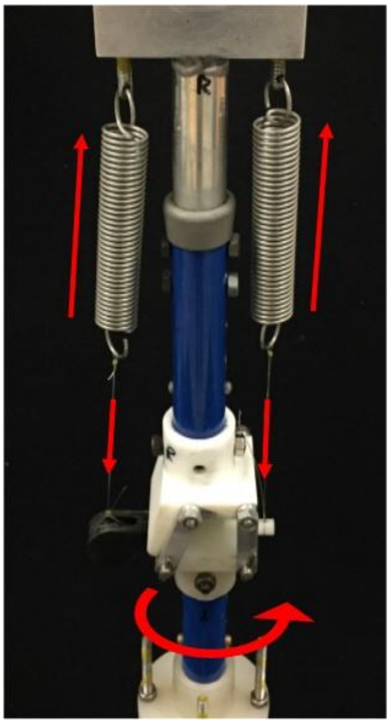

Figure 78 - Forces acting around the knee

However, before any flexion is achieved the walker must have some motion which is induced by the ankle joint. The gravitational energy and the reaction forces acting on the walker causes sideward force on the walker resulting in a roll motion. This is because the contact of the foot during the terminal stage of the stance phase is not purely on the toe region but there is also contact from the side of the foot. This translates some of the energy into sideward motion. Hence the level of knee activation is reduced. The method of launching largely determines the initial distribution of forces between the two joints. Moreover, the results of only the tests runs where a minimum amount of knee activation was observed were noted. The spring-system acts as the stabilising mechanism along with controlling the motion of the knee. However most knee units regardless of their complexity have two different mechanisms responsible for each aspect, hence this is reflected in the difficulty of achieving full knee activation by the passive walker.

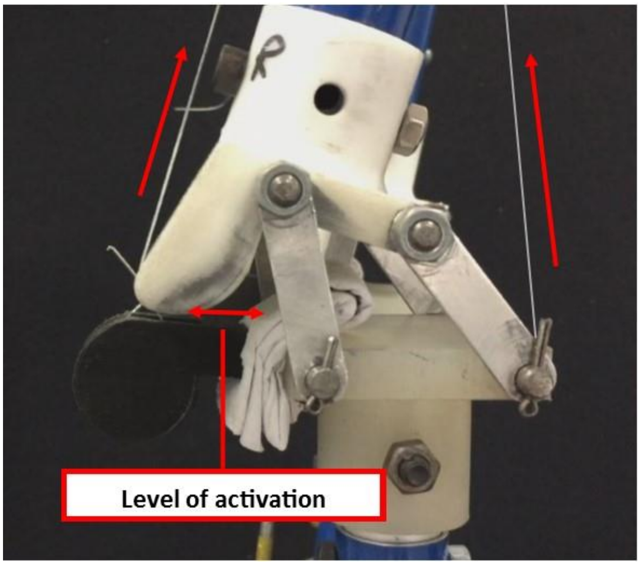

Figure 79 - Level of knee engagement

6.3.2 Set – 1

The results of set 1 are presented below. The best performance in this set was for test number 13 where the walker was able to take a total of 4 steps and traversed a distance of 21.6 cm. The average number of steps taken by the walker was 1.07 and the average distance traversed was 5.5 cm.

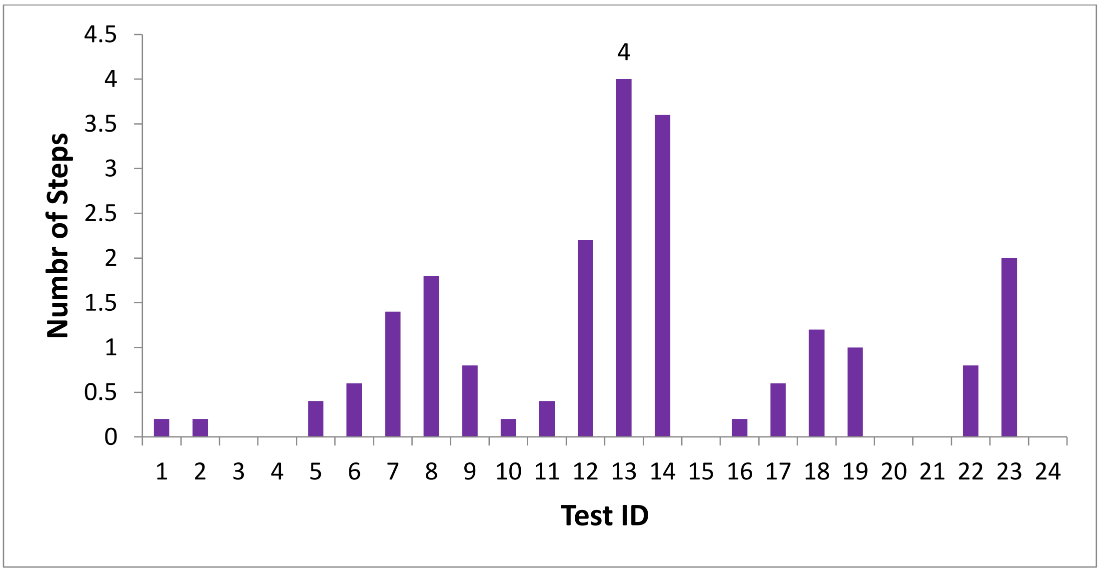

Figure 80 - Number of steps for set 1

Since there are no springs in the anterior position for the first four test runs, the walker immediately fails as the knee joint is permanently flexed due to the absence of a restoring force. The walker performs best for test runs 13 and 14 in terms of distance traversed and steps taken. The spring configurations for these runs were [2, 3] and [2, 4].

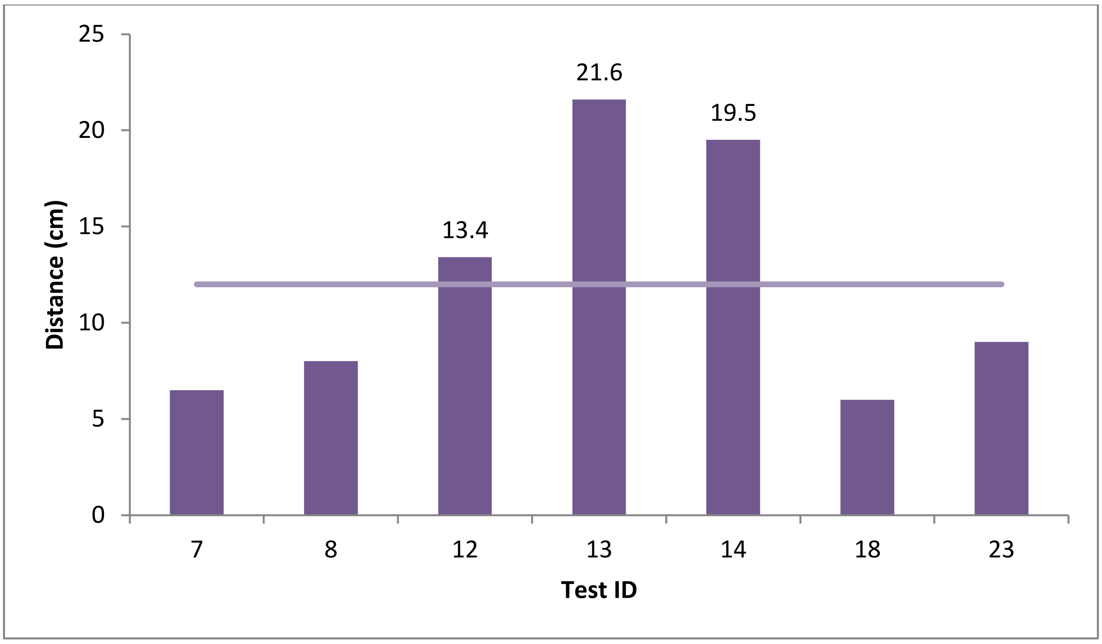

Figure 81 - Distance of most successful test run, set s

The distance traversed by the most successful test runs is shown in the above graph. Although the average distance was 5.5 cm for this set, when considering only the above cases the average distance increases to 12 cm.

The poor results observed for the first few test runs is due to a lack of restoring force present which leaves the walker permanently flexed as soon as there is a small level of knee activation. However, the unsatisfactory performance of the walker in the later test runs is attributed to the lack of flexion moment around the knee joint. Hence for these test runs the knee joint is unable to achieve any level of activation.

Anterior – posterior comparison, set 1

To analyse the results of the various springs on each position, the average number of steps taken by that spring in each location is calculated. For example, to analyse the performance of spring number 1 in the posterior position all the tests with the configuration [x, 1] were averaged in order to negate their effect. The results obtained are presented below. Note a similar analysis is carried out for sets 2 and 3.

Table 8 - Average number of steps for each spring configuration, set 1

Spring No.	1	2	3	4
Posterior	0.28	1.04	1.94	1.08
Anterior	1	2.08	0.6	0.56

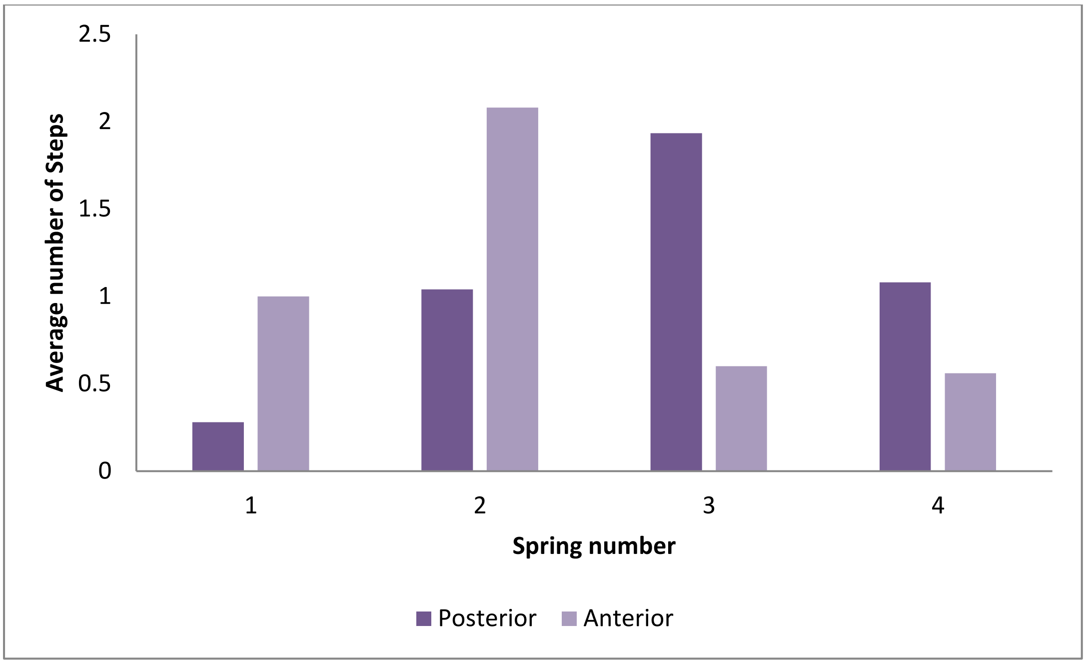

Figure 82 - Effect of each spring type in the anterior and posterior plane

Notice that springs of lower stiffness perform better in the anterior position whereas springs with the higher stiffness perform better in the posterior position. Spring number 2 performs best in the anterior position and spring number 3 in the posterior position. As stated above the best spring configuration for this set was test ID 13 [2, 3]. The results of test ID 17 [3, 2] reflect this as the walker is able to only take an average of 0.6 steps under this configuration.

However, this does not imply that having a spring with higher stiffness in the posterior position will always improve the performance. The interaction between both the planes changes throughout the various sub phases of the gait cycle. Hence the above average is only representative of the entire gait cycle and cannot represent the performance at the various sub phases of the cycle. It does reflect that the walker under these settings requires more energy to flex.

6.3.3 Set – 2

A similar analysis is carried out for set 2. There was a remarkable improvement in the performance of the walker in set 2 with the highest number of steps taken at 30.6 for test ID 11 that traversed a distance of 170.3 cm. The average number of steps taken in this set was 11.93 and the average distance was 67.2 cm. Moreover as shown in the graph below, the walker under this configuration shows an upward trend in performance.

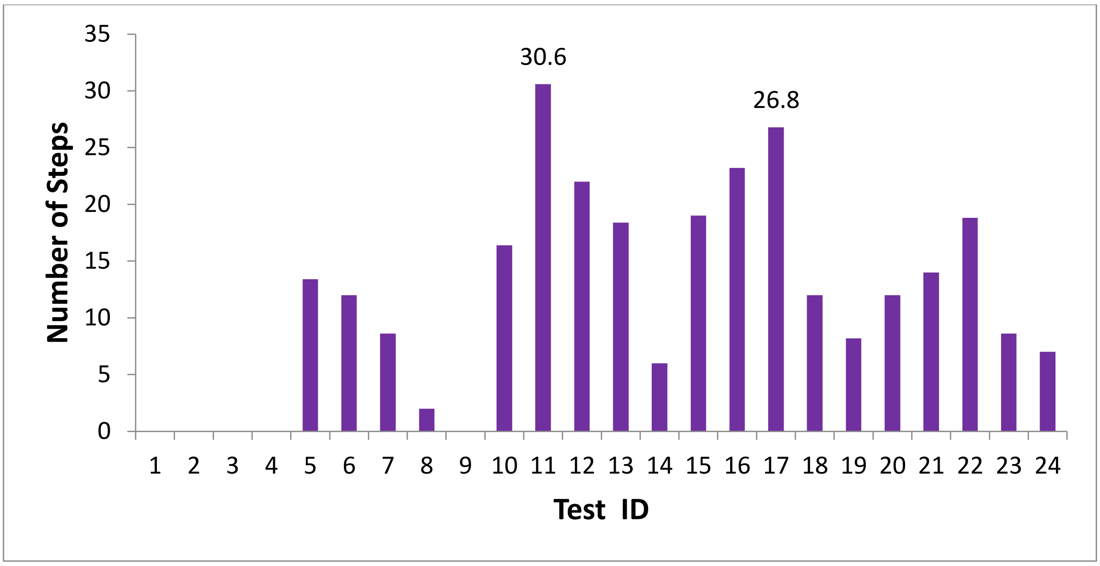

Figure 83 - Number of steps for set 2

The first four test runs showed identical results to that of set 1. Due to the absence of an anterior spring, the walker is under permanent flexion due to the spring in the posterior position. It can be noticed that when a spring is introduced in the anterior position from test run 5 onwards, the walker begins to demonstrate a stable gait pattern. The best results are observed for test runs 10 to 17 with the exception of test number 14. The spring configurations for the top two test runs which were 11 and 17 was [2, 1] and [3, 2]. The graphs below isolate the most successful test runs in order to analyse their performance in terms of number of steps and distance traversed.

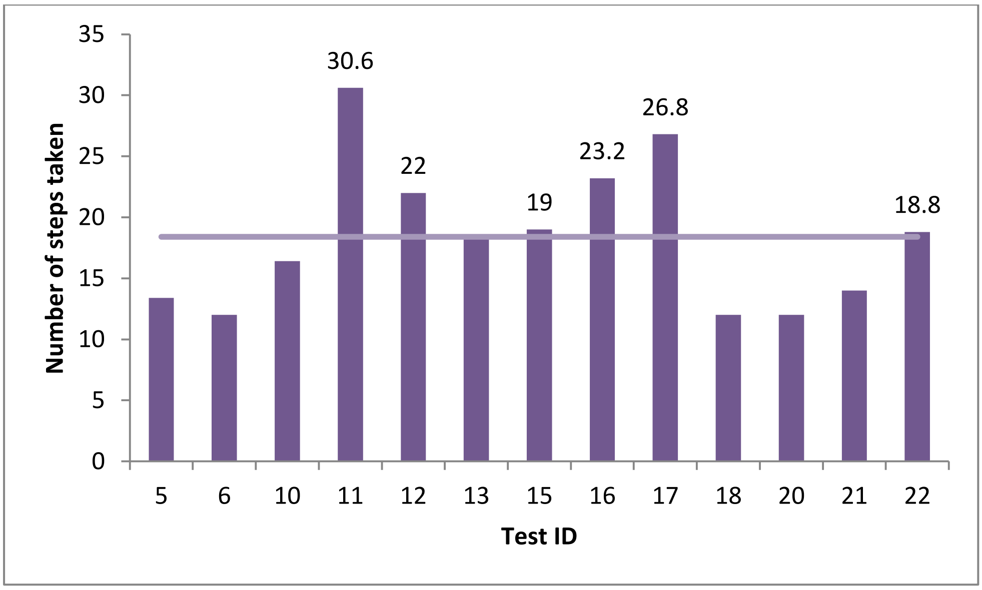

Figure 84- Number of steps taken for the best performing configurations, set 2

The average number of steps taken increases to 18.4 when neglecting the test runs with poor performance. The average distance also increases to 99 cm.

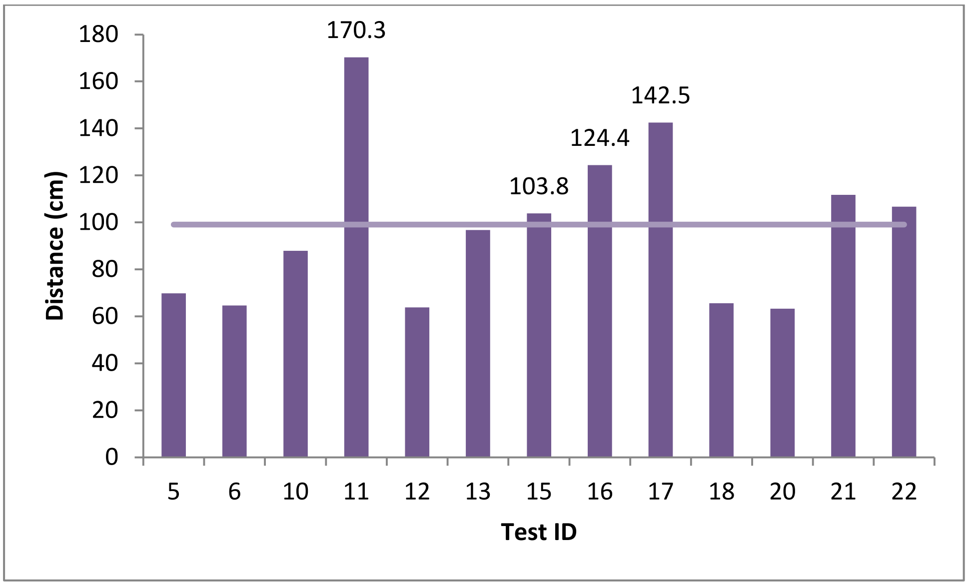

Figure 85 Distance travelled for the best performing configurations, set 2

Anterior – posterior comparison, set 2

The result of this analysis shows that the posterior plane contributes to a more stable gait pattern when it is fit with springs of low stiffness. With the increase in the stiffness of the spring there is a clear reduction in the average number of steps the walker is able to achieve. Moreover, the results for spring 4 show extremely poor results in this position and spring number 1 performs the best in the posterior plane. This is unlike set 1 were the walker performed better when placing springs with higher stiffness in the posterior position. The difference in the results observed must be attributed to the change of initial angle of the walker.

In the anterior position, spring number 2 performs the best, similar to set 1. However the walker also exhibits a stable gait pattern with springs 3 and 4 which is again in contrast with the results obtained for the previous set. However this pattern is more reflective of human morphology since the muscles in the anterior are overall more activated than the muscles in the posterior side (refer to chapter 2).

The data and the graph for this comparison are presented below. Although it is not apparent from the graph since the walker performs well under spring 1 and 2 in the posterior position, but certain configurations tested under this set were able to achieve a stable gait absent any spring in the posterior plane. Test ID 5, 10, 15, and 20 have no spring in the posterior plane and are yet able to take a combined average steps of 15.2. This was unexpected and was not observed in set 1. One way of interpreting this data is that due to the change in the initial angle of the knee, it is now predisposed to performing flexion and the anterior spring acts as a stabilising factor.

In set 1 it is clear from the anterior-posterior analysis that the knee joint requires relatively more force in the posterior plane to perform flexion. And thus such a pattern was not observed. However, other data confirms that the spring in the posterior plane contributes to the stability of the walker as the average number of steps taken increases to 19.95 for all sets with spring 1, not including test ID 1.

Table 9 - Average number of steps for each spring configuration, set 2

Spring No.	1	2	3	4
Posterior	15.96	15.24	8.2	0.28
Anterior	7.2	18.68	17.84	12.08

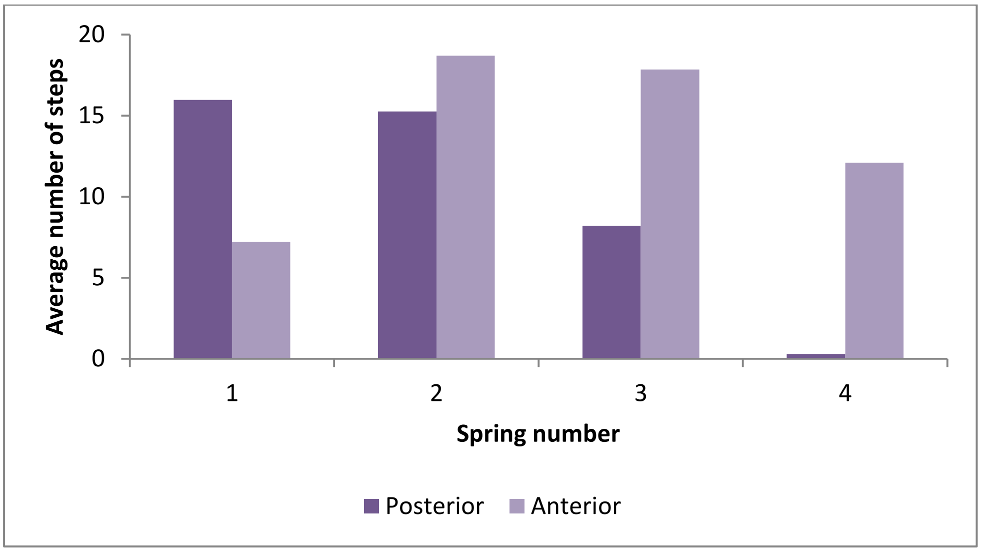

Figure 86 - Effect of each spring type in the anterior and posterior plane, set 2

6.3.4 Set – 3

The walker under these settings was either able to achieve a stable gait pattern or failed immediately with very few test runs showing intermediary results. Increasing the angle further did not reflect an improvement in the performance of the walker. The best performance for set 3 was test ID 16 taking an average of 17.4 steps. The average distance traversed for this test ID was 97.3 cm. The average number of steps taken in this set was 7.14 and the average distance traversed was 40.35 cm.

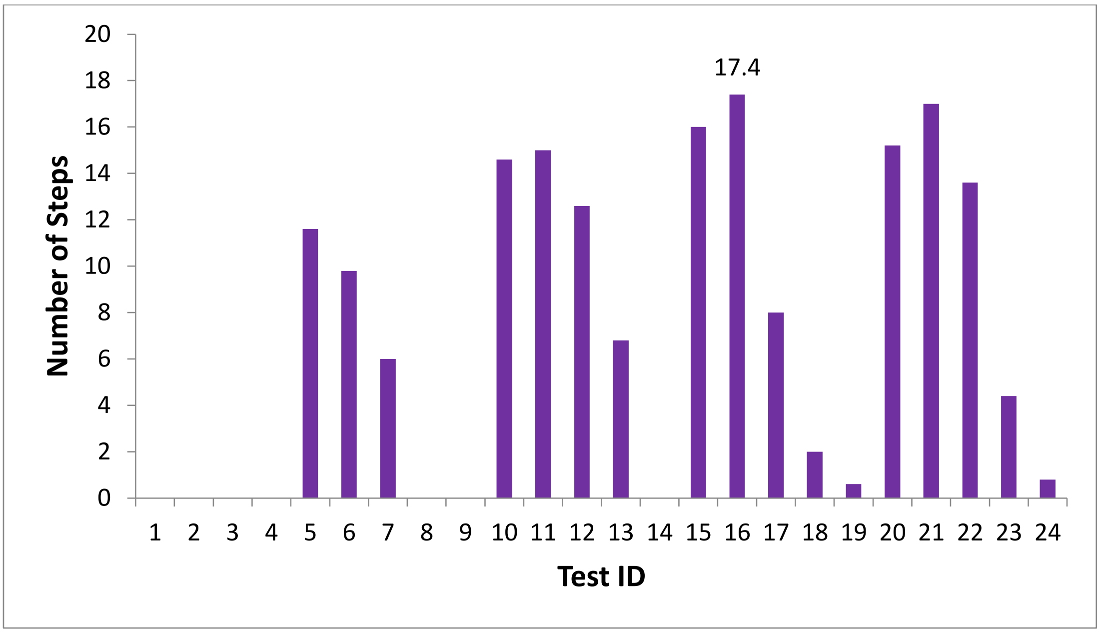

Figure 87 - Number of steps for set 3

Similar results to set 2 can be observed here with failure happening immediately for cases 1 through 4. The data below presents the results of the most successful test runs. It can be observed that when isolating the most successful runs, a fairly stable gait pattern is achieved.

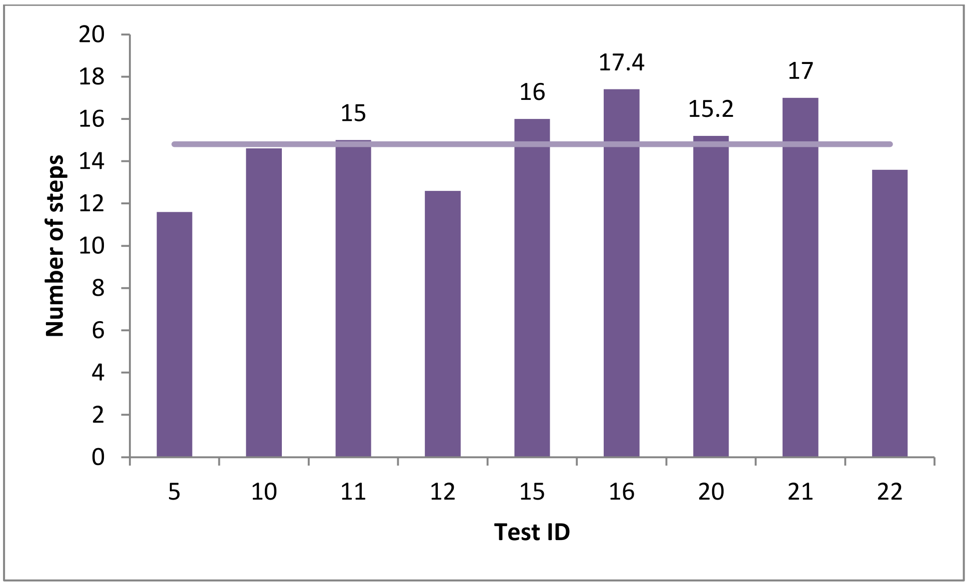

Figure 88 - Number of steps taken for the best performing configurations, set 3

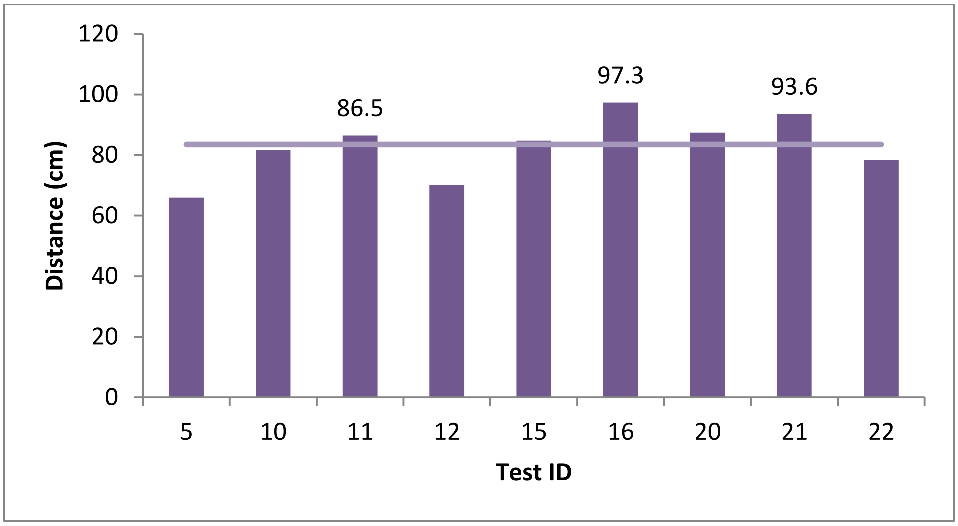

Figure 89 - Distance travelled for the best performing configurations, set 3

The average number of steps for these cases is 14.8 and the average distance traversed is 83.5 cm.

Anterior – posterior comparison, set 3

The comparative analysis of the anterior and posterior plane for the set 3 reveals that the walker is able to perform better when springs of low stiffness is placed in the posterior position. In the anterior plane; the knee joint performs fairly consistently regardless of the stiffness on the spring. However the best performing spring in this position is number 4, just barely performing better than springs 2 and 3. This is an interesting result as it could imply that after installing a spring of sufficient stiffness in the anterior position, the posterior plane eventually dictates the performance of the walker under these settings. However correlation should not be mistaken for causation, and data gathered from all three sets must be analysed together in order draw conclusive results. This is to say that although a greater variation of performance is observed for the posterior plane under this knee angle, it is not indicative of the passive walker under all settings. Such an analysis does not reveal any dominant plane.

Table 10 - Average number of steps for each spring configuration, set 3

	1	2	3	4
Posterior	11.84	8.04	2.64	0.28
Anterior	5.48	9.8	8.8	10.2

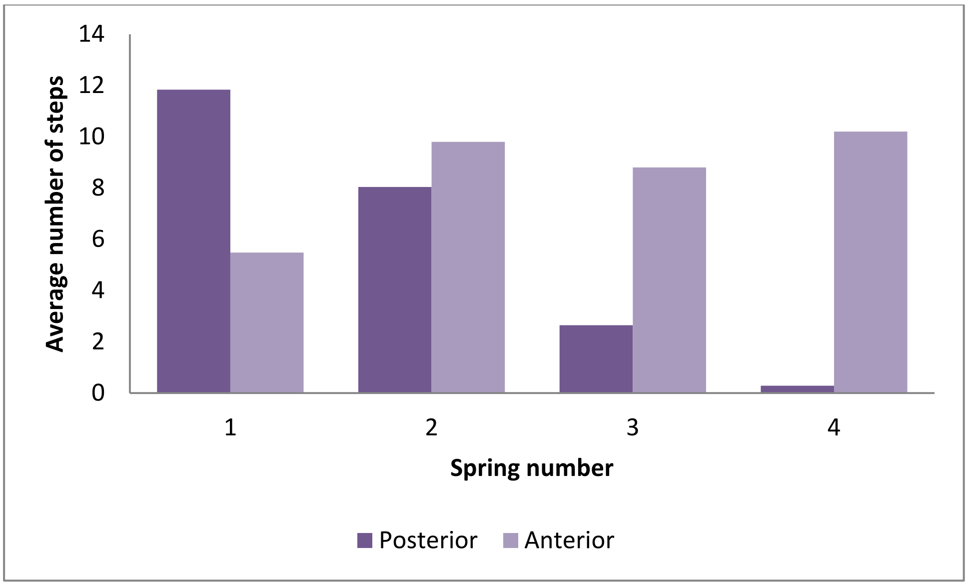

Figure 90 - Effect of each spring type in the anterior and posterior plane, set 3

Test runs 11, 15, 16, 20, and 21 performed the best taking at least 15 steps at an average. The spring configurations for these tests were [2, 1], [3, 0], [3, 1], [4, 0], and [4, 1] respectively. This reflects that the stiffness in the anterior plane must be much higher in relation to the stiffness of the spring in the posterior plane. This is because the knee joint is able to flex much easily under a higher initial angle. Hence the force in the anterior plane needs to be higher in order to balance the knee joint's predisposition to flexing under these settings. The above results are reflective of this fact. Moreover, installing a spring of high stiffness in the posterior plane can drastically change the performance of the walker. For instance the walker takes 17.4 steps under the spring configuration [3, 1] which is reduced to 8 for the spring configuration [3, 2].

In conclusion, unlike the ankle spring system, the knee joint does not have a particularly dominant plane that is to say that neither the posterior or the anterior plane outperformed the other under every spring configuration. The stiffness of the spring at each location does however drastically affect the performance of the walker. Set 2 and set 3 were however able to achieve a stable gait without any spring in the posterior position.

The spring in the posterior plane promotes flexion while the spring in the anterior plane promotes extension of the leg during the gait cycle. The interaction between the two planes and the balance of forces is crucial to achieving a stable gait cycle.

Set 1 performs better when the stiffness of the springs in the posterior position is higher than the stiffness of the spring in the anterior position. Whereas sets 2 and 3 perform better with high stiffness springs in their anterior position.

6.3.5 Best Spring Configuration

An analysis to find the best spring stiffness is carried out below. Results for each spring are averaged for every case and compared. The average number of steps taken for all spring stiffness is presented in the table and graph below.

Table 11 - Average number of steps for each spring configuration

	1	2	3	4
Set 1	0.64	1.56	1.266667	0.82
Set 2	11.58	16.96	13.02	6.18
Set 3	8.66	8.92	5.72	5.24

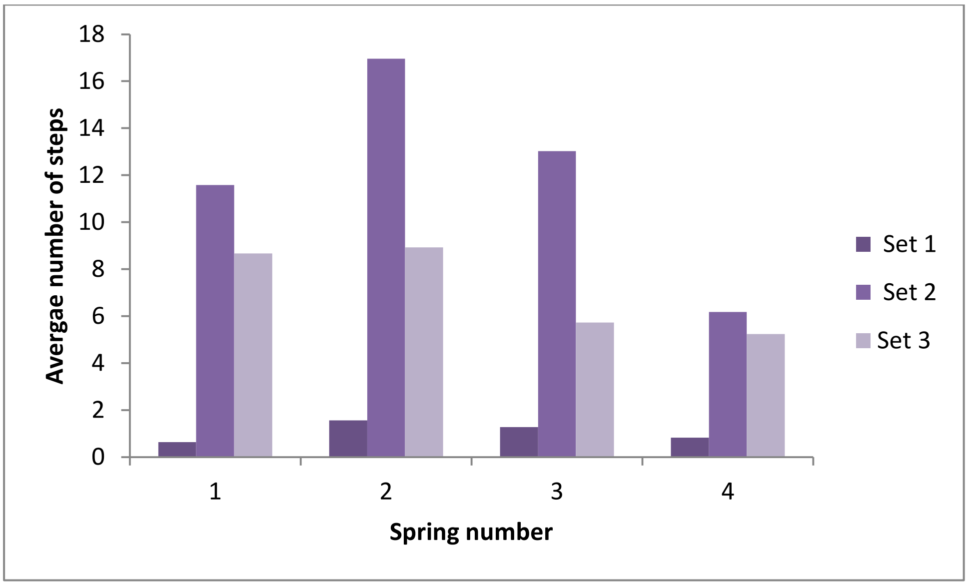

Figure 91 - Average number of steps of all the springs

Spring 2 has a stiffness of 1430 N/m and performs the best in every set whereas a decrease in performance is observed for springs 3 and 4 for set 2. The walker is able to take an average of 16.9 steps for all configurations tested under set 2. Furthermore, sets 2 and 3 perform identical under spring 4 and the largest difference in their performance is noticed under spring 2 and 3.

Although the analysis of spring stiffness was useful in understanding which springs improve the performance of the walker, it can be seen that it is not the key factor contributing to the stability of the gate cycle. To analyse this, the average results of all the test runs in each sets are analysed.

6.3.6 Comparative analysis between each set

Average data of all the tests for each set are compared to determine the effect of changing the initial angle on the performance of the walker. The table and graph below present the data obtained for this comparative analysis.

Table 12 - Average number of steps taken in every set

Set No.	Avg. steps
Set 1	1.07
Set 2	11.93
Set 3	7.14

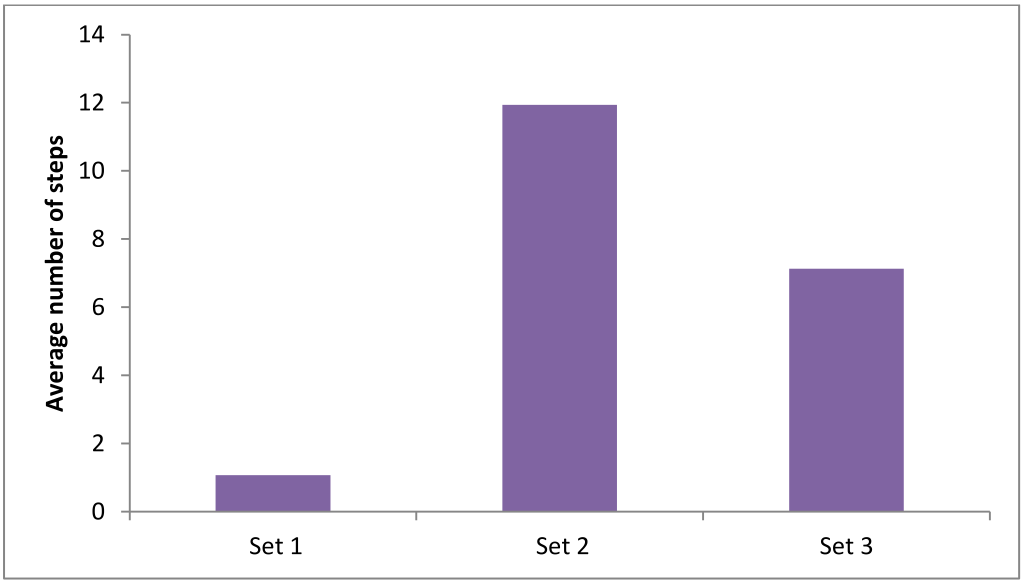

Figure 92 - Average number of steps taken in every set

It can be seen that after isolating all other factors, changing the initial angle of the knee from 0° to 2° has a significant influence on improving the performance of the walker. In the first set, the average number of steps taken is only 1.07 while the average number of steps taken for set 2 is 11.93. Compared to the previous analysis, the most significant improvement in performance is observed here. However, the performance of the walker is not further improved upon increasing the angle. This is not necessarily indicative of the fact that 2° would be the best initial angle for this design. Since a stable gait was observed in set 3, perhaps testing the walker with springs with even higher stiffness that are able to better control the knee joint under these settings could result in an improved performance. It is hypothesized that the reason such a remarkable improvement is noticed with a change in the initial angle is due to the ICR of the knee joint moving across the load line.

As shown in the figure below, the ICR of the knee joint is posterior to the load line at stance position. As discussed in the previous chapter, this configuration fulfils Oberg's (1983) criteria of stability at stance.

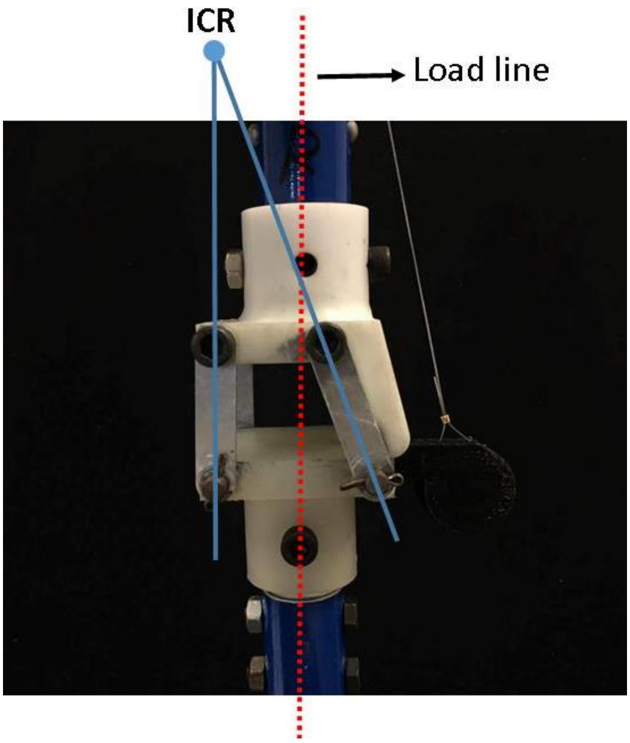

Figure 93 - ICR when angle is 0°

With the initial angle set at 2°, the ICR shifts anterior to the load axis. This is the pre-requisite in order for flexion to occur. Hence it is theorized that due to the ICR position now anterior to the load line, less force around the knee joint is required in order to activate it. The figure below shows the location of the ICR for set 2 at stance. Moreover the results obtained in the previous analysis are reflective of this fact. That is set 1 performs better when springs with higher stiffness are placed in the posterior position reflecting the requirement of more energy in order to flex and overcome the initial resistance.

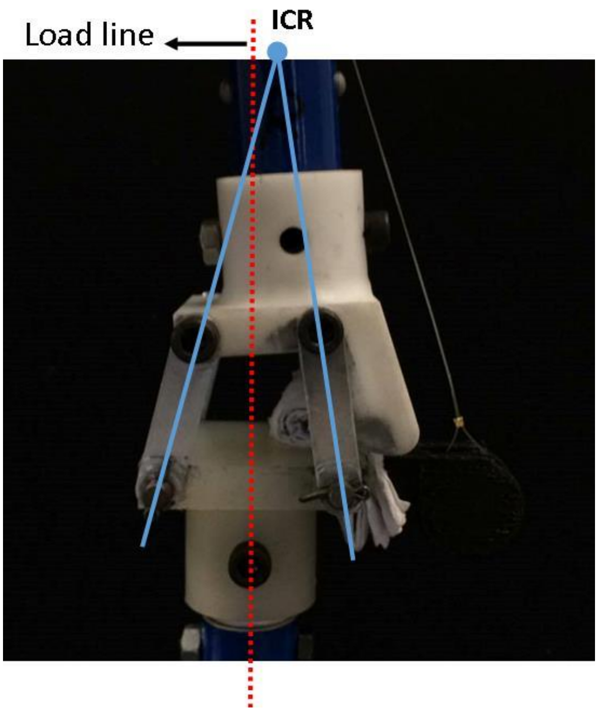

Figure 94 - ICR when angle > 2°

The improved performance observed here is not in contradiction to Oberg's (1983) criteria since the theory was developed with the human gait as the main focus. Hence the improvement observed here is solely due to the gait pattern adapted by the passive walker.

Knee systems in prosthetics that prevent early stance buckling employ this principle of placing the knee axis posterior to the centreline of the prosthesis. This technique is called "alignment stability" (Romo, 2000) and it ensures that the GRF from early to late stance creates a large extension moment about the knee, preventing the knee from buckling. However, this technique causes a delay in the initiation of the knee flexion during pre-swing (Radcliffe, 1994). Hence the results obtained from changing the angle is due to the fact that the extension moment around the knee joint for set 1 at stance is higher than that for set 2 and 3.

6.4 Conclusion

In conclusion, the walker with locked knee was able to successfully recreate stable gait reflecting the characteristics of its predecessor despite having variations in the design. Hence it could be stated that the flat feet with ankle springs is an adaptable system.

The walker with locked knees tested successfully where the predicted results were observed. The data reflected the working principles of the bipedal, albeit without knees. However as discussed earlier, this was a crucial stage before moving on to kneed leg testing.

Moreover a stable gait for kneed walker was also achieved with the best results noted for test 2 – [10] took an average of 30.6 steps. However the knee was not able to achieve proper activation and hence the angle of flexion was very limited. The results from testing different spring stiffness in different combinations proved to be useful providing insight to the functioning of the polycentric knee mechanism. Changing the initial angle of the knee at stance was the key variable in achieving gait as noted by the vast difference between the results of set 1 and 2.

The highest number of steps taken by the locked-kneed walker was 55.5 and by the kneed-walker was 30.6. The reduction in the total number of steps could be attributed to the fact the walker with knees requires more energy and hence would come to a stop sooner. The engagement of the various muscle groups change over the phase of one stride in humans. This was not replicable in the passive walker due to the complexity that would be required to adjust the spring stiffness throughout the gait cycle. The simple mechanical system proved efficient for a preliminary analysis of the knee joint complex.

Chapter 7 - Conclusion

It should first be noted that the results obtained from this research should not be compared with human walking features as many aspects of both gaits differ. The fact that the knee joint was unable to fully activate required a certain degree of roll. Moreover, the reaction forces are not purely acting on the front edge of the walker's feet but also on the lateral edges which would be difficult to completely eliminate without toes.

The main aim was to analyse the effects of gait behaviour with the addition of knees. Preliminary tests were first conducted to find the best robot parameters after which test of locked knee walker were carried out. These tests were successful and validated the passive walker's performance. The walker was able to take 55.5 steps on average under the best configurations.

The main experiments with knees were performed using four different spring stiffnesses to analyse the effects of stiffness on the knee joint. Moreover, this allowed the analysis of both the planes involved in knee flexion, i.e. the posterior and anterior plane. Each of these configurations was tested under three different angles. Spring number 2 with stiffness of 1430 N/m performed the best under every set. Springs with a low stiffness performed well in the posterior plane for sets 2 and 3 which is similar to human muscle functions. Springs with a higher stiffness did better in the posterior position under set 1 highlighting the high extension moment present at the knee joint.

Set 2 which set the knee at an initial angle of >2° performed the best and a remarkable improvement in the results were observed between set 1 and set 2. The most stable gait was found under these settings. The walker was able to take an average of 30.6 steps and demonstrated stable gait for many of the test runs under this set. The difference in performance is attributed to the shift of the ICR from behind the load line to the front.

There were two main modes of failures; the walker would fall due to over-flexion due the inability of the walker to recover or it would fall due to uneven activation between the knee joints. Overextension usually occurred when a spring of sufficient stiffness is not placed in the anterior plane. Torsional forces were created due to the uneven activation of the knee joints causing the walker to topple over.

In conclusion, the research successfully adapted a prosthetic knee design to a passive dynamic walker and the key properties of the walker were analysed. The tests bore interesting results and provided an in-depth understanding in the field of robotics. However, In order to make progress in this field of study it is vital to integrate the various branches such as prosthetics with the field of robotics. This will help gain a more comprehensive understanding of the underlying biological principles.

7.1 Future work

The problems faced by this passive walker must first be addressed in any future research. Firstly, it is crucial to use more precise manufacturing methods as small errors lead to big disturbances. The second thing that must be addressed is the level of knee activation. Although the aim is to develop complete passive structures, this might not be possible with an efficient knee design. Regardless of the complexity of the knee joint, all of them require an additional mechanism for stability and another mechanism to control motion. It would prove useful to add simple control mechanism at the knee joint that could provide some forward motion in order to overcome the high extension moments present at the knee joint.

The addition of toes will also be fruitful as a reduction in the roll moment might also enable the knee to be activated more. Furthermore, it is advised to explore the effects of using a treadmill over traditionally used slopes. The parameters of the ramp would not limit the analysis of the study. Also the effects of stability could be studied with further isolation.

Future work should also investigate the exact force vectors acting on the knee joint during the gait cycle. A study analysing this could draw comparable results to the use of muscles in humans and perhaps even the ligaments.

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Appendix

Table 13 – All ankle spring configurations

1 - [1,1,1,1]	22 - [1,3,2,1]	43 - [2,2,3,1]	64 - [3,2,1,1]
2 - [1,1,1,2]	23 - [1,3,2,2]	44 - [2,2,3,2]	65 - [3,2,1,2]
3 - [1,1,1,3]	24 - [1,3,2,3]	45 - [2,2,3,3]	66 - [3,2,1,3]
4 - [1,1,2,1]	25 - [1,3,3,1]	46 - [2,3,1,1]	67 - [3,2,2,1]
5 - [1,1,2,2]	26 - [1,3,3,2]	47 - [2,3,1,2]	68 - [3,2,2,2]
6 - [1,1,2,3]	27 - [1,3,3,3]	48 - [2,3,1,3]	69 - [3,2,2,3]
7 - [1,1,3,1]	28 - [2,1,1,1]	49 - [2,3,2,1]	70 - [3,2,3,1]
8 - [1,1,3,2]	29 - [2,1,1,2]	50 - [2,3,2,2]	71 - [3,2,3,2]
9 - [1,1,3,3]	30 - [2,1,1,3]	51 - [2,3,2,3]	72 - [3,2,3,3]
10 - [1,2,1,1]	31 - [2,1,2,1]	52 - [2,3,3,1]	73 - [3,3,1,1]
11 - [1,2,1,2]	32 - [2,1,2,2]	53 - [2,3,3,2]	74 - [3,3,1,2]
12 - [1,2,1,3]	33 - [2,1,2,3]	54 - [2,3,3,3]	75 - [3,3,1,3]
13 - [1,2,2,1]	34 - [2,1,3,1]	55 - [3,1,1,1]	76 - [3,3,2,1]
14 - [1,2,2,2]	35 - [2,1,3,2]	56 - [3,1,1,2]	77 - [3,3,2,2]
15 - [1,2,2,3]	36 - [2,1,3,3]	57 - [3,1,1,3]	78 - [3,3,2,3]
16 - [1,2,3,1]	37 - [2,2,1,1]	58 - [3,1,2,1]	79 - [3,3,3,1]
17 - [1,2,3,2]	38 - [2,2,1,2]	59 - [3,1,2,2]	80 - [3,3,3,2]
18 - [1,2,3,3]	39 - [2,2,1,3]	60 - [3,1,2,3]	81 - [3,3,3,3]
19 - [1,3,1,1]	40 - [2,2,2,1]	61 - [3,1,3,1]	
20 - [1,3,1,2]	41 - [2,2,2,2]	62 - [3,1,3,2]	
21 - [1,3,1,3]	42 - [2,2,2,3]	63 - [3,1,3,3]	

Table 14 – Test results for Ankle springs

Test ID	Number of Steps	Distance Travelled
1	0.2	0.6
2	0.4	1
3	0.2	0.4
4	0.2	0.4
5	0.6	2.2
6	0.6	2
7	0.2	0.4
8	0.4	1.6
9	0.4	0.8
10	0.2	0.4
11	0.2	0.4
12	0.6	1.4
13	0.2	0.4
14	0.4	1.2
15	0.4	1.4
16	0.2	0.4
17	0.2	0.4
18	0.2	0.4
19	0.4	1
20	0.2	0.4
21	0.4	1.2
22	0.2	0.8
23	0.2	0.4
24	0.4	1
25	0.2	0.4
26	0.4	0.6
27	1.6	6
28	0.4	1
29	0.4	0.6
30	0.4	1
31	0.4	1
32	0.4	1.4
33	0.2	1
34	0.4	1.4
35	0.4	1.4
36	1.4	5
37	0.4	1.6
38	2	7.6

39	0.8	2.8
40	1.8	7.6
41	1.6	13.2
42	0.4	2.4
43	0.6	1
44	0.4	1.8
45	1.6	4
46	6	20.8
47	10	36.6
48	8.7	24
49	13.3	60.4
50	18.6	60.4
51	12.6	36.6
52	17.1	55.8
53	5.3	14.2
54	18.8	21.4
55	15.3	26
56	4.2	9.6
57	4.7	17
58	31.5	113
59	9.1	26.2
60	11.9	58
61	11	26.2
62	10.1	34.4
63	9.3	48
64	3.4	13.4
65	17.8	67.2
66	14.8	54.6
67	15.9	74
68	39	160.4
69	15.4	41.8
70	10.5	23
71	10.8	30
72	7.5	27.6
73	17.2	50
74	18.2	68.2
75	17.8	40
76	37.8	121.8
77	55.5	230
78	10.8	15.6
79	11.4	39
80	19.2	80