EXPERIMENTAL STUDY ON PASSIVE DYNAMIC BIPEDAL WALKING: EFFECTS OF PARAMETER CHANGES ON GAIT PATTERNS

by

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Abstract

Passive dynamic walking is a gait developed, partially or in whole, by the energy provided by gravity. Research on passive dynamic bipedal walking helps develop an understanding of bipedal walking mechanics. Moreover, experimental passive dynamic research provides a base to compare and validate simulation results. An improved kneed bipedal walking mechanism and an improved measurement system are used to study the passive gait patterns. Gait measurements are conducted on the treadmill to evaluate the effects of the treadmill angle of inclination, mass distribution of the biped, treadmill belt speed, length of flat feet and thigh-shank length on the gait patterns. Most of these dynamic and geometric parameters have significant effects on step length, step period and robustness of the passive gait. Difficulties have been faced with the study of the flat feet and the leg length variation. Suggestions have been provided for future work. Experimental results are compared with previous work based on both the experimental and the computer simulation.

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Acknowledgments

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This thesis is dedicated to my parents. You know who you are.

Chapter 1

Introduction

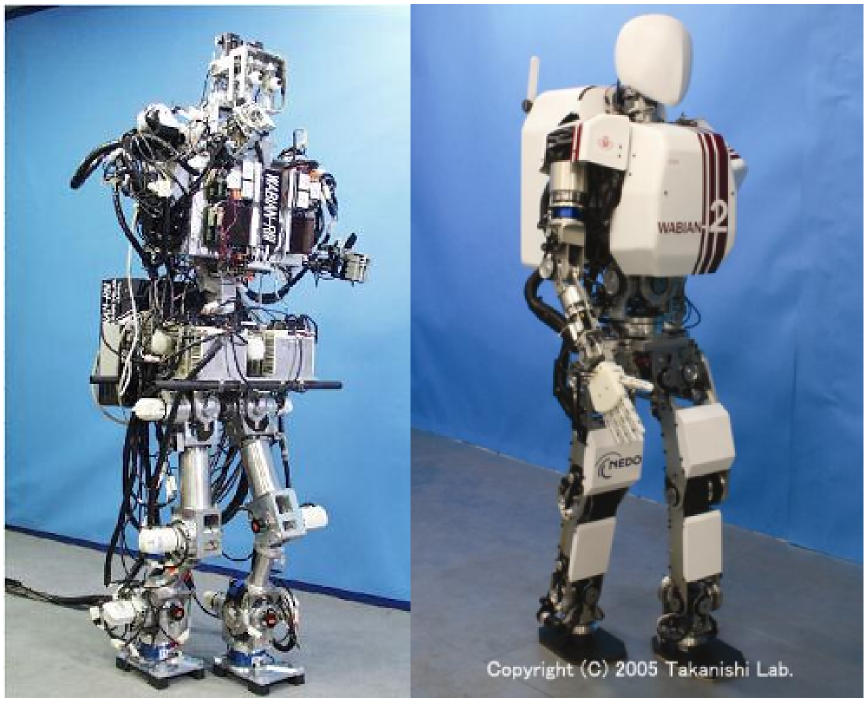
The developments of humanoid biped robotics have attracted much attention over the last 15 years for several reasons. It is easier for people to interact with walking robots with a humanoid shape rather than robots with nonhuman shape [1]. It is also easier for a biped robot to function in areas designed for people (e.g. houses, factories) [2]. The purpose of designing and creating humanoid biped robots is to help humans in their lives by imitating physical and mental tasks that humans undergo. Some humanoid biped robots are used to assist elderly or sick people, conduct dangerous tasks such as hazardous chemical handling and fire fighting, etc. Bipedal robots can access areas that are normally inaccessible to wheeled robots, such as staris and areas with obstacles that make wheeled locomotion impossible. Also humanoid robots are used as scientific tools for conducting research. Researchers use these kind of robots to understand biomechanics and to build better prostheses and ostheses. Humanoid robots can use tools and operate equipment and vehicles designed for the human form, so humanoid robots could theoretically perform any tasks a human being can, so long as they have the proper software. Humanoid biped robots can be classified as active biped robots and passive biped robots. Active robots require motor to drive some or all joints, while passive biped robots can walk on a shallow slope without any kind of actuators.

1.1 General Background

Waseda University is one of the leading research institutions for humanoid biped robots. They started in 1970 with the WABOT project. In 1997, they designed the first full-scale human-like robot, WABIAN, shown in Figure 1.1a, to work with human partners in their living environment. WABIAN-2R (2006), shown in Figure 1.1b had 41 degree of freedoms (DOF), and improvements in the knee joint, toe joint and ankle joint made WABIAN-2R mimic humans and successfully act as a human motion simulator.

Honda began the humanoid robotics research in 1986. The goal was to design biped robots for home use. They designed and built several biped robots, E0-E6, which did not have an upper body like a human. In 1993, Honda developed the P1, shown in Figure 1.2a. This was the first human-like model with an upper body and limbs. Two more similar robots, P2 and P3, were built by Honda in the period of 1993-1997. But, the size, weight and low energy efficiency of these robots made them less convenient. ASIMO, shown in Figure 1.2b, the first high profile humanoid biped robot that attracted public attention was designed and built by Honda in November, 2000. ASIMO guaranteed the greater freedom of locomotion and manipulation as it had the right size and weight. It was the only robot at the time that could ascend and descend stairs independently. Moreover, the interaction of ASIMO with humans was better as it had recognition technology. But still the cost of transport was high for ASIMO, which made it less energy efficient.

In 2003, Sony unveiled QRIO, shown in Figure 1.3a, which was small in size and

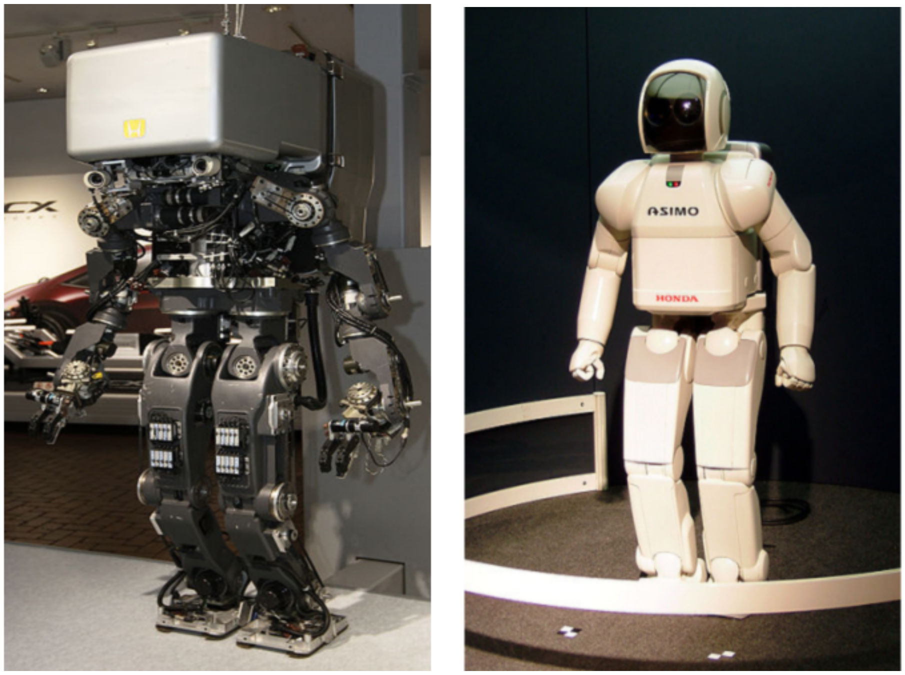


(a) (b)

Figure 1.1: Full-scale humanoid robot built by Waseda University, Japan (a) Wabian (B) WABIAN-2R (Photo: www.takanishi.mech.waseda.ac.jp)

could run at a speed of 23cm/s. It was also capable of recognizing voice and faces, which helped it to interact with people. Fujitsu also designed and built some small sized active biped robots. Hoap-1(2001), shown in Figure 1.3b, was their first commercial humanoid robot. It had a USB interface, which made easier to communicate via a computer and was mainly used for robotics research and developement purposes. Hoap-2 and Hoap-3 were the successors of Hoap-1 and came out in 2003 and 2005 respectively.

There are more bipedal active robots built by diffirent companies for various purposes. Some of them were designed to help people in their daily life as a partner robot, some were designed for entertainment purposes and some were developed for research and to further humanoid robot technology. Examples include, TOPIO,

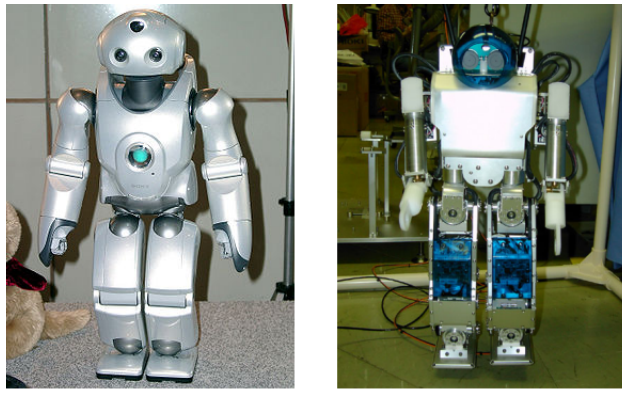


(a) (b)

Figure 1.2: Advanced humanoid robot built by Honda (a) P1 (photo: en.wikipedia.org) (b) ASIMO (photo: en.wikipedia.org)

TOPIO 2, TOPIO 3 by TOSY Robotics, KHR-1, KHR-2HV, KHR-3HV by Kondo Kagaku, Surena II by Tehran University, etc. The most successful one, ASIMO among the active robots described above could imitate humans by walking quite well, but it required complex, fast and precise control mechanisms and used far more energy than a walking human would [3].

Research groups in MIT, Cornell University, and Delft University, etc. have been continuing to develop energy efficient humanoid biped robots. In the period of 1996-2000,the research group in MIT designed and built a planar named biped robot Spring Flamingo, shown in Figure 1.4. Their goals were to make the robot walk as fast, energy efficient, reliable and robust as possible. Spring Flamingo required a small amount of power during walking. The improved design of the feet and the actuated



(a) (b)

Figure 1.3: (a) QRIO: Humanoid biped built by Sony in 2003 (photo: en.wikipedia.org) (b) HOAP-1: Commercial humanoid robot built by Fujitsu in 2001 (photo: www.plasticpals.com/?p=1117)

ankle were implemented to Spring Flamingo, which resulted in a robot that could walk quickly.

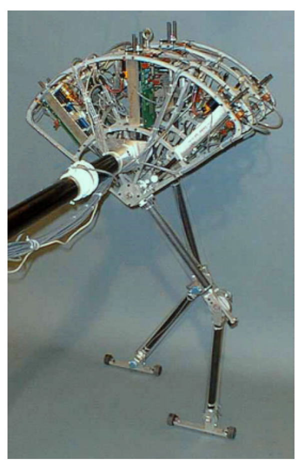
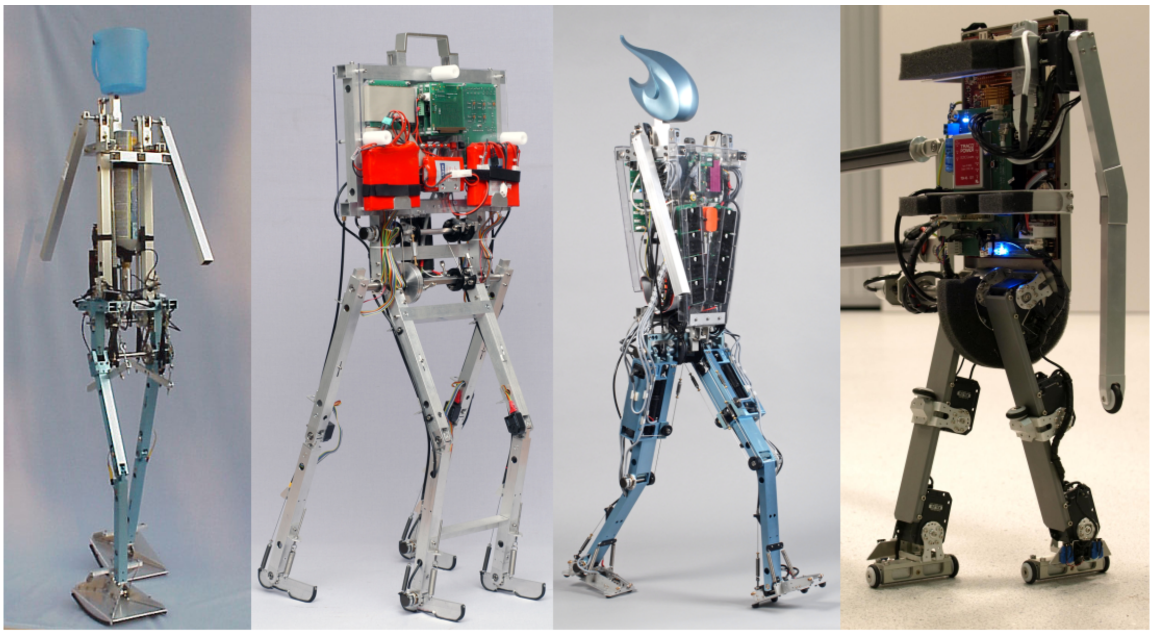


Figure 1.4: Spring Flamingo: Humanoid biped walking robot built by MIT in 1996 as an experimental platform (photo: http://www.ai.mit.edu/projects/leglab/)

The biorobotics lab in TU Delft University started to build energy efficient biped robots in 1995. Stappo was the name of their first energy effcient biped robot. Denise (2004), shown in Figure 1.5a, built by this lab had a human like configuration. They used passive dynamic walking concept to design Denise, which resulted in an energy efficient walker. Meta(2005), Flame(2007) and Leo(2009), shown in Figure 1.5b, 1.5c and 1.5d respectively, are examples of some humanoid robots built by Delft University.



(a) (b) (c) (d)

Figure 1.5: Humanoid robot built by Biorobotics Lab of TU Delft University (a) Denise(2004) (b) Meta(2005) (c) Flame(2007) and (d) Leo(2009) (photo: Delft Biorobotics lab, TU Delft University)

The biorobotics and Locomotion lab in Cornell University designed and built several energy efficient humanoid active biped robots. Ranger 2006, shown in Figure 1.6a, was their first energy efficient biped robot, which was designed without knees. This robot could walk for a distance of 3km. In fall 2008, the same group re-designed their first active robot and built Ranger 2008, which could walk 9.07 km and used less energy than Ranger 2006. Another version of Ranger came out in 2010, shown in Figure 1.6b. The final version of this series of robot came out in 2011, Ranger 2011, shown in Figure 1.6c, which walked non-stop for 40.5 mile. The walking efficiency of Ranger 2011 was much closer to the way in which humans walk. Collins and Ruina [4] designed and built a passive based, fully autonomous, 3-D bipedal walking robot in

Biped	Weight (kg)	Specific Cost of Transport
ASIMO(Honda)	54	3.2
Denise(Delft Uni.)	8	5.3
Spring Flamingo(MIT)	13.5	2.8
Ranger 2011(Cornell Uni.)	9.91	0.28
Ranger 2010(Cornell Uni.)	8.64	0.249
Cornell Robot(Collins)	12.7	0.20
Human	Average	0.2

Table 1.1: Estimated Specific Cost of Transport of Bipeds[3]

2005, which consumed little energy shown in Figure 1.6d. This robot was designed with hip, ankle and knee joints. The comparison of cost of transport between different humanoid active walkers is shown in Table 1.1 [4] and from this comparison it is clearly observed that the robots built with passive dynamic walking concepts are the most energy efficient. So it is obvious that research on passive dynamic walking would help to design more energy efficient active robots.

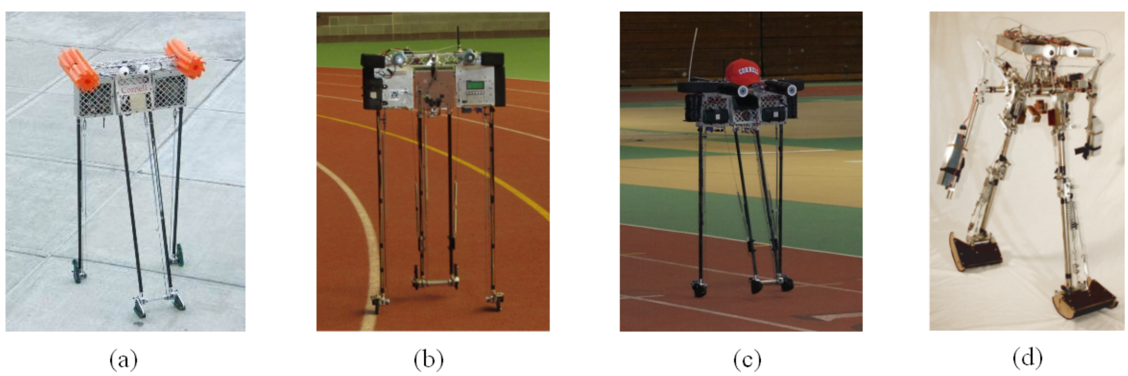


Figure 1.6: Humanoid robot built by Cornell University (a) Ranger 2006 (b) Ranger 2010 (c) Ranger 2011 (photo (a), (b), (c): Biorobotics andLocomotion Lab, Cornell University) and (d) Most energy efficient bipedal robot built by S. Collins [4]

1.2 Literature Review on Passive Dynamic Walker

The history of passive dynamic walking starts with walking toys. Fallis of Missouri in 1888 first patented his design [5] of a walking toy, shown in Figure 1.7a, which could walk on an inclined surface. Later, Bechstein in 1912 [6], Mahan in 1914 [7] and Wilson in 1938 [8] patented their design of walking toys shown in Figure 1.7a, 1.7b and 1.7c respectively. These designs were just for making toys. Inspired by a toy given to him, in the early 1950s, probably a “Wilson Walkie”, McMahon started to study the mechanics of locomotion [9]. He developed a mathematical model of walking in his work. Later, McGeer was inspired by his work and started research on passive dynamic walking [10].

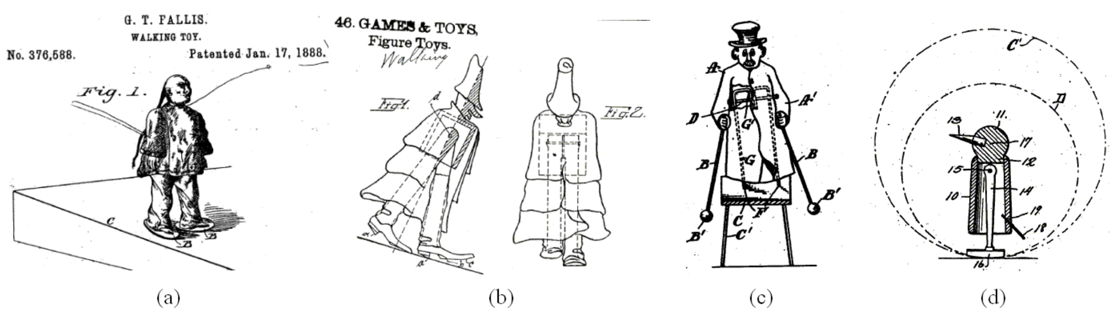


Figure 1.7: Walking toy by (a)Fallis (b) Bechstein(1912) (c) J. Mahan(1914) and (d) Wilson(1938)

Passive dynamic walkers are a class of mechanisms, once they start walking on a shallow slope, they will settle into a stable gait remarkabley similar to human walking without the help of actuation or control. Research into passive walking was pioneered by McGeer [10, 11]. Interest in passive dynamic bipedal walking has increased as these kind of walkers show humanlike natural gaits and are extremely energy efficient. McGeer demonstrated the passive dynamic gait through simulations and experiments [10]. The existence of a humanlike gait from a simple mechanism suggests that the natural dynamics may largely govern the walking pattern. Information gained from the study of passive dynamic biped walkers provides insight into human locomotion [12].

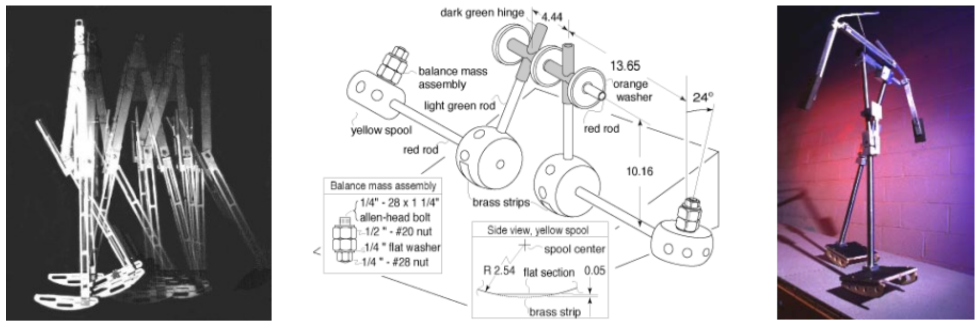
Two approaches have been used to study passive dynamic walking: the computer modeling and simulation approach and the experimental approach. Mathematical and computer models have been widely used to study passive dynamic walking. The nonlinear dynamics of passive walkers were explored with simple models as in [13–17],where the period doubling bifurcations of the passive gait were studied; in [18, 19], where the limit cycle developed by passive walking was examined, and in [16, 18, 20–24], where the orbital and local stability of passive walking was investigated. Liu et al. [25] carried out simulation work to find the effects of parameter variation on the basins of attraction of passive walking models for both the straight and the kneed walker. The slope angle, foot radius, moment of inertia and center of mass were the parameters they varied to study the change of the size of basin of attraction using the cell mapping method [25]. Effects of the dynamic and the geometric parameters of passive walker on gait patterns have also been studied through computer simulations. McGeer first studied the effects of dynamic parameters on the step length and the step period using both straight and kneed walkers. He considered the foot radius, hip mass, leg inertia, leg mismatch, position of the center of mass, etc. as the dynamic parameters of the passive walker. Hass et al. [26] investigated the optimal mass distribution for passive bipedal robots through simulations where they tried to tune the mass distribution to achieve maximum walking speed and stability. In their simulation work, they used a straight legged passive walker model. Some simulation work has been focused on foot shape of the passive walker and tried to find out the optimal foot shape with either arc feet or flat feet [11, 27–32]. Asano and Luo [33, 34] carried out simulation work to prove that the dissipation of energy during the heel strike with an arc foot is less than that of flat foot. This group also studied the effects of the arc feet on step period and walking speed with a knee joint passive walker model. The ankle spring has allowed the use of the flat feet instead of the arc feet and provided similar locomotion [29, 31]. Kuo [35] extended the planar motions to allow for tilting side to side and found that passive walking exists. He also found the rocking motion to be unstable. Wisse et al. [36] proposed a mathematical design for a 3D passive walker with a pelvic body, which compensated the yaw and the roll. The goal here was to understand the characteristics of 3D passive dynamic walkers to use the energy efficiency concept in real world applications. Computer simulation and modeling are powerful tools in the areas where physical experiments are not feasible. But in many cases the computer model has shown poor agreement with the experimental results [10, 37]. Misleading simulation results have been produced. For example, there are some contradictory simulation results regarding the effect of the inclination angle on the step period of the passive walker. Exemplifying this, Goswami et al. [14] reported that step period increases with the inrease of the inclination angle, while some simulations [10, 11, 26] showed the step period decreases significantly. Kuo [38] and Zhao et al. [27] documented that the inclination angle has no effect on the step period. Although there are some differences among the simulation models, it is essential to validate and justify the model with experimental results.

Studying passive dynamic walkers through an experimental approach provides physical insight into passive dynamic walking. They also provide a reference to validate mathematical models of passive walking and prevent misinterpretation of simulation results. Like the computer modeling approach on the biped passive walker, McGeer also built a physical biped passive walker, shown in Figure 1.9a, from Simon

Fraser University [10]. Ruina et al. [39] at Cornell University built a simple two-legged toy, shown in Figure 1.9b, that walked stably down a shallow slope, but was statistically unstable in all standing positions.The first 3D two-legged kneed passive biped walker, shown in Figure 1.9c, was designed and built by the same group [40]. This 3D walker was designed with curved feet, a compliant heel and a mechanically constrained arm, which helped it to achieve stable gait. Success in passive dynamic bipedal walking has boosted the research to develop energy-efficient bipedal walking robots. Using the concept of the passive dynamic biped walker Wisse et al. [20, 41] in Delft University built several energy efficient bipedal walkers. They first developed a straight legged passive walker with hip actuation [20] and then added an upper body to the walker by means of a bisecting hip mechanism [41]. In both works they used the principle of the passive dynamic biped walker. Similarly, Tedrake et al. [24, 42] in MIT developed 3D energy efficient walker to obtain successful gaits. The 3D energy efficient walker built at MIT was not completely passive as it was equipped with position controlled servo motors at the ankle joint to control the roll and the yaw motion. But the hip joint was completely passive. They tried to use the principle of the bipedal passive walker to design the energy efficient walker. Takeguchi et al. [43] inspired by Tedrake's work, conducted simulation and experimental work on the walking mechanism of the 3D passive dynamic motion. Fujimoto's research group in Japan built an improved 2D passive walker, which so far has the highest number of step counts for a fully passive walker [44]. They also studied the effect of the arc feet on the dynamic motion of the passive walker [23] and designed the desired circular arc feet. Trifonov and Hashimoto at Waseda University designed active knee locking mechanisms [45] for the kneed passive walker to create a simpler and easier mechanism to adjust knee locking. Their walker is shown in Figure 1.8. Currently, the physical models have often been restricted to demonstrate the existence of passive dynamic walking [40, 44] and some physical models have been to make the walking energy-efficient [20, 23, 24, 46, 47]. Experimental research on the effects of dynamic and geometric parameters on the passive gait patterns are few in number. There are some experimental works [46, 48, 49], where they built either a straight or a kneed passive walker to perform experimental analysis.

Figure 1.8: Passive dynamic walker with active knee locking mechanism built in Waseda University, Japan

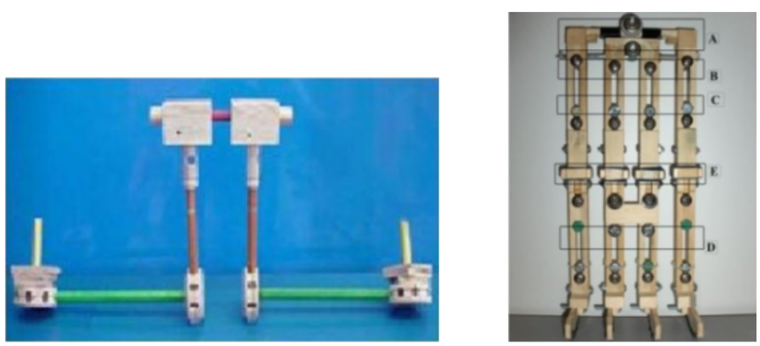
In the University of Manitoba, research on the passive dynamic walker started in 2004. A straight legged passive dynamic walker with flat feet, shown in Figure 1.10a, was first built by Nabil and Wu [50] to conduct experimental gait analysis. Following in 2007, a kneed passive walker with arced feet, shown in Figure 1.10b, was built by Jie and Wu [37] to carry out the same experiments. In 2008, the second kneed passive walker, Dexter, shown in Figure 1.11a, was designed and built at the University of Manitoba. The height of Dexter was more than double that of the Jie's walker. Dexter



(a) (b) (c)

Figure 1.9: (a) McGeer's passive dynamic walker (b) Tinkertoy by Colemen and Ruina (c) 3D passive dynamic walker by Collins

was also used for gait analysis. Also in 2008, Dexter II was designed and built by Koop and Fearly [51], shown in Figure 1.11b. Koop, in 2009, built Dexter MK III, shown in Figure 1.12b, to test the equivalency of test platforms [52]. He showed that testing on a treadmill with a passive walker was equivalent to testing on a ramp. Brien also built a kneed passive dynamic walker [53] in 2009, shown in Figure 1.12a, which gave 1900 steps in one trial. This is the highest number of step counts from a passive walker built by the University of Manitoba.



(a) (b)

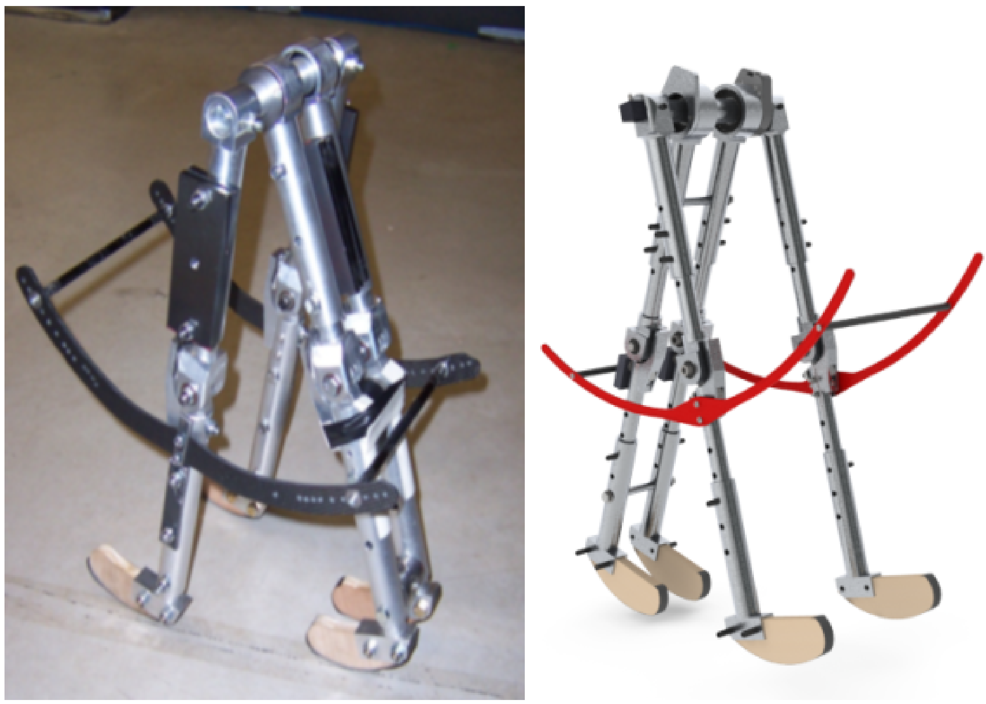
Figure 1.10: Passive dynamic walker (a) Straight legged passive walker with flat feet (b) First kneed biped passive walker from the University of Manitoba

Using the walkers built at the University of Manitoba, effects of the inclination angle, mass distribution, ramp surface friction and the size of flat feet were studied on gait parameters systemetically. However, the previous research [37, 50] suffers from two drawbacks. Firstly, video cameras were used to measure the step length and the step period. Due to the relatively low frequency of the camera, the trend of the changes in the step period, when the dynamic parameters were varied, was not conclusive. Secondly, the previous experiments were conducted on the ramp. Thus, the number of steps was limited by the size of the ramp.

Tuning the dynamic and geometric parameters of the passive walker for steady walking is the toughest challenge. It is a tedious work to hit the perfect combination of such parameters so that the walker is able to provide steady and robust walking. An improved measurement system is required to measure the gait patterns accurately. Also the use of a ramp as a testing platform will limit the trial length. Therefore, a treadmill is required to overcome this limitation. The effects caused by the mechanical differences between a ramp and a treadmill were checked previously [52] and found to have almost similar gait patterns.

(a) (b)

Figure 1.11: Passive dynamic walker with knee joint and arc feet (a) Dexter (b) Dexter II



(a) (b)

Figure 1.12: Passive dynamic walker (a) Brien's walker: Walked 1900 steps in one single trial (b) Dexter III: Designed and built to perform the equivalency experiment of test platforms

1.3 Objectives and Layout of the Thesis

The objectives of this thesis are to investigate the effects of the dynamic and the geometric parameters on gait patterns developed on a treadmill by a passive walker, Dexter MK III. The gait parameters to be analyzed are the step length, step period and hip velocity when different dynamic and geometric parameters, such as the inclination angle, center of mass location, treadmill belt speed, length of flat feet, thigh-shank length ratio of the passive walker are changed. Dexter MK III is equipped with an accelerometer and an encoder. The use of these sensors improves the measurement accuracy and thus allows clear trends of the gait patterns to be found when the dynamic and the geometric parameters are changed. Also a treadmill is used here as the test platform to overcome the limitation of trial length. The research work presented in this thesis with the passive dynamic biped walker is performed with the belief that the investigation of the passive gait patterns experimentally will allow to justify the computer models and also give the opportunity to understand the insights and the the mechanics of bipedal walking.

This thesis is organized as follows: The design of the passive walker is described in chapter 2. The measurement system, experimental setup, experimental procedure and data acquisation and analysis are detailed in section 3. In section 4, results are discussed, followed by concluding remarks in setion 5.

Chapter 2

Methodology

In this chapter the design of the passive walker used in this research will be described. Also, the measurement protocols will be detailed in this chapter in the experimental gait analysis section.

2.1 Design: Dexter MK III

Dexter MK III, shown in Figure 2.1, is the fifth biped passive dynamic walker built at the University of Manitoba and is designed to facilitate the measurement of passive dynamic gait. The legs and the hips of the passive walker were constructed out of aluminum tubes, designed to be strong yet light weight to reduce wear on the bearings and to reduce the amount of mass needed to change the center of mass. The weight of Dexter MK III is 8.35 Kg and the height is 54.62 cm. The leg design allows for the length of the legs to be adjusted and the feet to be interchangeable. The lengths of the thigh and the shank were 26.04 cm and 28.58 cm, respectively. As well, a leg cage is incorporated into the design, which keeps the outer shanks in sync. The leg cage also helps to limit the step length, which aids in the launching procedure. the cage is made of composite material to make it lighter in weight. The feet of Dexter MK III are changeable and supported on both sides to prevent any misalignment. The incorporation of different sensors is taken into consideration during the design of the passive walker. Plastic tape is used as sole of the feet, which also reduced the friction between the feet and the treadmill surface. This tape is required to be replcaed after certain trials as it wears out due to the rubbing against the treadmill surface during walking and the wearing is not symmetric for all four feet. Foam is used to reduce the impact at each knee. These also wear out gradually after several trials and need to be replaced with new foam.

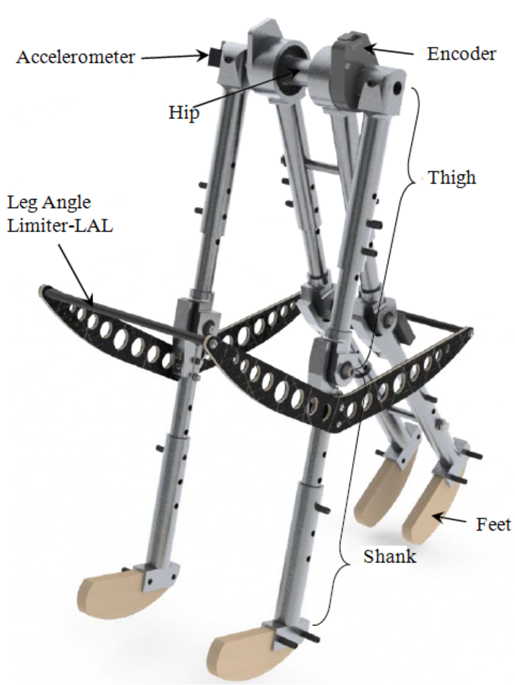


Figure 2.1: Dexter MK III

Not all configurations of the passive walker's parameters produce a steady gait. To tune the passive walker to a steady gait pattern, the length, mass, and mass distribution of the legs of the passive walker were varied. A list of the geometric parameters of the passive walker that were used in the experiments can be found

Item	Symbol	Measurement	Ratio to l
Walker height	l	54.62cm	100%
Thigh length	l_t	26.04cm	47.7%
Shank length	l_s	28.58cm	52.3%
Walker width	W	20.32cm	-
Foot radius	ρ	10.92cm	-
Foot Center	δ	26.78°	-

Table 2.1: Walker Geometric Parameter

in Table 2.1. While tuning the passive walker, a thigh/shank mass ratio of two was qualitatively found to produce a more robust gait than lower ratios. Similarly, a center of mass of the shanks below the midpoint of the shank was also found to produce a more robust gait. However, the dynamics of the passive walker are complex and these trends may be limited to the specific geometric and dynamic parameters tested.

2.2 Experimental Gait Analysis

In this section the protocol of measuring the passive gait parameters will be discussed. This includes the measurement system, experimental procedure and the data analysis.

2.2.1 Meaurement System and Experimental Setup

The step length, step period and hip velocities are the fundamental gait parameters of the passive dynamic walking system. These three parameters are to be measured and calculated for all the trials conducted. To measure and calculate the aforementiond gait parameters an accelerometer, encoder, video camera, data acquisition board and computers were used. The experimental setup consisted of a treadmill, sensors, video camera, tether support and a data acquisition system as shown in Figure 2.2. A tether support frame was used to hold the hanging sensor cables and to support the walker when it loses balance or falls.This support did not interfere with the gait developed of the walker. The data acqusition system shown in Figure 2.3 consisted a data acquisition board and a computer.

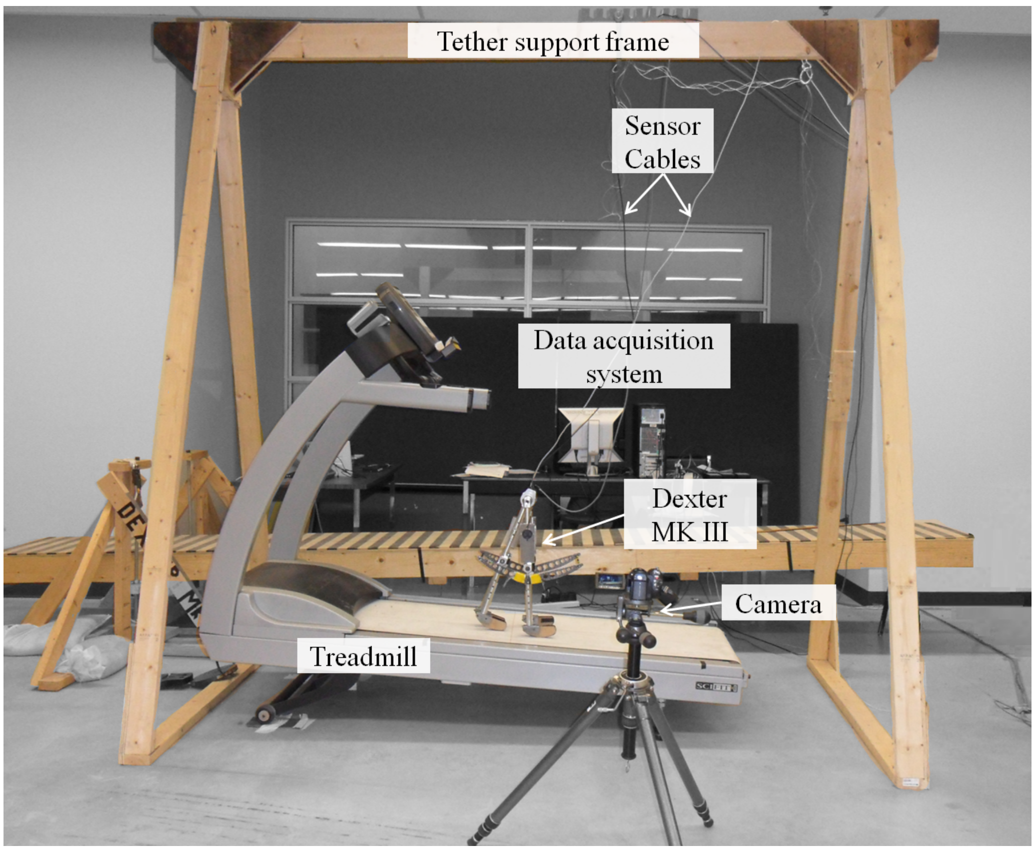


Figure 2.2: View of experimental setup

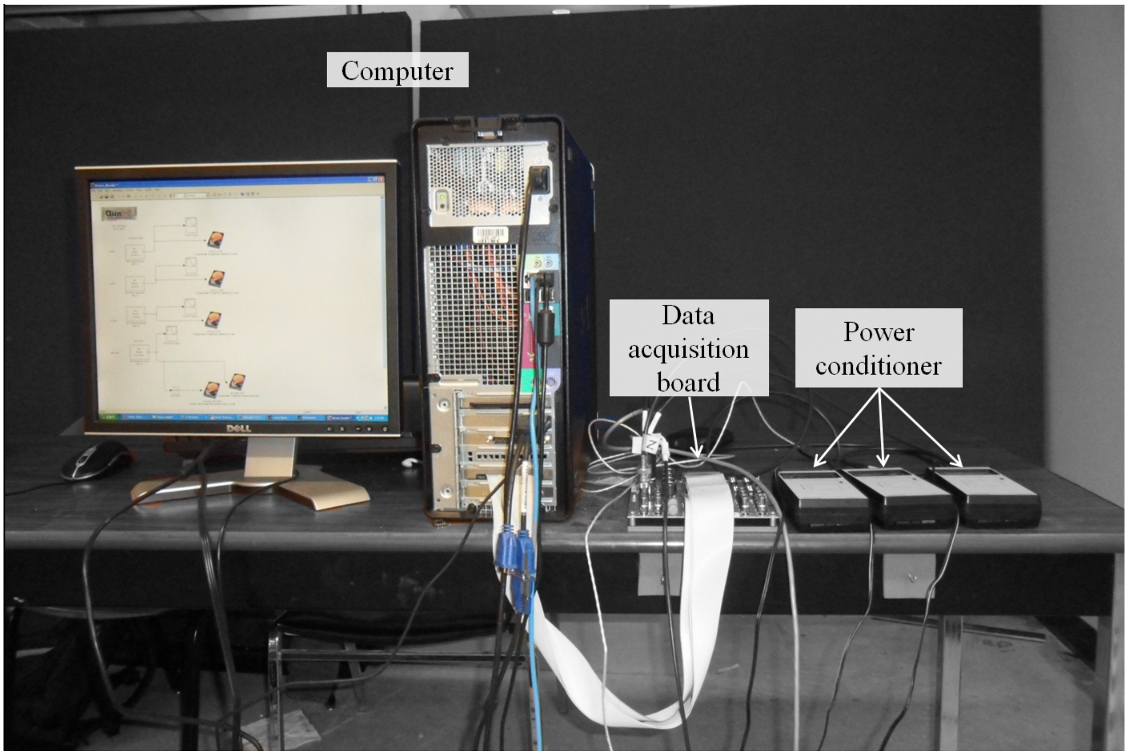


Figure 2.3: Data acquisition system: Computer and data acquisition board to collect and store data. Power Conditioners are used to provide the power to the accelerometer.

The accelerometer was mounted on the hip of the walker, shown in Figure 2.4 and it was a triaxial accelerometer with the range $\pm 5g$.The position of the encoder was on hip of the walker as shown in Figure 2.4. The encoder disk was attached to the hip shaft via a set screw. The sampling rate of the accelerometer and encoder was 1000 Hz. The high frequency of the sensors made the measurement system for the experiments more reliable and efficient. A digital video camera was used to capture all the motion of the passive dynamic biped walker during the trials. Later these videos were used to sync the trials with the data collected from the encoder and the accelerometer. Also, the videos helped to look at the shifting of the passive walker and to find out if there was any external disturbance during walking.

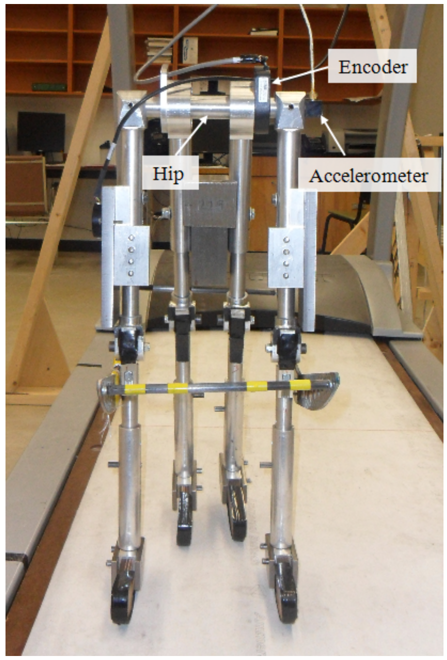


Figure 2.4: Position of the accelerometer and the encoder on Dexter MK III

2.2.2 Experimental Procedure

Experiments were conducted to study the effects of the dynamic and geometric parameters on the step length, step period and hip velocity. Trials were completed with different dynamic and geometric parameters on the treadmill. The previous study [52] showed that the passive walker walking on the ramp and the treadmill had the same trend of gaits. The treadmill was used to have more step counts. For each parameter variation five or more trials were completed. In some cases only three trials were taken due to the unsteady walking of the biped. Various steps were taken to complete each trials. All these steps were followed carefully for each of the trials. The steps are described in the following section.

Initializing Accelerometer

The accelerometer was attached to the hip of the walker by wax, shown in Figure 2.4. The accelerometer was powered by three 12V batteries. The power supply units requiried stabilizing time to settle down at 12V. So the accelerometer's power was tuned on atleast 20 minutes before the time the trial started. Also, the base of the accelerometer was maintained to be parallel with the ground before starting the trial and during the trials a small disturbance on it would result in displacement from the original position. Extra precaution was taken not to touch the accelerometer during the trials.

Initializing Encoder

The encoder provides an incremental quadrature signal and the inclinometer provides an emulated quadrature signal. As a result both of these need to be zeroed on startup. The legs are to be locked to zero the encoder.

Video Capturing

Videos were taken of the passive walker during the trials so that the correct trial could be correlated with the proper data. For this reason the data capture computer was in view of the camera. The video also helped to detect any shifting of the walker during walking. The video was started before starting the trials and stoped after finishing the trials. the video frame covered the whole measurement sytem in order to check any kind of discrepencies or errors during the trials. The video camera was placed at a fixed position for all of the trials, so that later the video could be used for calibration if needed. The position of the video camera is shown in Figure 2.2.

2.2.3 Data Acquisation and Data Analysis

The raw data captured, shown in Figure 2.5 as an example, was used to determine the step length, step period, and hip velocity. A program in Matlab was developed by Koop [52] to automatically sort and analyze the data collected from the accelerometer and the encoder. The program was modified for the flat feet experiments in this thesis. The heel strikes, noted as a square in Figure 2.5, were automatically determined by the program by searching near the inner leg angle maxima and minima.

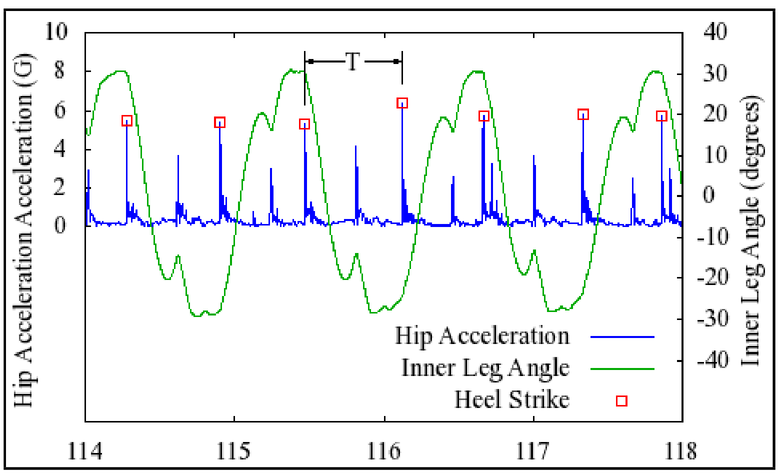


Figure 2.5: Raw data sample

To determine the step period, the program determines the time difference between two consecutive heel strikes (T), shown in Figure 2.5. Note that the impact with a lower acceleration between consecutive heel strikes is due to the impact at the knee extension. Using the location of the heel strikes, the program calculates the step length with the corresponding encoder measurement at the same time. The average hip velocity was calculated by dividing the step length by the step period.

The step length, S, is the distance between the contact points of the two arc feet with the ground shown in Figure 2.6. The angel between the outside and inside leg, inner leg angle (α), was measured by the encoder. Using the inner leg angle, α and the geometry of the walker, the step lengths for the arc feet walker were calculated as shown in Equation 2.1 and 2.2. l is the length of leg, ρ is the foot radius and δ is the angle of the foot center, which are the geometric parameters of Dexter Mk III. Their dimensions are mentioned in Table 2.1. ϕ_1 is used as an intermediate angle to calculate the step length.

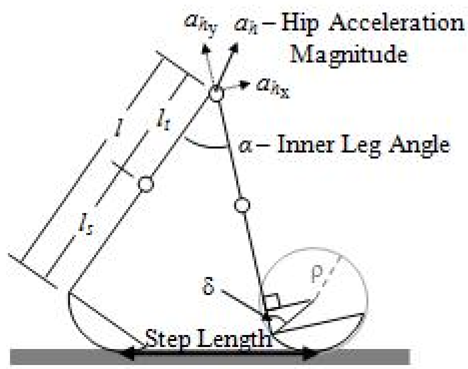


Figure 2.6: Diagram of parameters and measurements with the arc feet

$$\phi_1 = atan\left[\frac{(1-cos\alpha)(l-\rho cos\delta) - sin\alpha(\rho sin\delta)}{sin\alpha(l-\rho cos\delta) + (1-cos\alpha)(\rho sin\delta)}\right] \tag{2.1}$$

$$\begin{aligned} S = & sin\phi_1\left[(1-cos\alpha)(l-\rho cos\delta) - sin\alpha(\rho sin\delta)\right] \\ & + cos\phi_1\left[sin\alpha(l-\rho cos\delta) + (1-cos\alpha)(\rho sin\delta)\right] \end{aligned} \tag{2.2}$$

For the flat feet walker Equation 2.3 and 2.4 were used to calculate the step lengths where, b is the height of the flat foot and l_f is the length of the flat foot. The step length for a flat feet is shown in Figure 2.7.

$$\phi_1 = atan\frac{(l+b)(1-cos\alpha)+l_f sin\alpha}{(l+b)sin\alpha + l_f cos\alpha} \tag{2.3}$$

$$S = (l+b)\left[sin\phi_1 + (1-l_f)cos(\alpha-\phi_1)\right] \tag{2.4}$$

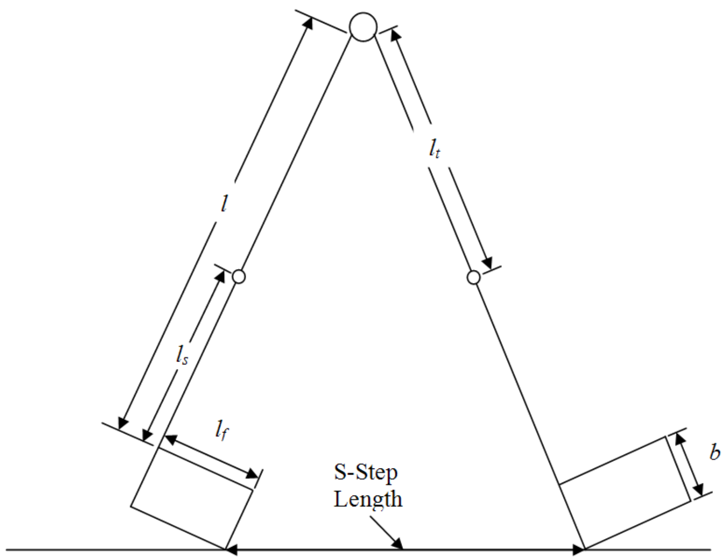


Figure 2.7: Diagram of parameters and measurements with the flat feet

The mean and standard deviation of the gait patterns i.e. step length, step period and hip velocity were calculated over all the trials conducted for each set of parameter variation.

The (in)efficiency of passive walking and the merit of walking are often used to describe the gait patterns of the passive dynamic walker. The walking (in)efficiency is defined in Equation 2.5 [13, 39].

$$\eta = \frac{mechanicalwork}{weight \times steplength} \tag{2.5}$$

The term mechanical work is the amount of energy input to the passive walker. Here, the input energy is converted from gravitational energy. The energy inefficiency on the basis of path distance is $\eta = tan\gamma$, where γ is the ramp angle. For small slopes we can write $\eta \approx \gamma$. Perfect passive locomotion is obtained when $\eta = 0$. The merit of walking is represented by the Froude number or dimensionless velocity, $\frac{V}{\sqrt{lg}}$, where l is the length of the leg [39]. In this work, a non-dimensional form of the gait patterns is also presented. This non-dimensional form will allow the work presented in this thesis to be compared with previous works and also help others in the future to compare with the results published here. Gait patterns result from two different passive dynamic walkers, i.e. the passive walkers have a different physical structure so it is always prefered to compare the results in nondimensional form. The step length is normalized with the walker's leg length l, step period is normalized with $\sqrt{l/g}$ and the hip velocity is normalized with $\sqrt{gl}$ to give a non-dimensional form [39].

Chapter 3

Results and Discussion

The child-sized passive dynamic walker, Dexter MK III, can walk on a treadmill for 1,500 steps without falling. The robustness of walking is high in that with limited practice, it can walk easily on the treadmill. Such a passive walker is used for evaluating the effects of various dynamic parameters on passive gait patterns. The dynamic parameters of the Dexter MK III before performing any changes on it are shown in Table 3.1.

Item	**Thigh**		**Shank**	
Mass(kg) : % of Total	5.793	66.4%	2.929	33.6%
Center of Mass (cm) : % of Limb Length	13.02	50.0%	15.72	55.0%
Radius of Gyration (cm) : % of Limb Length	5.91	22.7%	9.44	33.0%
Total Mass (kg)	8.722			
Thigh/Shank Mass Ratio	1.98			

Table 3.1: Dynamic Parameters of Dexter MK III

3.1 Effects of the Treadmill Inclination Angle

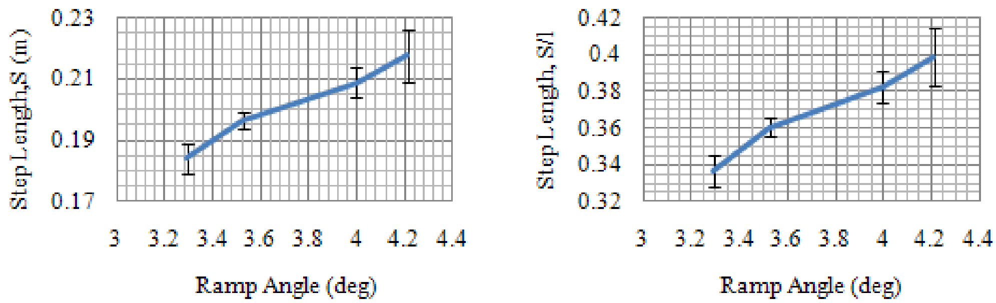
The relation of gait parameters with the treadmill inclination angle will be discussed here. The range of the treadmill inclination angle was between 3.29° and 4.21° for steady walking. The number of trials, average steps for each parameter set and the standard deviation of the parameters are listed in Table 3.2. The measured and calculated gait parameters are shown in Figure 3.1 - 3.3, with the gait parameters as the vertical axis and the treadmill inclination angle as the horizontal axis. The plots of gait parameters versus the treamill inclination angle are placed in two columns. The left column represents dimensional gait parametesr and the right column represents the dimensionless gait parameters. The step length is normalized by the length of Dexter MK III, l, the step period is normalized by $\sqrt{l/g}$ and the hip velocity is normalized by the Froude number, $\sqrt{lg}$ to convert the gait parameter to a nondimensional form.

From Figures 3.1 - 3.3, it can be viewed that increasing the treadmill inclination angle has a significant effect on the gait patterns of the passive walker. The step length, S, shown in Figure 3.1, increases as the treadmill inclination angle increases. However the step period, T, from Figure 3.2 decreases with the increased inclination angle. As a result, the hip velocity increases as shown in Figure 3.3. Both changes in the step length and the step period are significant with low standard deviations.

The robustness of the gait is often referred to the step counts. Table 3.2 shows that at an inclination of 3.53° and 4.0° angle the walker has a higher number of step counts. The effect of changing the treadmill inclination angle on the step length is similar to both of the previous research results using the simulation approach [10, 11, 14, 33] and using the experimental approach [37, 50]. However, the previous simulation results on the effect of the inclination angle on the step period are conflicting, Goswami et al. [14] reported that step period increases with the increase of inclination angle, Kuo

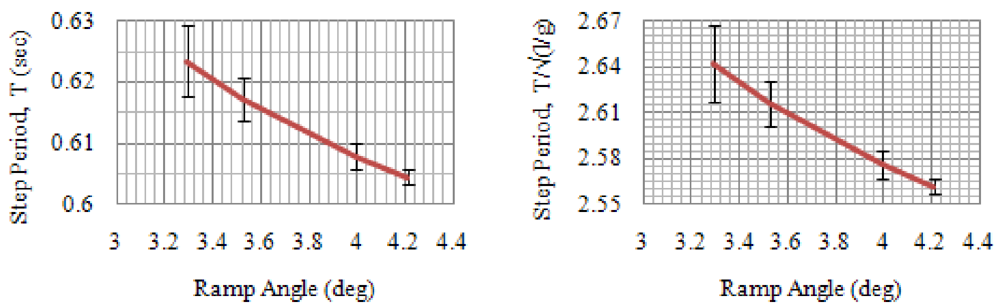
Treadmill Ramp Angle (deg)	No of Trials	Avg. Steps	Step Length		Step Period		Hip Velocity	
			Avg.(m)	Stand. Dev.	Avg.(s)	Stand. Dev.	Avg.(m/s)	Stand. Dev.
3.29	7	10	0.1839	0.0092	0.6234	0.0189	0.2951	0.022
3.53	6	14	0.1967	0.0109	0.6172	0.0211	0.3187	0.0271
4	7	18	0.2088	0.0131	0.6078	0.0194	0.3436	0.0265
4.21	5	9	0.2177	0.0105	0.6044	0.0145	0.3602	0.0233

Table 3.2: Gait Parameters with the Treadmill Inclination Angle



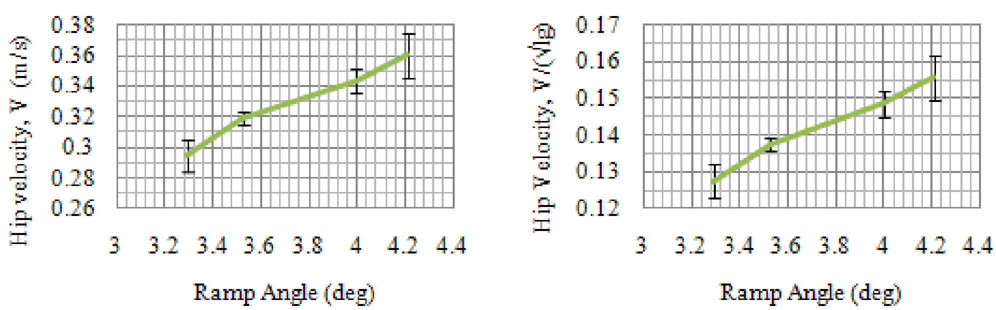
(a) (b)

Figure 3.1: Step length vs treadmill inclination angle (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.2: Step period vs treadmill inclination angle (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.3: Hip velocity vs treadmill inclination angle (a) Dimensional (b) Non dimensional

and Zhao [27, 35] suggested that the inclination angle has no effect on the step period. The measurements of the step period is reliable in this experiment due to a large number of trials that have been conducted. Here, experimental result concludes that the step period has a decreasing trend with an increase of the inclination angle. To the best of author's knowledge, this is the first experimental result showing that the step period decreases with the increase in the inclination angle of the walking surface.

Less mechanical work is required at a low inclination angle, this indicates higher walking efficiency. From the merit of walking viewpoint, the experimental results obtained in this section show that a lower inclination angle results in a shorter step length, longer step period and lower hip velocity, which means a lower merit of walking. The conflict between walking efficiency and merit of walking has also been discussed in the previous work [10, 11, 37, 50]. Since the length of the leg is not changed, the walking speed, in this work, reflects the merit of walking. The average gait parameters from all of the trials conducted during the treadmill inclination angle study are added in Appendex A.

3.2 Effects of Mass Distribution

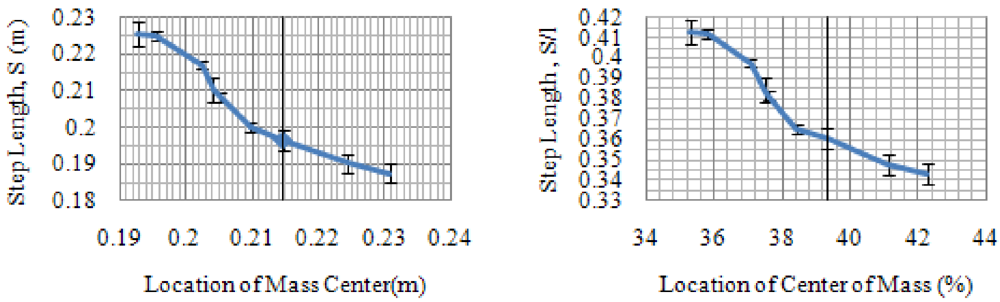
The mass distribution of the biped was altered to change the locations of the mass centers of the thigh and the shank. As a result the static mass center of the passive walker was also changed. Here the static mass center is defined as the mass center of the whole walker measured from the hip when the knees of the walker are fully extended. The static mass center used in this study was 21.47 cm measured from the hip of the walker before making any changes in the mass distributions. From Table 3.3, adding weights only on the thigh raised the center of mass towards the hip and adding weights only on the shank lowered the mass center. Altering the mass distribution also changes the inertia of the legs. McGeer [10] suggested that, changing the radius of gyration of the leg or changing the mass distribution had the similar effects on the gait parameters. This section will discuss how the merit of walking changes with the change in location of center of mass.

In Figures 3.4- 3.6 the gait parameters are plotted on the vertical axis and the location of mass center is plotted in the horizontal axis. Plots on the left column are the dimensional gait parameters and on the right column are the dimensionless gait parameters. The center of mass location is normalized by the walker leg length, l. A solid vertical line is drawn through the static mass center 21.47 cm, which is the mass center of the passive walker without altering the weights. The two points on the right side of the vertical solid line are the gait parameters when the mass centers were lowered. For the other points on the left side of the solid line, weights were added to the thigh, the hip or on both. The last three points on the left end of Figures 3.4 - 3.6 are the gait parameters when the weights were added on the hip, where the center of mass was raised towards the hip. It is observed from Figure 3.4, as the mass center is raised towards the hip, the step length increases. The hip velocity is also dominated

	Position of added mass	Location of the mass center from the hip (cm)	Radius of gyration (cm)	Thigh-Shank mass ratio
Raised Mass Center	Standard	21.47	15.66	2.48
	152gm on inside thigh and 160gm on outside thigh	20.98	15.49	2.61
	400gm on inside thigh and 322gm on outside thigh	20.41	15.47	2.78
	368gm on hip and 160gm on outside thigh	20.25	15.99	2.70
	528gm on hip and 320gm on outside thigh	19.55	16.14	2.83
	507gm on hip and 480gm on outside thigh	19.27	16.11	2.89
Lowered Mass Center	160gm on inside shank and 160gm on outside shank	22.45	16.17	2.19
	160gm on inside shank and 320gm on outside shank	23.09	16.39	2.01

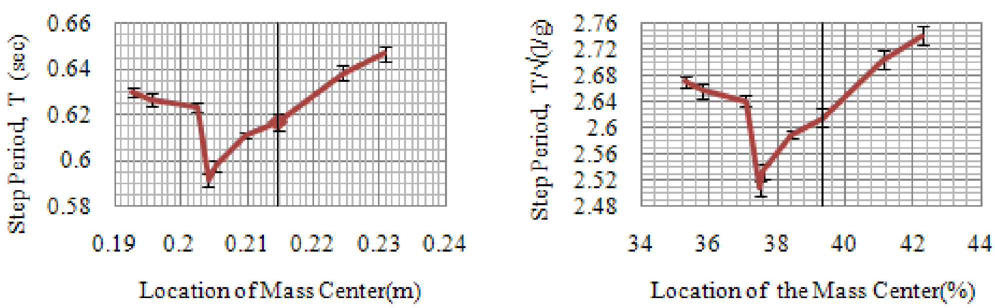
Table 3.3: Mass Center Location with Different mass Distribution

by the step length, i.e., raising the static mass center increases the walking speed. A clear trend is achieved for the step length, which is similar to previous work [37, 50].



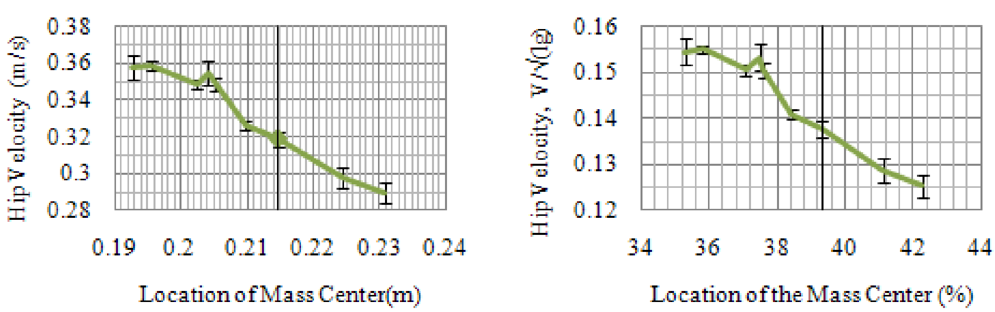
(a) (b)

Figure 3.4: Step length vs center of mass location (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.5: Step period vs center of mass location (a) Dimensional (b) Non dimensional



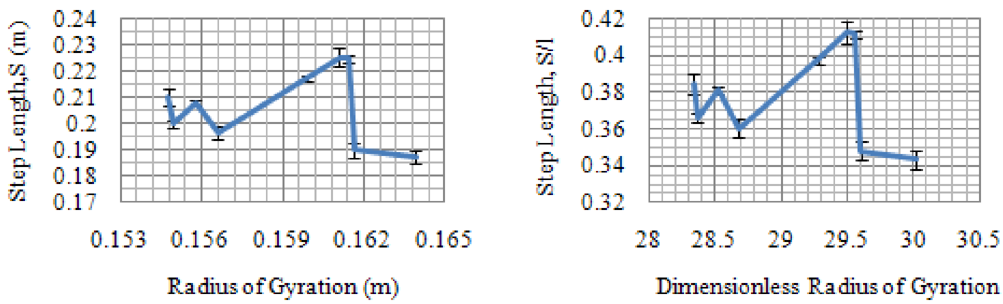
(a) (b)

Figure 3.6: Hip velocity vs center of mass location (a) Dimensional (b) Non dimensional

The step period increases when the weight is added to the shank and the step period decreases when the weight is added to the thigh, i.e. lowering the static center of mass from the original one increases the step period, while raising the static center of mass decreases the step period. This trend is clearly observed in Figure 3.5 except for the last three points on the left end where weights were added to the hip. A different trend is visible for adding weights to the hip. Adding weights to the hip raises the center of mass towards the hip, but it results in an increase in the step period rather than a decreasing of the step period. Three trials with a different mass distribution on hip were conducted and all of the trials provided the same results, which are visible in Figure 3.5. Similar results were obtained in McGeer's simulation work [10].

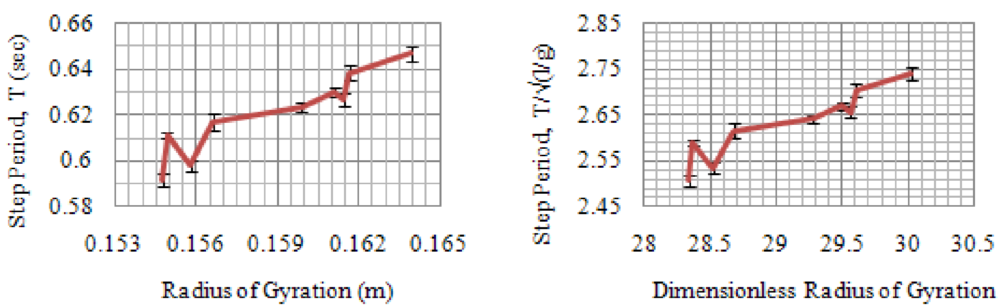
The step length and the hip velocity have a similar trend, as found in previous simulation work [10, 26] and the experimental work [50]. In a previous experimental work [50] due to poor sensitivity of the measuring system no conclusion was drawn on the step period trend, but in this experiment using accurate measuring devices it was possible to find a clear trend for the step period with a change in the center of mass location. It was also observed that when the input energy was fixed i.e. treadmill inclination angle was fixed; raising the mass center can improve the walking merit as compared to lowering the mass center.

When adding weights to a passive walker, there are five dynamic parameters that can be changed: the center of mass of the thigh and the shank, radius of gyration of the thigh and the shank, and the thigh to shank mass ratio. These five dynamic parameters all have an effect on the passive gait. The sensitivity of the gait to these five dynamic parameters is different and it is speculated that the effects of the above five dynamic parameters cannot be simplified as just the change in the location of the static mass center alone. Further research is needed to identify the cause of the change in the trend of the step period when weights are added to the hip.



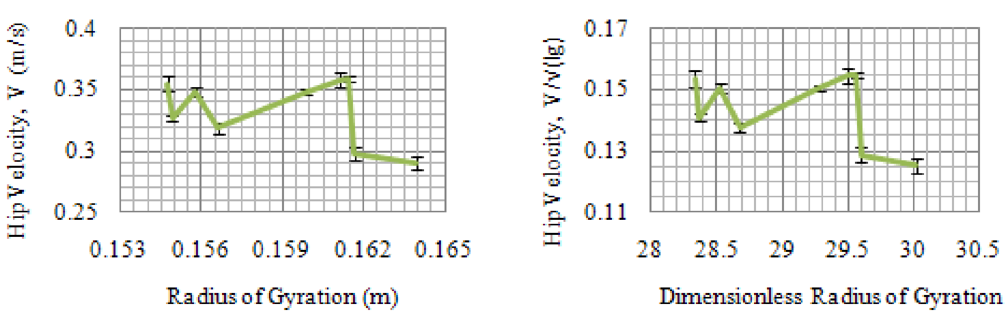
(a) (b)

Figure 3.7: Step length vs radius of gyration (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.8: Step period vs radius of gyration (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.9: Hip velocity vs radius of gyration (a) Dimensional (b) Non dimensional

The gait patterns were also plotted against the radius of gyration of the passive walker. The radius of gyration of the passive walker was changed when weights were added or removed from the walker. From Figures 3.7- 3.9, the gait patterns were plotted on the vertical axis and the radius of gyration was plotted on the horizontal axis. Here, from Figure 3.8 the step period is observed to increase with the increase in the radius of gyration. The step period has an tendency to increase with the increase in the radius of gyration for all of the changes of mass location. Incase of the center of mass location, step period increased only when weights were added to shank and thigh. The step length and the hip velocity of the walker did not have a clear trend with the change of the radius of gyration. McGeer did mention in his work [10] that increasing the radius of gyration of the legs or moving the center of mass towards the hip while keeping the radius of gyration constant would have similar effects on the gait parameters. The change in the radius of gyration for the mass distribution study is plotted against the change in the location of the center of mass in Figure 3.10. This figure does not exhibit any relation between the change in the radius of gyration and the center of mass. Therefore, further studies are required entailing the effects of the radius of gyration on gait parameters to determine whether there is any similarity with the effects of the mass center. Focusing only to the trials when weights were added on the hip, results of the step length, step period and hip velocity has increasing tendency as the radius of gyration increased, shown in Figures 3.11- 3.13.

The weight of the shank and the thigh of the passive walker was different from one another. Also, the amount of weights added or removed from the shank and the thigh were different. So, every time weights were added or removed either from the shank or the thigh, the result was a change in the thigh-shank mass ratio. McGeer [10] suggested in his work to have a thigh-shank mass ratio of 2.5 for steady passive walking.

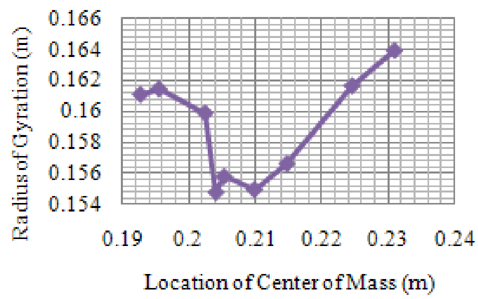


Figure 3.10: Radius of Gyration vs. Location of Mass Center

Before altering the mass location, the thigh-shank mass ratio was 2.49 and this ratio produced the most steady walking. It was also observed that during the experiment, a thigh-shank ratio below 2 did not produce stable or steady walking. Adding mass to the shank reduced the ratio from 2.49 to a ratio approaching 2. The added mass on the shank made the shank heavier which resulted in forward falling. The walker was not fast enough to put its swing leg infront of the stance leg in order to prevent it from falling. Also, when the ratio was above 2.9, it concluded in unsteady walking aswell. Weights needed to be add to the thigh of the walker to make the ratio of 2.49 approach 2.9. Adding weights resulted in making the legs heavier. The result was the same as adding weights to the shank i.e. falling forward. Moreover, as the increased weight made Dexter MK III heavier, the impact of the feet on the treadmill surface was also increased. The treadmill surface was not as hard as the surface of the ramp. The base of the treadmill has only three supports, shown in Figure 3.14. This base has a limit of impact force which it can withstand without any kind of vibration. So, the high impact from the heavy passive walker made the base vibrate, which in return made the passive walker unsteady. Increased impact also means more energy loss during the heel strike.

The gait patterns are plotted on the vertical axis, shown in Figures 3.15- 3.17,

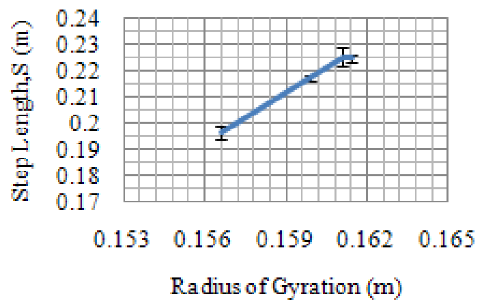


Figure 3.11: Step Length vs Radius of Gyration(mass adeed only on hip)

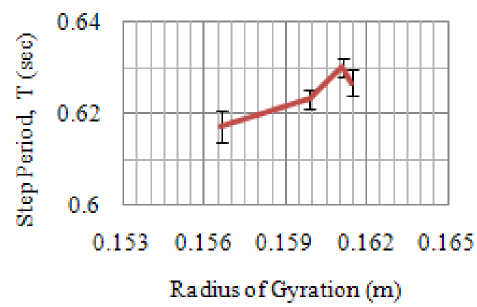


Figure 3.12: Step Period vs Radius of Gyration(mass adeed only on hip)

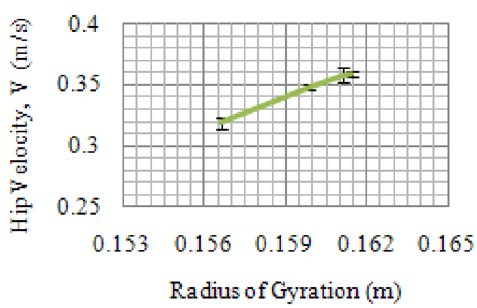


Figure 3.13: Hip Velocity vs Radius of Gyration(mass adeed only on hip)

where the thigh-shank ratio are plotted as the horizontal axis. The left column represents dimensional gait patterns and the right column represents dimensionless gait patterns. Both the step length and hip velocity has an increasing trend with an increase in the ratio between the thigh mass and the shank mass. The step period has a decreasing tendency with the increase of the thigh-shank mass ratio except for the

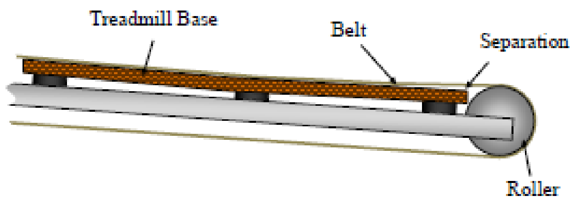
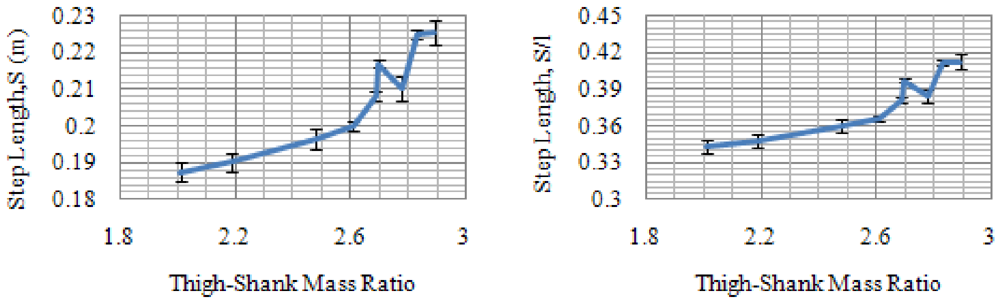


Figure 3.14: Treadmill belt and base

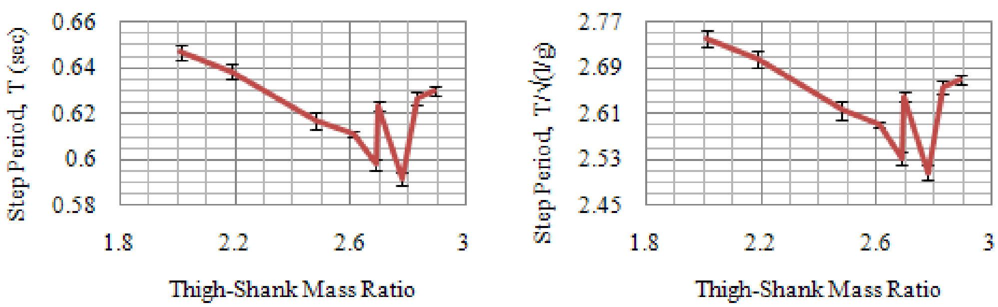
cases when weights were added to the hip. The effects of the thigh-shank mass ratio on gait patterns are opposite to the effects of the center of mass.

The range of the angle of inclination and the center of mass location tested were found to change the step length by 17% and 11%, respectively. However, the range of the angle of inclination tested changed the step period by only 3%, while the range of the center of mass location tested changed the step period by only 9%. Both the range of the angle of inclination and the center of mass location tested had sizable effects on the gait pattern. However, the change in the center of mass location had substantially more effects on the step period, which leads to the conclusion that, like a pendulum, the location of the center of mass is a dominating parameter that effects the period of motion.The average gait parameters from all the trials conducted during the mass distribution study are added in Appendex B.



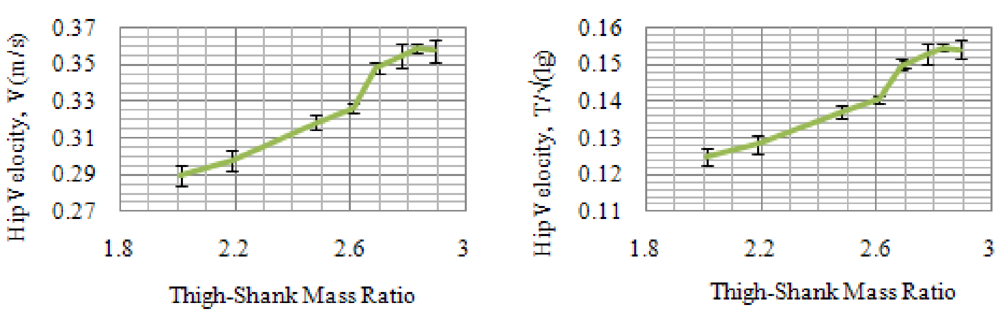
(a) (b)

Figure 3.15: Step length vs Thigh-Shank mass ratio (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.16: Step period vs Thigh-Shank mass ratio (a) Dimensional (b) Non dimensional



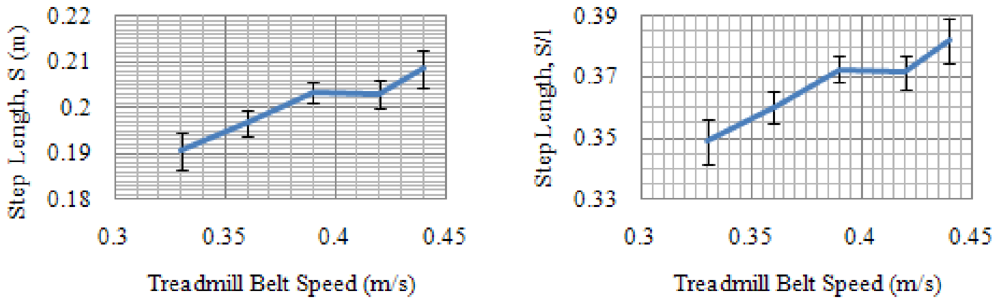
(a) (b)

Figure 3.17: Hip velocity vs Thigh-Shank mass ratio (a) Dimensional (b) Non dimensional

3.3 Effects of Treadmill Belt Speed

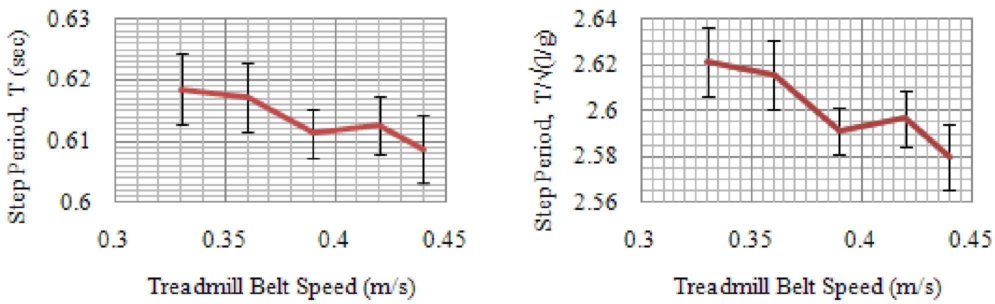
In this section the effects of treadmill belt speed at a fixed inclination angle on gait parameters i.e. the step length, step period and the average hip velocity will be discussed. This study was carried out at a treadmill inclination angle of 3.53° . In Figures 3.18- 3.20 the effects of the treadmill belt speed on the gait parameters are shown. The treadmill belt speed is plotted on the horizontal axis and the gait parameters are plotted on the vertical axis. From Figure 3.18 we see that the step length of the walker increases with the treadmill belt speed and has a low standard deviation. The step period is decreasing in Figure 3.19 with the increase in the treadmill belt speed. Here the amount of increase is low, but the standard deviation is relatively high. The average hip velocity in Figure 3.20 appears to increase slightly with the increasing treadmill belt speed and has a high standard deviation. To the best of our knowledge, we are the first to investigate such an effect.

However, before drawing the conclusion that the walking speed increases with the treadmill speed, it was noticed from the video of the trials for the treadmill belt speed variation, that for 0.36 m/s the walker walks steadily without any shifting. As the speed was decreased to 0.33 m/s the walker had a shifting tendency in forward direction which was visible in the video footage of the trials. Also, when the speed was increased to 0.39, 0.42 and 0.44 m/s the walker had the tendency to shift in the backward direction. Figure 3.21 shows the backward shifting of Dexter MK III when the treadmill belt speed was 0.39m/s. The left column of Figure 3.21 are the steps when the outside feet are striking the heel and the right column are the steps when the inside feet are striking the heel.The first row left column represents the first step of the outside leg and the right column represents the first step of inside leg. Both the position of the inside and outside legs are marked with a coloured



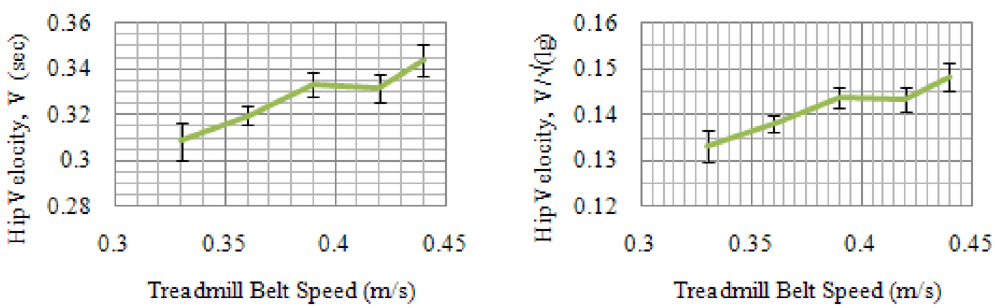
(a) (b)

Figure 3.18: Step length vs treadmill belt speed (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.19: Step period vs treadmill belt speed (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.20: Hip velocity vs treadmill belt speed (a) Dimensional (b) Non dimensional

bar to show the position of the leg during that steps and the number above the bar represents the step number. It can easily be viewed from the figure that for each step the walker is shifting in the backward direction. The shift of the walker indicates that the walker cannot adapt to the treadmill belt speed. Thus the gait parameters shown in Figures 3.18- 3.20, especially the hip speed, is the relative speed with respect to the treadmill, rather the absolute speed with respect to the ground. Schenau [54] had argued that the mechanics of locomotion on the treadmill are similar to that of over ground locomotion as long as the velocities during treadmill and over ground locomotion are constant. With the observed shifting, it is speculated that the walking speed relative to the ground should remain constant in spite of the changes in the treadmill speed. This is due to the fact that when the inclination angle is fixed, the energy input to the passive walker is fixed. As the dynamic parameters, i.e. center of mass, shank-thigh ratio etc. are fixed; the walker should have the same merit of walking. Thus the experimental results show that the merit of walking is uniquely determined by the geometric and dynamic parameters of the walker.

The same experiment with a different treadmill ramp angle was also carried out. It would be nice to have another set of trials for the treadmill belt speed study with inclination angle variation to verify the previous result conducted with an inclination angle of 3.53° . The treadmill inclination angle was 4° while carring out the experiment. The treadmill belt speed 0.39 m/s was the suitable speed for the walker at a 4° treadmill inclination angle to have steady and robust walking. It was difficult to obtain any trend with the belt speed variation with this inclination angle as the passive walker was very sensitive to the belt speed. The high standard deviation and low change in results of gait patterns did not indicate any trend. The average gait parameters from all the trials conducted during the treadmill belt speed study are added in Appendex C.

During the backward shifting at a high treadmill belt speed, it was observed that the cables attached to the walker for safety reasons and the data cables pulled the

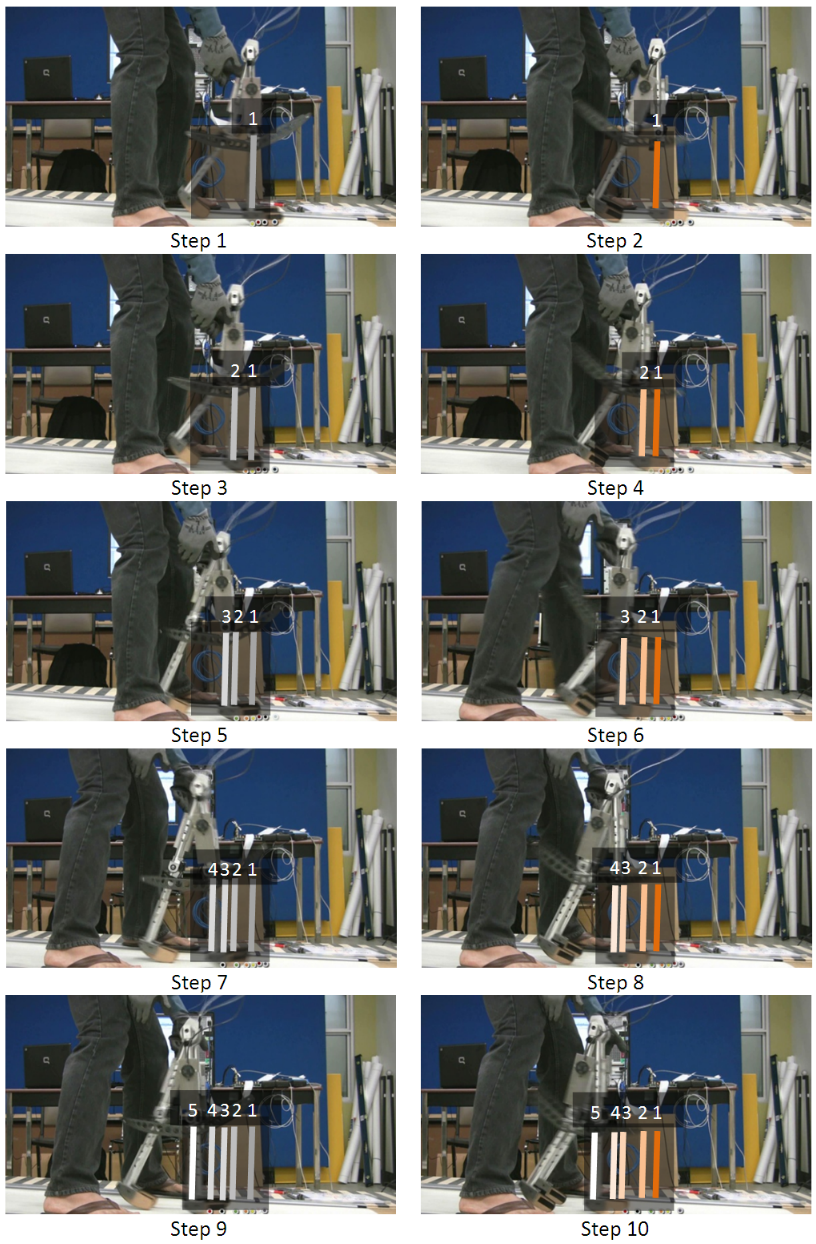


Figure 3.21: Shifting towards backward direction

walker, and the walker still continued to walk and adapted to the new walking speed. This observation shows the robustness of the passive walker to the external force and the adaptability of the walker to the new treadmill belt speed with some assistance from the external force.

3.4 Effects of Length of the Flat Feet

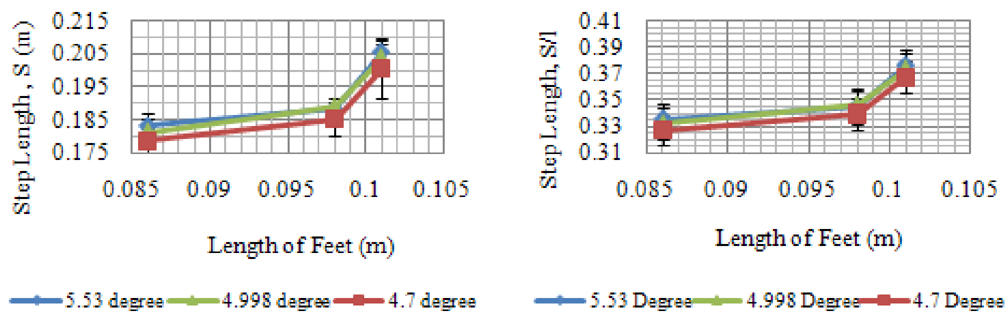
Research with passive walkers was mostly carried out with arc or semicircular feet. McGeer stated that the semicircular foot was considered for mathematical convenience rather than a physical necessity [10]. Only a few studies have been completed regarding the effects of flat feet on passive dynamic walking and most of the studies were completed using mathematical models and simulations. Here the author intends to explore the relationship between the length of the flat feet and the gait parameters. The width of the flat feet was fixed, but the lengths of the flat feet were varied to 0.086m, 0.098m and 0.101m. The heel was connected to the shank of the walker as shown in Figure 3.22. So there was no provision to vary the feet ankle ratio as discussed in the literature [29, 32]. Three different ramp angles (5.53°, 4.998° and 4.7°) were used to conduct the experiment, where all the previous works were done at a constant ramp angle [29, 30, 32]. Here the effects of the length of the flat feet on the gait parameters of the passive dynamic walker are discussed. Figure 3.23- 3.25 shows the relation between the step length, step period and hip velocity with the length of the flat feet. The above gait parameters are plotted on the vertical axis and the length of feet on the horizontal axis. Dimensionless gait parameters are also plotted here against the length of the flat feet, shown in the figures on the right column.

From Figure 3.23, we see that the step length of the walker increases with the length of the flat feet. This trend is consistent in all inclination angles of the treadmill. This finding is similar with the previous work [28, 29, 32]. The step period, shown in Figure 3.24, increases with the increase in the length of the flat feet. This is also consistent for all three inclination angles used here. This result of step period, to the best of author's knowledge is the first documented from this experiment. With the data collected in this experiments, the changes in the hip velocity of the passive

Figure 3.22: Diagram of the flat feet

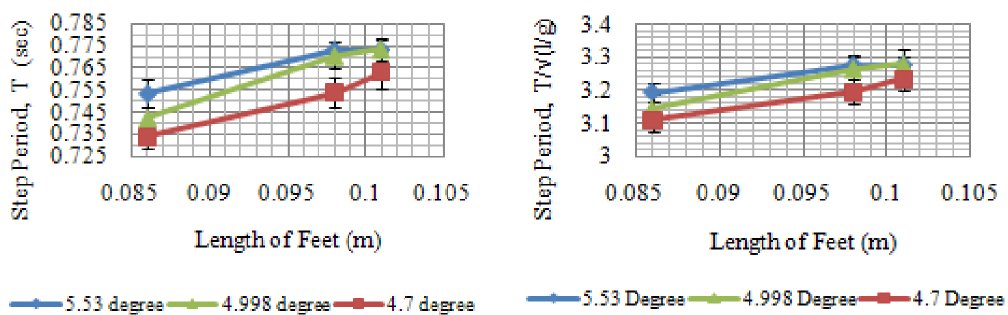
walker is not significant as the length of the flat feet increases due to the relatively high standard deviations as shown in Figure 3.25. The hip velocity results indicate that although the length of the flat feet has effect on the step length and the step period, it has a small effect on the merit of walking. We can see that for the flat feet, higher inclination angles are required for steady walking then those of arced feet. This higher energy is expected as the biped with flat feet requires higher energy to transport the support from the heel to the toe and to rotate the flat feet in order to initiate the next step. Although a flat foot resembles human like walking, it also requires high ramp angles, which means lower efficiency as compared to an arced feet.

The increase in step period with the increase of the inclination angle is noticed for the same flat feet, which is contradictory to the results using arc feet. Kinugasa et al. [49] got a similar trend of the step period versus inclination angles. However, in their experiments, the leg lengths and the inclination angles were changed simultaneously. Thus, it was hard to conclude whether the increase in the step periods was due to the effect of the inclination angle or the leg lengths. In our experiment, flat feet experienced higher friction and lower impact with the walking surface as compared to



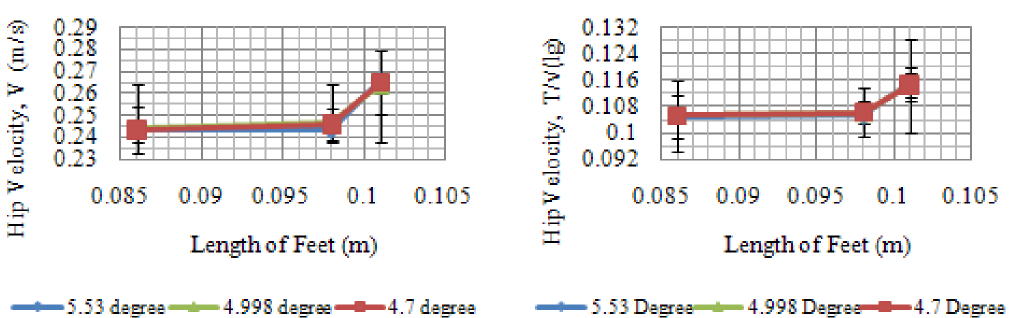
(a) (b)

Figure 3.23: Step length vs length of flat feet (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.24: Step period vs length of flat feet (a) Dimensional (b) Non dimensional



(a) (b)

Figure 3.25: Hip velocity vs length of flat feet (a) Dimensional (b) Non dimensional

those experienced by the arc feet. High friction prevented the walker from walking steadily. It was noticed that the robustness of passive walking with flat feet was

Type of Feet	Inclination Angle	Step Length (m)	Step Period (sec)	Hip Velocity (m/s)
Arc Feet	3.53°	0.1967	0.6172	0.3187
Flat Feet (0.086m)	4.7°	0.1786	0.7337	0.2434

Table 3.4: Comparison between Arc Feet and Flat Feet

low as it was more difficult to launch successful passive walking with the flat feet as compared to the one with the arc feet. As a result, the standard deviations of the gait parameters were higher than the one of the arc feet. The smallest flat feet, 0.086m was taken to compare it with arc feet. It was found with a 0.086m flat feet, a 17.65% change in the inclination angle has effects on the step period and the step length. Step period has increased by 2.65% and step length has increased by 2.52%. But, the inclination angle has no effects on hip velocity i.e. the merit of walking has not changed with the increase of inclination angle. Increased inclination angle means higher energy input, high friction and the mechanism of motion of the flat feet have consumed the most amount of energy, which caused the increased energy to affect the merit of walking. The merit of walking of the walker equipped with the flat feet is much lower than the arc feet walker, shown in Table 3.4.

In addition, Dexter MK III was specially designed and tuned for the arc feet. It is recommended here, in future work, to have the biped specifically tuned for the flat feet and that a more rigid treadmill is required to perform more measurements in order to find the effect of the inclination angle on the flat feet passive walker's gait patterns. Flat feel with ankle joints will provide arc feet like walking . Literature review also suggest to have ankle joints in the flat feet to have steady and robust walking. The average gait parameters from all the trials conducted during length of the flat feet study are added in Appendex D.

3.5 Effects of the Leg Length

The design of Dexter MK III allows to change the length of the thigh and the shank. This change results in the variation of other parameters, such as the length ratio of the thigh and the shank, total leg length, center of mass location and the radius of gyration. Such variation affects the gait parameters. It was intended to study the effects of variation in the length of legs on gait parameters by changing the leg lengths only i.e. keeping other geometric and dynamic parameters constant. But, I was successful in achieving steady gaits by varying both the leg length and the inclination angle. Thus in this section, the results of the gait paramters are plotted against the locations of the mass center and the angle of inclination. The change of the center of mass location and the radius of gyration with the leg length variations are shown in Table 3.5.

Gait paramters i.e. the step length, step period and hip velocity are normalized and plotted against the center of mass location and the inclination angle in Figures 3.26-3.28. It is hard to find the effect of the center of mass on the gait patterns as the inclination angle has an effect on it simultaneously. But, it was easy to find out the effects of center of mass location when it was varied by means of mass distribution.

The change in the length of legs changed the radius of gyration of the walker. The gait parameters are also plotted against the dimensionless radius of gyration and the inclination angle, shown in Figures 3.29 - 3.31. Similarly the individual effect of the radius of gyration on the step length, step period and hip velocity is hard to determine.

Kinugasa et al. [49] similarly conducted an experimental study on a straight legged passive walker and found that increasing the length of legs would increase the step length, step period and hip velocity. But, they also increased the inclination angle

Leg length (cm)	Thigh length (cm)	Shank length (cm)	Ratio	Center of mass location (cm)	Radius of gyration (cm)
54.61	26.035	28.575	0.911	21.47	15.66
52.07	26.035	26.035	1	21.12	14.98
49.53	26.035	23.495	1.11	20.62	14.11
52.07	28.575	23.495	1.22	21.59	15.09
54.61	28.575	26.035	1.09	22.09	15.95

Table 3.5: Mass center location and radius of gyration with different leg length

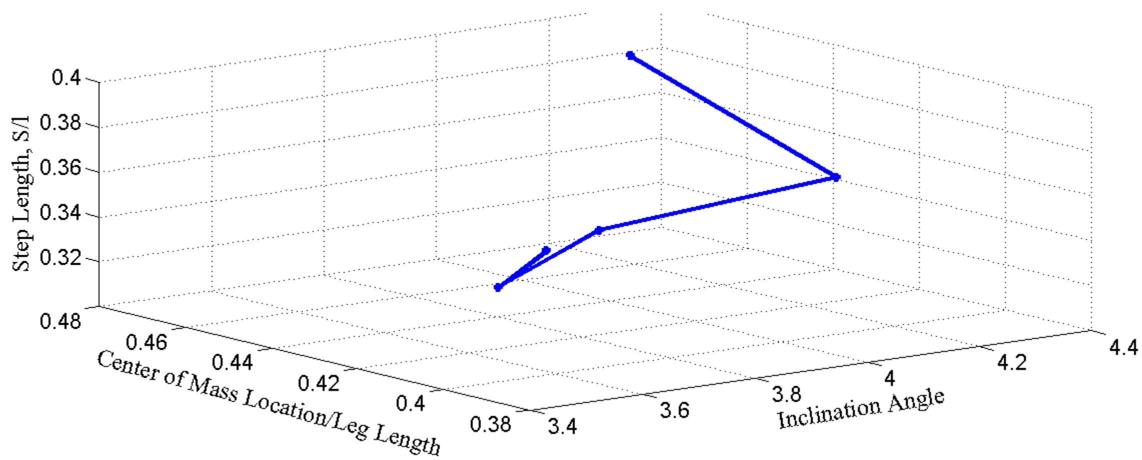


Figure 3.26: 3D plot of step length as a function of inclination angle and dimensionless center of mass location

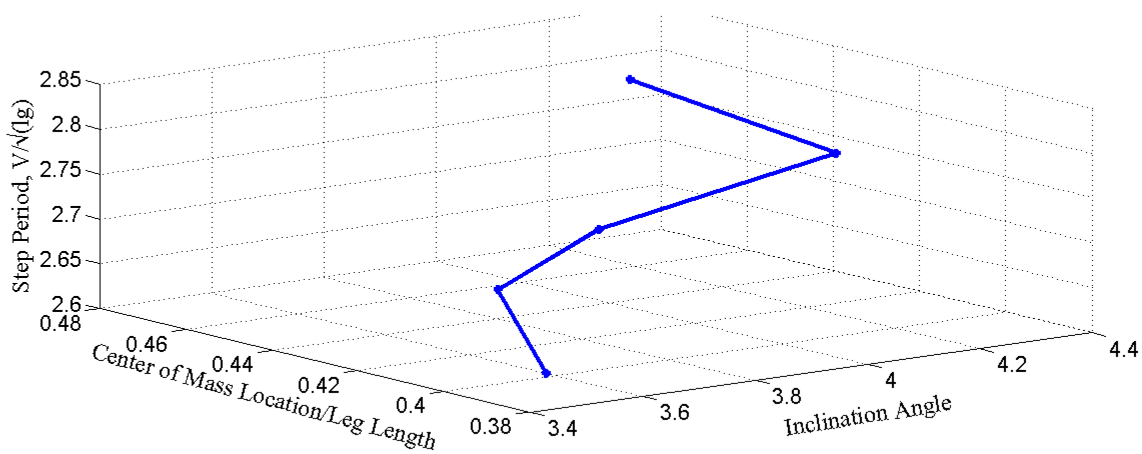


Figure 3.27: 3D plot of step period as a function of inclination angle and dimensionless center of mass location

with the increase of the length of legs to achieve periodic gait. It is meritorious to express the results in dimensionless gaits and dimensionless dynamic parameters of the passive walker. In Section 2.2.3, the normalization procedure of gait parameters are described. This will help to compare the results collected by Dexter MK III with the result of Kinugasa et al. [49], as the two walkers used were different in their physical

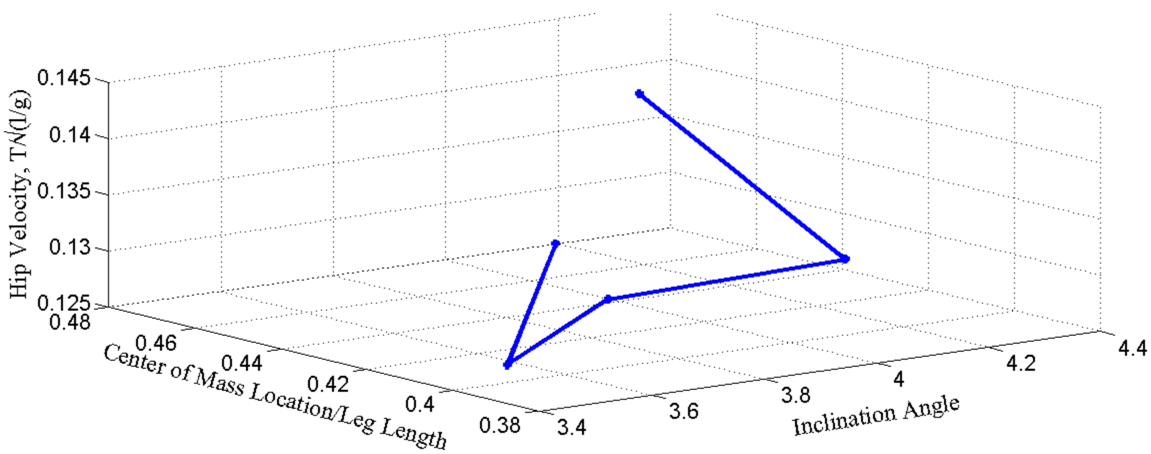


Figure 3.28: 3D plot of hip velocity as a function of inclination angle and dimensionless center of mass location

model and had different dynamic parameters. Five different combinations of thigh and shank lengths were used to conduct the experiment with Dexter MK III. Among them three combinations selected where the changes in the shank or the thigh increase the total length of the Dexter MK III and make it comparable with the walker used in [49]. The gait parameters measured from these three combinations are plotted against the dimensionless center of mass location. The mass center is normalized by the total length of the leg of the passive walker. Similar normalization is also done to the results of Kinugasa et al. [49] , as they only showed the results in a table format. The dimensionless gait parameters are plotted against the dimensionless center of mass location and inclination angle, shown in Figures 3.32 - 3.34. It is observed from the figures that all the dimensionless gait parameters have an increasing trend with the dimensionless center of mass location for both the passive walkers.

The center of mass location was varied earlier by changing the mass distribution and the results obtained for the gait parameters were also plotted agianst the dimensionless center of mass location, shown in Figure 3.4b, Figure 3.5b and Figure 3.6b. Only the

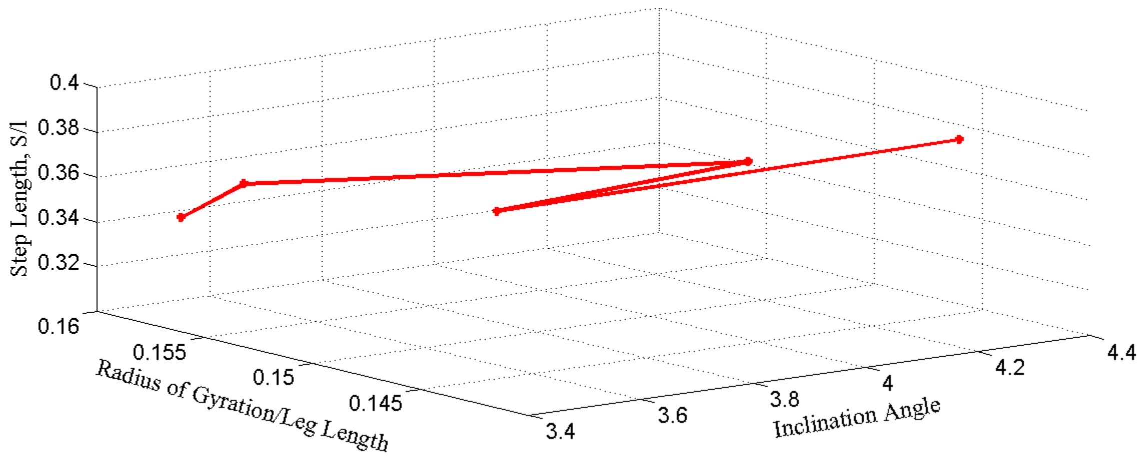


Figure 3.29: 3D plot of step length as a function of inclination angle and dimensionless radius of gyration

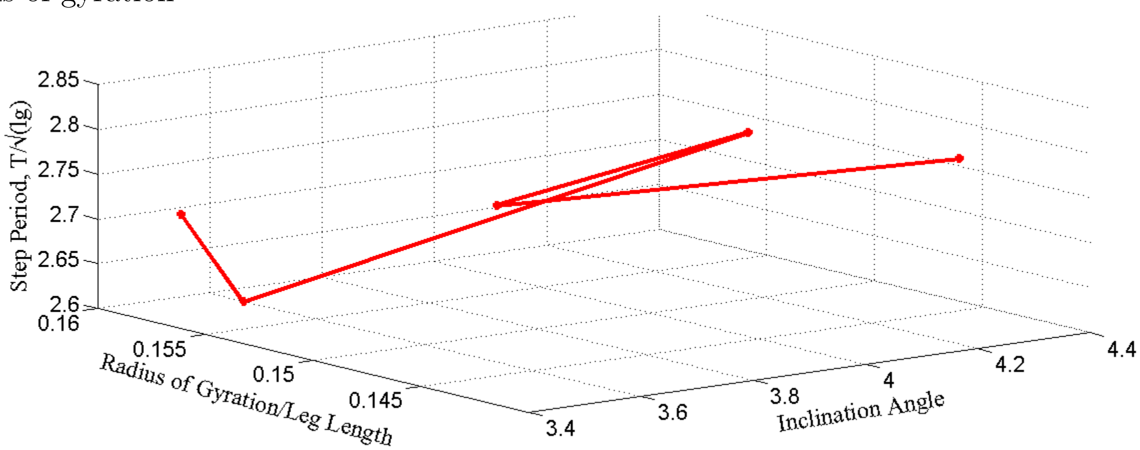


Figure 3.30: 3D plot of step period as a function of inclination angle and dimensionless radius of gyration

dimensionless step period follows the similar trend when center of mass location was varied either by mass distribution or by changing the leg length. The dimensionless step length and hip velocity from mass distribution followed opposite trends with respect to the results obtained by changing leg length. The incliantion angle might made the difference between mass distribution experiment and leg length variation experiment as the inclination angle remained constant during the mass distribution

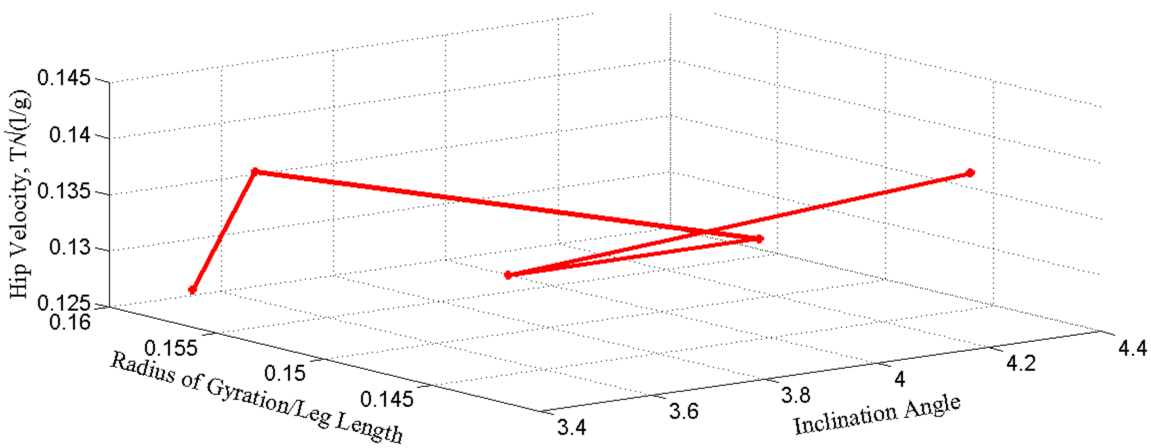
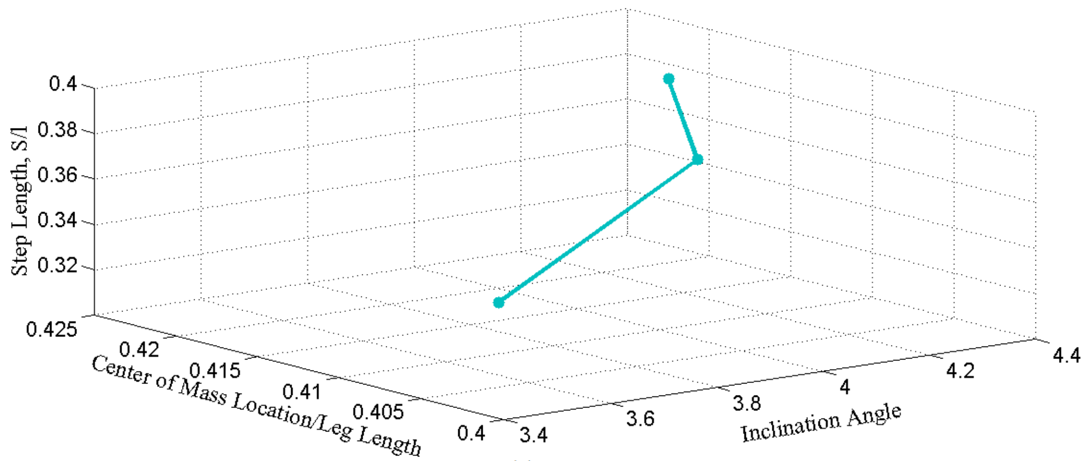


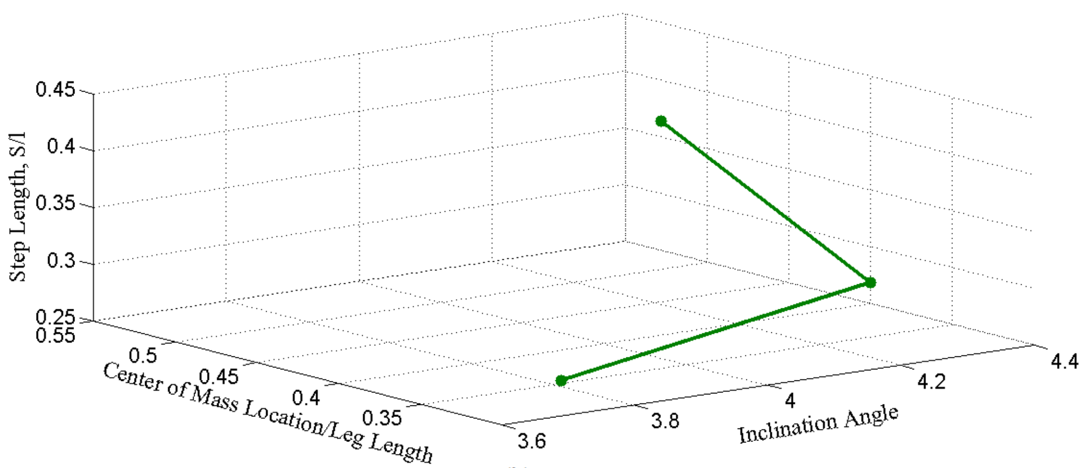
Figure 3.31: 3D plot of hip velocity as a function of inclination angle and dimensionless radius of gyration

case and varied for the latter case.

It is difficult to draw any conclusion on gait parameters with the leg length variation. Multiple factors affecting the gait patterns is one of the main reasons for this inconclusive results. The variation in the length of the thigh or the shank has changed the center of mass location of over all walker as well as the ratio of the thigh and the shank length. Furthermore, it was not possible to conduct experiments for all leg lengths at a constant inclination angle. A private discussion with Kinugasa, one of the authors of [49], was done by email. Kinugasa also confirmed the sensitivity of the passive walker to the leg length variation. In their work, they have also varied the inclination angle with the length of legs. The experiments described in the inclination angle study (section 3.1) and the mass distribution study (section 3.2) were relatively easy to perform as the walker was designed for such experiments. To carry out the study of the effects of variations in the length of the legs, passive walker should be designed in such a way that the effects of multi factors can be reduced as much as possible. The following recommendations are made from the experiences gathered



(a)



(b)

Figure 3.32: Step length as a function of the dimensionless center of mass and the inclination angle (a) Dexter MK III (b) Passive walker of Kinugasa et al.

particularly from this experiment described in this section.

1) Conduct the variation in the length of legs study keeping the ratio of the length of the thigh and the shank the same in every trial i.e. increasing or decreasing the thigh and the shank length at the same ratio.

2) Keep the total leg length of the walker constant in every trial, this is possible

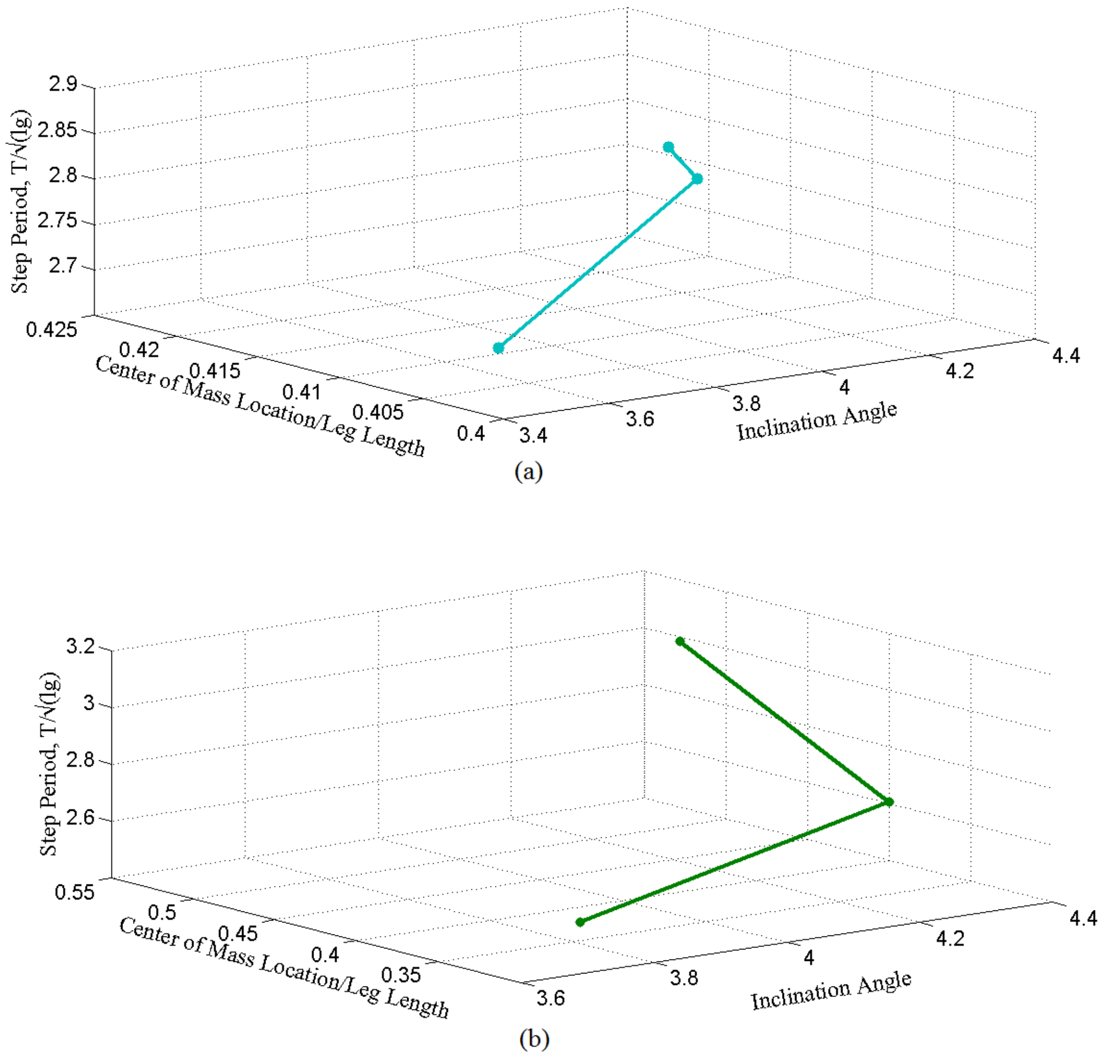


Figure 3.33: Step period as a function of the dimensionless center of mass and the inclination angle (a) Dexter MK III (b) Passive walker of Kinugasa et al.

by increasing the thigh and by decreasing the shank or vice versa.

3) Changing the length of thigh and the shank in such a way that the over all center of mass location or the radius of gyration remains constant or tuning the mass distribution of the thigh or the shank to keep the center of mass location constant.

The average gait parameters from all the trials conducted during the variation in

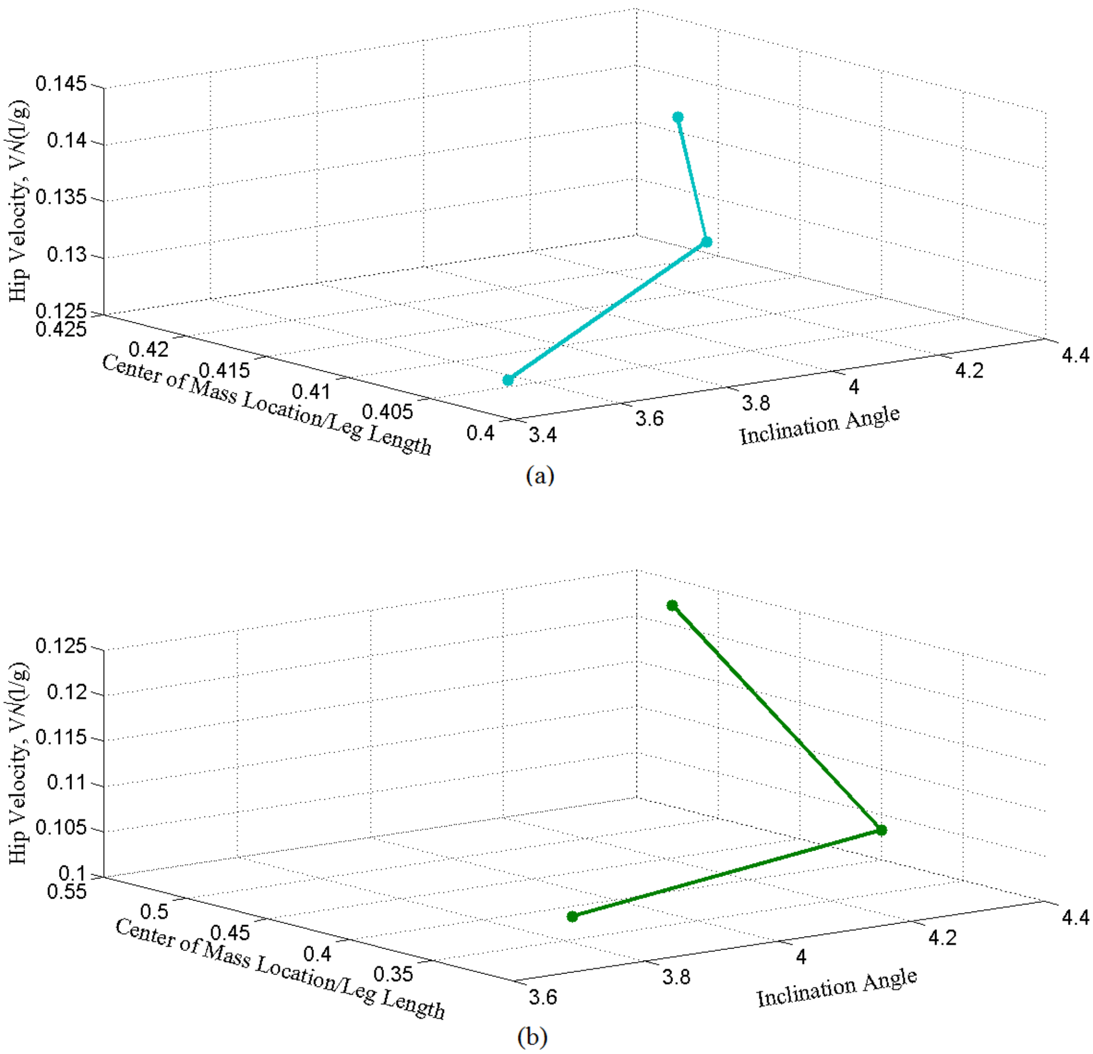


Figure 3.34: Hip velocity as a function of the dimensionless center of mass and the inclination angle (a) Dexter MK III (b) Passive walker of Kinugasa et al.

the length of the legs study are added in Appendex E.

Chapter 4

Conclusion and Future Recommendation

4.1 Conclusions

In this thesis experimental research has been carried out to evaluate the effects of the dynamic and the geometric parameters on passive dynamic walking. Dexter MK III walked on the treadmill for 1,500 steps without falling. Equivalence between the passive gait on a ramp and a treadmill with Dexter MK III was established. Dexter MK III and a treadmill were used to evaluate the effects of the dynamic and the geometric parameters on the passive gait parameters i.e. the step length, step period and hip velocity. The dynamic and the geometric parameters include the the treadmill inclination angle, location of the center of mass, treadmill belt speed, length of flat feet and thigh-shank length. The indication of such effects in terms of the walking (in)efficiency and the merit of walking was discussed.

The conclusions for this thesis are seperated into five sections: the treadmill inclination angle, mass distribution, treadmill belt speed, flat feet length, thigh-shank length. These sections provide final statement on their respective experimental studies.

4.1.1 Treadmill Inclination Angle

It has been found that the inclination angle has significant effects on passive gait patterns. To be specific, increasing the treadmill inclination angle increased the step length, while decreasing the step period, which leads to a higher walking speed. The energy efficiency of the passive walker depends on the inclination angle of the treadmill. The increase in the treadmill inclination angle indicates higher energy input, i.e. lower energy efficiency. The merit of walking (defined in Section 2.2.3) depends on the hip velocity of the passive walker. The increase in the hip speed indicates the improvement in the merit of walking. Thus the extra energy input with a higher treadmill inclination angle is converted to the merit of walking, i.e. higher walking speed.

4.1.2 Mass Distribution

Raising the mass center towards the hip increases the step length and decreases the step period except for the cases when the weights were added to the hip of the walker. The hip speed increased as the mass center was raised, regardless of the way in which the mass center was raised. The increase of the hip velocity indicates that as the energy input is fixed i.e. the inclination angle is fixed, the merit of walking can be improved by raising the mass center. Regarding the change in the step period when the weights were added to the hip, it is speculated that other dynamic or geometric parameters rather than the location of the static mass center may play a more important role, and further research is needed.

Mass distribution also changes the the thigh-shank mass ratio. This mass ratio also affects the gait patterns. The merit of walking can be improved by increasing the thigh-shank mass ratio. The thigh-shank mass ratio and the location of mass center of this study have the same effects on gait patterns. But, for every passive walker design this ratio has a boundary limit beyond which the walker will be unable to produce steady gaits.

4.1.3 Treadmill Belt Speed

The passive walker was also tested on the treadmill with a fixed inclination angle, but varying belt speed. It was found that with the "right" belt speed, the walker can walk on the treadmill without shifting. While as the belt speed was changed, the shift cannot be avoided, indicating that the merit of walking depends on the mass distribution of the bipedal walker. Also, it was observed that the walker can withstand an external force to a certain degree.

4.1.4 Length of Flat Feet

The effects of length of the flat feet on the passive gait were also investigated. Although the trends of the increases in the step length and the step period were observed, the standard deviation is higher than other measurements, and the amount of changes are relatively low. The merit of walking for a fixed length of the flat feet is not sensitive to the inclination angle. Additional future research is required to confirm these findings. Tuning the passive walker specifically for the flat feet and using a more rigid treadmill are recommended as well.

4.1.5 Thigh-Shank Length

The leg length i.e. the thigh length and the shank length was also varied to investigate the effects on passive gait. It was hard to find an individual affect of the length of the legs on the gait parameters, the inclination angle was changed in order to produce steady walking. It was also observed that for a certain thigh-shank length ratio the walker provided most robustness and steady walking. So for every passive walker there is a certain combination of the thigh and the shank length for which the walker would be energy efficient as well as have a reasonable merit of walking. The sole effect of the length of the legs on the gait parameters can be idealy achieved by making other dynamic and geometric parameters constant. It is desirable to explore these possibilities to design such an ideal walker.

The high sensitivity of the measuring system enabled this thesis to successfully evaluate the effects of the dynamic and the geometric parameters on passive gait. Such an evaluation helped to better understand the passive walking mechanics. The results will also help to validate the mathematical models of the passive biped walker.

4.2 Future Recommendation

Even though Dexter MK III was well designed and provided 1500 steps of walking, its weight was high. It was not possible to add more weights to it to change the mass center location. So in the future it is recommended to use lighter material like magnesium alloy or composite materials to construct the passive walker. It is better to have passive walkers only designed and tuned for the flat feet to carry out the experiments. This kind of walker will provide more opportunity to vary the dynamic parameters and observe the effect on gaits using the flat feet. Also, the length of leg variation study can be performed more accurately by using a walker which is designed for such a study as mentioned earlier. The walker should be designed with nuts and bolts for the joints instead of a pin joint. It is tedious work to disassemble any joint if it is a pin joint. Also a press machine is required to take out the pin from the joint.

The treadmill used in this research work was not as rigid of a surface as it must be. A heavy passive walker will result in bouncing and shaking of the treadmill surface board. It will be more advatageous to use a treadmill with a more rigid surface. The surface of the treadmill can be sensored with a force measuring sensor, which would help to measure the pressure force of the walker. Also using encoders at the knee joint will provide the opportunity to find the knee angles during walking, which will help to calculate the dynamic center of mass of the whole passive walker.

A research group in Kobe University carried out both simulation work and experimental work on an active robot with counter weights at the hip [55]. They found using counter weights at hip can increase the merit of walking by 70%. The counter weights helped the walker to restore some of the mechanical energy which was lost during the heel strike. The idea of counter weights can be incorporated with Dexter MK III. The hip of the walker need to be redesigned inorder to make room for the counter weights. The counter weights will be placed in a aluminum strip and the aluminum strip should also have room to place weights at different distance on it. This will allow both weights and the distance of the weights from the hip to be controlled. The idea here is to use the counter weights to increase the merit of walking at a given inclination angle. Also, at a lower inclination angle sometimes it is not possible to make the walker walk due to insufficient energy. The belief here is counter weights will allow Dexter MK III to walk at low ramp angles.

Appendix A

Trials Data for Treadmill inclination Angle

Table A.1: Summary of Treadmill Ramp Angle Trials Data

Ramp Angle 3.29°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
10	0.6253	0.1776	0.2841
8	0.6280	0.1812	0.2885
10	0.6130	0.1905	0.3108
14	0.6231	0.1840	0.2954
10	0.6305	0.1796	0.2848
8	0.6245	0.1843	0.2952
10	0.6193	0.1899	0.3066
Average	0.6234	0.1839	0.2951
Standard Dev.	0.93%	2.67%	3.52%

Ramp Angle 3.53°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
20	0.6202	0.1975	0.3184
16	0.6201	0.1935	0.3120
14	0.6206	0.2006	0.3233
10	0.6158	0.1988	0.3229
10	0.6134	0.1951	0.3180
15	0.6131	0.1945	0.3172
Average	0.6172	0.1967	0.3187
Standard Dev.	0.57%	1.41%	1.30%

Ramp Angle 4°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
14	0.6082	0.2147	0.3531
36	0.6103	0.2087	0.3419
12	0.6060	0.2161	0.3566
14	0.6081	0.2035	0.3346
15	0.6089	0.2057	0.3379
18	0.6038	0.2055	0.3404
20	0.6088	0.2072	0.3404
Average	0.6078	0.2088	0.3436
Standard Dev.	0.36%	2.31%	2.36%

Ramp Angle 4.21°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
9	0.6043	0.2208	0.3654
7	0.6031	0.2207	0.3659
9	0.6054	0.2026	0.3346
11	0.6032	0.2214	0.3670
7	0.6058	0.2229	0.3680
Average	0.6044	0.2177	0.3602
Standard Dev.	0.20%	3.90%	3.98%

Appendix B

Trials Data for Mass Distribution

Table B.1: Summary of Mass Distribution Trials Data

Center of Mass at 21.47cm and Radius of Gyration 15.66cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
20	0.6202	0.1975	0.3184
16	0.6201	0.1935	0.3120
14	0.6206	0.2006	0.3233
10	0.6158	0.1988	0.3229
10	0.6134	0.1951	0.3180
15	0.6131	0.1945	0.3172
Average	0.6172	0.1967	0.3187
Standard Dev.	0.57%	1.41%	1.30%

Center of Mass at 22.45cm and Radius of Gyration 16.17cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.6393	0.1897	0.2967
11	0.6370	0.1904	0.2990
11	0.6381	0.1888	0.2958
6	0.6336	0.1945	0.3069
7	0.6425	0.1870	0.2911
Average	0.6381	0.1901	0.2979
Standard Dev.	0.51%	1.46%	1.95%

Center of Mass at 23.09cm and Radius of Gyration 16.39cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
6	0.6432	0.1905	0.2963
6	0.6497	0.1863	0.2868
6	0.6475	0.1857	0.2868
Average	0.6468	0.1987	0.2899
Standard Dev.	0.51%	1.41%	1.89%

Center of Mass at 20.24cm and Radius of Gyration 15.99cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
6	0.6240	0.2167	0.3473
10	0.6199	0.2181	0.3519
7	0.6252	0.2155	0.3446
7	0.6234	0.2177	0.3493
7	0.6234	0.2173	0.3485
Average	0.6232	0.2171	0.3483
Standard Dev.	0.32%	0.48%	0.77%

Center of Mass at 20.41cm and Radius of Gyration 15.47cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
6	0.5936	0.2140	0.3605
6	0.5908	0.2102	0.3559
7	0.5932	0.2063	0.3478
6	0.5940	0.2071	0.3487
6	0.5871	0.2123	0.3615
Average	0.6232	0.2100	0.3549
Standard Dev.	0.48%	1.56%	1.81%

Center of Mass at 19.55cm and Radius of Gyration 16.14cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
9	0.6255	0.2232	0.3568
7	0.6284	0.2262	0.3600
7	0.6275	0.2256	0.3595
6	0.6225	0.2249	0.3613
8	0.6298	0.2241	0.3559
Average	0.6267	0.2248	0.3587
Standard Dev.	0.46%	0.53%	0.64%

Center of Mass at 19.27cm and Radius of Gyration 16.11cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
7	0.6280	0.2303	0.3668
8	0.6322	0.2245	0.3552
8	0.6314	0.2227	0.3528
7	0.6291	0.2240	0.3561
Average	0.6302	0.2254	0.3587
Standard Dev.	0.31%	1.49%	1.73%

Center of Mass at 20.98cm and Radius of Gyration 15.49cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.6098	0.1988	0.3260
8	0.6123	0.1986	0.3242
10	0.6112	0.2011	0.3290
Average	0.6111	0.1995	0.3264
Standard Dev.	0.20%	0.69%	0.73%

Center of Mass at 20.5294cm and Radius of Gyration 15.58cm			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
9	0.5948	0.2096	0.3523
11	0.5952	0.2088	0.3507
8	0.5992	0.2090	0.3488
10	0.6001	0.2075	0.3457
10	0.6003	0.2065	0.3441
Average	0.5979	0.2083	0.3484
Standard Dev.	0.45%	0.59%	0.98%

Appendix C

Trials Data for Treadmill Belt Speed Variation

Table C.1: Summary of Treadmill Belt Speed Variationn Trials Data

Treadmill Belt Speed 1.2 km/hr and Ramp Angle $3.53°$			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
7	0.6133	0.1964	0.3203
10	0.6195	0.1886	0.3045
7	0.6214	0.1882	0.3028
10	0.6200	0.1888	0.3045
Average	0.6185	0.1905	0.3081
Standard Dev.	0.58%	2.08%	2.67%

Treadmill Belt Speed 1.3 km/hr and Ramp Angle 3.53°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
20	0.6202	0.1975	0.3184
16	0.6201	0.1935	0.3120
14	0.6206	0.2006	0.3233
10	0.6158	0.1988	0.3229
10	0.6134	0.1951	0.3180
15	0.6131	0.1945	0.3172
Average	0.6172	0.1967	0.3187
Standard Dev.	0.57%	1.41%	1.30%

Treadmill Belt Speed 1.4 km/hr and Ramp Angle 3.53°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
11	0.6111	0.2025	0.3314
8	0.6080	0.2066	0.3399
8	0.6127	0.2033	0.3318
10	0.6135	0.2011	0.3278
Average	0.6113	0.2034	0.3327
Standard Dev.	0.40%	1.16%	1.54%

Treadmill Belt Speed 1.5km/hr and Ramp Angle 3.53°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.6081	0.2070	0.3404
10	0.6141	0.2024	0.3296
9	0.6141	0.2015	0.3282
10	0.6114	0.2044	0.3344
9	0.6155	0.1992	0.3236
Average	0.6126	0.2029	0.3313
Standard Dev.	0.48%	1.46%	1.93%

Treadmill Belt Speed 1.6 km/hr and Ramp Angle 3.53°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
6	0.6063	0.2053	0.3386
6	0.6071	0.2071	0.3411
8	0.6137	0.2073	0.3377
6	0.6078	0.2145	0.3530
Average	0.6087	0.2085	0.3426
Standard Dev.	0.55%	1.96%	2.06%

Treadmill Belt Speed 1.2 km/hr and Ramp Angle $4.0°$			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
6	0.6173	0.1964	0.3182
6	0.6156	0.1959	0.3183
7	0.6107	0.2050	0.3357
Average	0.6145	0.1991	0.3241
Standard Dev.	0.56%	2.56%	3.11%

Treadmill Belt Speed 1.4 km/hr and Ramp Angle $4.0°$			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
14	0.6082	0.2147	0.3531
36	0.6103	0.2087	0.3419
12	0.6060	0.2161	0.3566
14	0.6081	0.2035	0.3346
15	0.6089	0.2057	0.3379
18	0.6038	0.2055	0.3404
20	0.6088	0.2072	0.3404
Average	0.6078	0.2088	0.3436
Standard Dev.	0.36%	2.31%	2.36%

Treadmill Belt Speed 1.5 km/hr and Ramp Angle $4.0°$			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
5	0.6120	0.1985	0.3243
5	0.6058	0.2000	0.3302
6	0.6085	0.2016	0.3313
5	0.6100	0.2101	0.3445
Average	0.6091	0.20261	0.3326
Standard Dev.	0.43%	2.57%	2.56%

Appendix D

Trials Data for Feet Length Variation

Table D.1: Summary of Flat Feet Trials Data

3.4 inch Flat Feet and 5.53° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.7451	0.1882	0.2526
8	0.7554	0.1860	0.2462
8	0.7596	0.1792	0.2359
9	0.7582	0.1822	0.2404
10	0.7480	0.1800	0.2406
Average	0.7532	0.1831	0.2432
Standard Dev.	0.85%	2.83%	2.66%

3.875 inch Flat Feet and 5.53° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
9	0.7584	0.1885	0.2486
7	0.7664	0.1883	0.2456
7	0.7687	0.1900	0.2472
9	0.7637	0.1901	0.2489
Average	0.7643	0.1892	0.2476
Standard Dev.	0.58%	0.51%	0.60%

4.0 inch Flat Feet and 5.53° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.7791	0.2022	0.2596
8	0.7711	0.2051	0.2659
8	0.7684	0.2092	0.2722
9	0.7776	0.2093	0.2692
10	0.7686	0.2014	0.2621
Average	0.7729	0.2054	0.2658
Standard Dev.	0.65%	1.81%	1.93%

3.4 inch Flat Feet and 5.0° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.7421	0.1822	0.2455
8	0.7473	0.1813	0.2425
8	0.7369	0.1802	0.2446
Average	0.7421	0.1812	0.2442
Standard Dev.	0.70%	0.55%	0.63%

3.875 inch Flat Feet and 5.0° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
7	0.7669	0.1909	0.2489
7	0.7776	0.1896	0.2438
6	0.7682	0.1861	0.2423
Average	0.7709	0.1889	0.2464
Standard Dev.	0.76%	1.32%	1.42%

4.0 inch Flat Feet and 5.0° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
7	0.7778	0.2094	0.2692
7	0.7783	0.2052	0.2637
7	0.7697	0.2009	0.2611
7	0.7691	0.2005	0.2606
Average	0.7737	0.2040	0.2636
Standard Dev.	0.65%	2.04%	1.48%

3.4 inch Flat Feet and 4.7° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.7293	0.1862	0.2553
8	0.7392	0.1740	0.2353
9	0.7326	0.1754	0.2395
Average	0.7337	0.1785	0.2433
Standard Dev.	0.69%	3.74%	4.33%

3.875 inch Flat Feet and 4.7° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.7591	0.1803	0.2376
7	0.7560	0.1874	0.2479
6	0.7461	0.1879	0.2518
Average	0.7538	0.1852	0.2458
Standard Dev.	0.90%	2.69%	2.97%

4.0 inch Flat Feet and 4.7° Ramp Angle			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.7558	0.2083	0.2764
8	0.7700	0.1912	0.2483
8	0.7635	0.2017	0.2642
Average	0.7631	0.2006	0.2629
Standard Dev.	0.93%	4.44%	5.56%

Appendix E

Trials Data for Leg Length Variation

Table E.1: Summary of Leg Length Variation Trials Data

Thigh Length 10.25inch and Shank Length 11.25inch			
Center of Mass 21.47cm, Radius of Gyration 15.66cm and Ramp Angle 3.53°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
20	0.6202	0.1975	0.3184
16	0.6201	0.1935	0.3120
14	0.6206	0.2006	0.3233
10	0.6158	0.1988	0.3229
10	0.6134	0.1951	0.3180
15	0.6131	0.1945	0.3172
Average	0.6172	0.1967	0.3187
Standard Dev.	0.57%	1.41%	1.30%

Thigh Length 10.25inch and Shank Length 10.25inch			
Center of Mass 21.12cm, Radius of Gyration 14.98cm and Ramp Angle 3.72°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
8	0.6335	0.1858	0.2940
8	0.6389	0.1833	0.2872
7	0.6250	0.2883	0.3021
Average	0.6325	0.1858	0.2944
Standard Dev.	1.11%	1.35%	2.53%

Thigh Length 10.25inch and Shank Length 9.25inch			
Center of Mass 20.70cm, Radius of Gyration 14.11cm and Ramp Angle 4.21°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
9	0.6306	0.1949	0.3102
8	0.6304	0.1929	0.3063
10	0.6294	0.1912	0.3045
9	0.6299	0.1967	0.3131
Average	0.6306	0.1939	0.3085
Standard Dev.	0.08%	1.23%	1.25%

Thigh Length 10.25inch and Shank Length 10.25inch			
Center of Mass 22.09cm, Radius of Gyration 15.95cm and Ramp Angle 3.57°			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
7	0.6343	0.1882	0.2970
9	0.6337	0.1829	0.2889
9	0.6393	0.1823	0.2861
7	0.6374	0.1863	0.2935
Average	0.6362	0.1849	0.2914
Standard Dev.	0.42%	1.53%	1.65%

Thigh Length 10.25inch and Shank Length 9.25inch			
Center of Mass 21.59cm, Radius of Gyration 15.09cm and Ramp Angle $4.21°$			
Number of Steps	Step Periods (sec)	Step Length (m)	Hip Velocity (m/s)
7	0.6397	0.1851	0.2894
7	0.6397	0.1853	0.2897
6	0.6387	0.1885	0.2966
6	0.6412	0.1894	0.2960
Average	0.6398	0.1871	0.2929
Standard Dev.	0.16%	1.18%	1.34%

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