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Experimental studies on passive dynamic bipedal walking

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ABSTRACT

Passive dynamic walking is a gait developed, partially or in whole, by the energy provided by gravity. The research on passive dynamic bipedal walking helps create an understanding of walking mechanics. Moreover, the experimental passive dynamic research provides a base to compare and validate computer simulation results. An improved kneed bipedal walking mechanism was designed and built to study the passive gait patterns. The first aim of this study is to determine the equivalency of testing a passive dynamic biped walker on a treadmill to testing on a ramp. Based on the small difference between the gait patterns measured on the two test platforms, testing on a treadmill was found equivalent to testing on a ramp. Gait measurements were then conducted on the treadmill to evaluate the effects of the treadmill inclination angle, mass distribution of the biped, and the length of flat feet on the gait pattern. Results show that most of these parameters had significant effects on the step length, step period and hip velocity of the passive walker. Our experimental results are also compared with previous experimental results.

1. Introduction

Passive dynamic walkers are a class of mechanisms, once started walking on a shallow slope they will settle into a stable gait without the help of actuation or control. The research into passive walking was pioneered by McGeer [1,2] who demonstrated the passive dynamic gait through simulations and experiments. Passive dynamic bipedal walking has attracted attention because of the human-like natural gait that is energy efficient. The existence of a human-like 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 insights into human location locomotion [3].

Two approaches have been used to study passive dynamic walking: a computer modeling and simulation approach, and an experimental approach. Mathematical and computer models have been widely used to study passive dynamic walking. The nonlinear dynamics of passive walkers have been explored with simple models, as in [4–7], where the period doubling bifurcations of the passive gait were studied, in [8,9] where the limit cycle developed by passive walking was examined, and in [7,8,10–14] where the orbital and local stability of passive walking was investigated. Liu et al. [15] carried out simulation work to find the effects of parameter variation on the basin of attraction of passive walking models, for both straight and kneed walkers using a cell mapping method. The slope angle, foot radius, moment of inertia, and center of mass were the parameters varied in [15]. Effects of dynamic and geometric parameters of passive walker on gait patterns also have also been studied through computer simulations. McGeer first studied the effects of dynamic and geometric parameters on step length and step period using both straight and kneed walkers [1,2]. He varied the foot radius, hip mass, leg inertia, leg mismatch, position of center of mass to determine the effects on the passive dynamic gait. Hass et al. [16] investigated the optimal mass distribution for passive bipedal robots through simulations where they tuned the mass distribution to achieve maximum walking speed and stability. Some simulation work has focused on effects of the foot shape on passive walking to determine an optimal foot shape [17–21]. Ankle springs allows the use of flat feet instead of arc feet and provides similar locomotion to that of arc feet [18,20]. Kuo [22] extended the planar motions of passive dynamic walkers to allow tilting side to side and found that passive walking exists, and found the rocking motion to be unstable. Wisse et al. [23] proposed a design for a 3D passive walker with a pelvis which reduced the rocking motion to have walking like 2D walker. Computer simulation and modeling are powerful tools and can provide insights into many areas where physical experiments are not feasible. However, in many cases simulation work has shown poor agreement with experimental results [1,24], which causes misleading simulation results. There are some contradictory simulation results regarding the effect of the inclination angle on the step period of passive walkers. For example, Goswmi et al. [5] reported that the step period increases with the increase of the inclination angle, while some simulations [2,3,16] showed that the step period decreases significantly and Kuo [25] documented that

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the inclination angle has no effects on the step period. Therefore it is essential to validate the models with experimental results.

Studying passive dynamic walkers through an experimental approach provides physical insights into the mechanics of passive walking. Experimental results provide a reference to validate mathematical models of passive walking and prevent misinterpretation of simulation results. Ruina et al. [26] at Cornell University built a simple two-legged toy that can stably walk down a shallow slope, but was statically unstable to stand in any position. The first 3D two-legged kneed passive biped walker was designed and built by the same group [27] and was designed with curve feet, a compliant heel and mechanically constrained arms which helped to achieve a stable gait. Success in passive dynamic bipedal walking has boosted the research to develop energy-efficient bipedal walking robots. Wisse et al. [10,28] at Delft University have built several energy-efficient walkers. They first developed a straight legged walker with hip actuation [10] and then added an upper body to the walker by means of a bisecting hip mechanism [28]. In both works Wisse et al. used the principle of passive biped walking to make an energy efficient biped. Similarly, Tedrake et al. [14,29] at MIT developed a 3D energy efficient walker that could obtain a steady gait. The 3D energy efficient walker built in MIT was not completely passive as the walker was equipped with position controlled servo motors at the ankle joint to control the roll and yaw. They used the principles of passive biped walking to design the 3D energy efficient walker. Inspired by Tedrake's work, Takeguchi et al. [30] conducted simulation and experimental work on a walking mechanism of 3D passive dynamic motion. Fujimoto's research group in Japan built an improved 2D passive walker, which so far has the highest step count of a fully passive walker [31]. Fujimoto's group also studied the effect of arc feet on the dynamic motion of a passive walker [13]. Currently, the physical models have often been restricted to demonstrate the existence of passive dynamic walking. There are a limited number of published experimental results on the effects of dynamic parameters on the passive gait pattern. At the University of Manitoba, the authors' research group first built a straight legged passive dynamic walker with flat feet [32] and then a kneed passive walker with arc feet [24]. Using the aforementioned walkers, the effects of the ramp angle, mass distribution, ramp surface friction and size of flat feet on the gait patterns were experimentally evaluated. The previous research [24,32] suffers from two main 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 trends between the step period and the dynamic parameters were not conclusive. Secondly, the previous experiments were conducted on a ramp which limits the number of steps.

In this paper, the design of a kneed passive dynamic walker, Dexter Mk III, is presented. Dexter Mk III is equipped with an accelerometer and an encoder at the hip to measure the step length, step period and hip velocity. The use of an accelerometer and an encoder improves the measurement accuracy and allows clear trends of the gait pattern to be found when the dynamic parameters are changed. Testing passive dynamic walkers on a treadmill is attractive since there is no limitation on the number of steps imposed by the test platform. However, the effects caused by the mechanical differences between a ramp and a treadmill are unknown. Therefore, trials are first completed on a ramp and on a treadmill to determine the equivalency of testing on a treadmill. Following the ramp–treadmill comparison, experiments are conducted with Dexter Mk III to study the passive gait patterns when the inclination angle, center of mass location, and length of flat feet of the passive walker are changed. The aim of this study is to produce experimental results of a passive dynamic gait. Such experimental results can be used for validating computer models of passive walking, as well, reveal insights into the dynamics of passive gait.

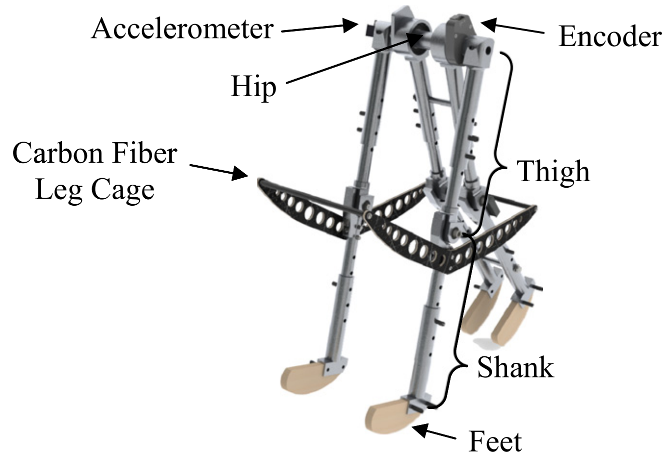

Fig. 1. Dexter MK III.

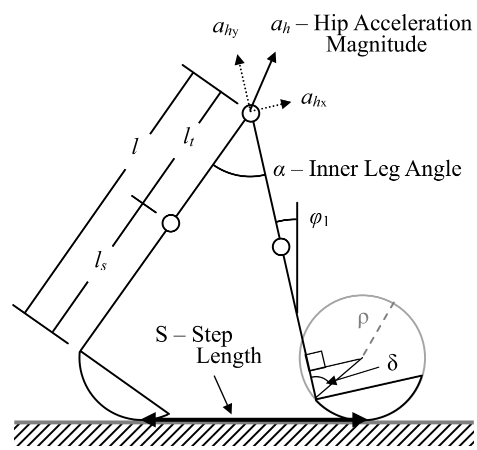

Fig. 2. Diagram of system parameters.

2. Passive walker design

Dexter Mk III, shown in Fig. 1, is the third passive dynamic walker built at the University of Manitoba and was designed to facilitate the measurement of the passive dynamic gait. Dexter Mk III has several main improvements as compared to our previous passive walkers [24]. For examples, the structure of Dexter Mk III is stronger, yet still relatively light weight and has an adjustable limb length. The legs and the hip of the passive walker were machined from aluminum. The leg design allows for the leg length to be adjusted and the feet to be interchangeable. Additionally, a carbon fiber leg cage was incorporated into the design which keeps the outer shanks in sync. The leg cage needed to be light weight so that the radius of gyration of the outer legs was not offset compared to the inner legs.

Another important improvement as compared to our previous work [24] is the use of advanced measurement sensors. An encoder and an accelerometer were implemented in the design for Dexter Mk III, as shown in Fig. 1. The encoder, with a 0.05° resolution, enables the angle between the outside and inside legs, known as the inner leg angle (α), to be measured (Fig. 2). The triaxial accelerometer used has a range of ±5 G in each direction. The accelerometer measures the accelerations, parallel (a_{hy}) and perpendicular (a_{hx}) to the outside legs. However, since the accelerometer was attached to the hip, which rotates with the outside legs, the direction of the measured acceleration components with respect to the ground is unknown. In this work, only the magnitude of acceleration was used to determine the step period.

Table 1
Passive walker geometric parameters.

Item	Symbol	Measurement	Ratio to l
Walker height	L	54.62 cm	
Thigh length	l_t	26.04 cm	47.7%
Shank length	l_s	28.58 cm	52.3%
Walker width	W	20.32 cm	
Foot radius	ρ	10.92 cm	20.0%
Foot center	δ	26.78°	

Not all combinations 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 used in the experiments can be found in Table 1. Table 2 outlines the dynamic parameters of the passive walker. 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 a passive walker are complex and these trends may be local to the specific geometric and dynamic parameters tested.

3. Experimental gait analysis

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

3.1. Measurement system and experimental setup

The step length, step period, and average hip velocity are fundamental gait parameters and were determined for all of the trials conducted. As well, the acceleration of the hip and the phase portrait of the inner leg angle were determined to compare the equivalency between the ramp and the treadmill for gait measurements. To measure the aforementioned gait parameters, a data acquisition board connected to a computer with Simulink was used to gather the data from the accelerometer and the encoder. The experiment setup is shown in Fig. 3. The data from the accelerometer and the encoder were captured at 1000 Hz sampling rate. Using the inner leg angle (α) provided by the encoder and the geometry of the walker, the step length is calculated with Eqs. (1) and (2):

$$\varphi_1 = atan\left[\frac{(1-\cos\alpha)(1-\rho\cos\delta)-\sin\alpha(\rho\sin\delta)}{\sin\alpha(1-\rho\cos\delta)+(1-\cos\alpha)(\rho\sin\delta)}\right] \quad (1)$$

$$S = \sin\varphi_1[(1-\cos\alpha)(1-\rho\cos\delta)-\sin\alpha(\rho\sin\delta)] + \cos\varphi_1[\sin\alpha(1-\rho\cos\delta)+(1-\cos\alpha)(\rho-\sin\delta)] \quad (2)$$

where φ_1 is the angle of the lead leg with respect to the normal to the incline, ρ is the foot radius, and δ is the foot center offset angle, as shown in Fig. 2. The step length is defined as the distance between the contact points of the two feet with the ground (S), shown in Fig. 2. The heel strikes were identified from the impulse measured by the accelerometer. The step period was determined from the time between consecutive heel strikes. Using the step period and the step length, the average hip velocity was determined.

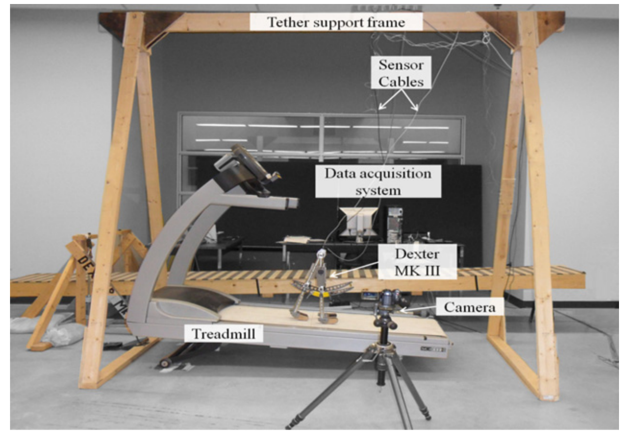

Fig. 3. Experimental setup: treadmill, safety tether, video camera, data acquisition system and passive walker.

3.2. Experimental procedure

To determine the differences between the gaits produced on the ramp and the treadmill, a series of trials were completed on both measurement platforms. A slope of 4.5° was set for both test platforms. Each trial consisted of multiple runs down the ramp and the treadmill. The gait of the passive walker is affected by the initial conditions (i.e. how it is launched) and will settle into a repeatable gait after a few steps. Therefore, for the trials on the ramp, the first two steps were removed from the data set. For the treadmill, since a greater number of steps are permissible, 10–15 steps were removed from the data set to further reduce the effects of the initial conditions. The resultant gait from each trial series were then analyzed and compared.

The effects of the dynamic and geometric parameters on the step length and the step period were studied next. Trials were completed with different dynamic and geometric parameters on the treadmill. For each parameter variation five or more trials were completed.

3.3. Data analysis

The raw data captured, shown in Fig. 4 as an example, was used to determine the step length, step period, and hip velocity. A program in Matlab was developed to automatically sort and analyze the data collected from the accelerometer and the encoder. The heel strikes, noted as a square in Fig. 4, were automatically determined by the program by searching near the inner leg angle maxima and minima. To determine the step period, the program

Table 2
Dynamic parameters of the designed passive walker.

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		**1.978**		

* Center of mass is measured from the hip for the thigh and from the knee for the shank.
** Radius of gyration is with respect to the center of mass.

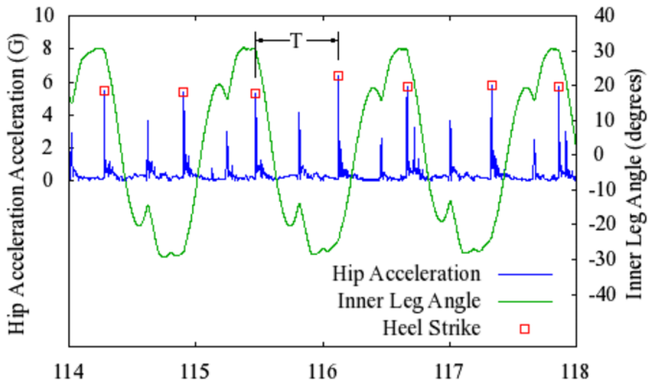

Fig. 4. Raw data sample from the treadmill.

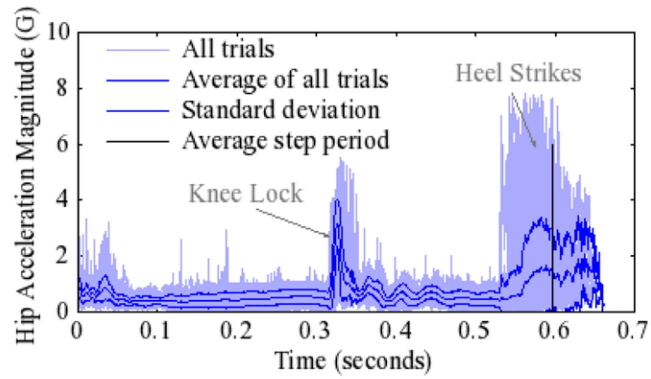

Fig. 5. Hip acceleration profile on the treadmill.

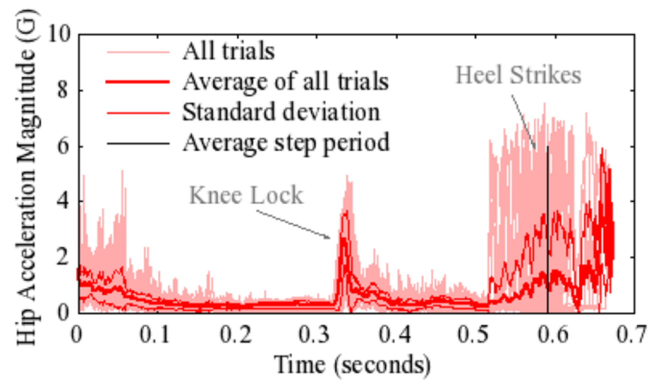

Fig. 6. Hip acceleration profile on the ramp.

determines the time difference between two consecutive heel strikes (T), shown in Fig. 4. 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 instant. The mean and standard deviation of the gait patterns i.e. the step length, step period and hip velocity were calculated over all the trials conducted for each set of parameter variation.

Walking (in)efficiency of passive walking and the merit of a walking are often used as a measure of passive dynamic walking. The walking (in)efficiency is defined in Eq. (3) [4,26].

$$\eta = \frac{mechanical\ work}{weight\ \times step\ length}. \quad (3)$$

In Eq. (3) the term mechanical work is the amount of input energy given to the system. In the case of a passive walker, the input energy is determined from the gravitational energy. The energy (in)efficiency on the basis of path distance is $\eta = \tan\gamma$, where γ is the ramp angle. For small slopes we can approximate the energy (in)efficiency as $\eta \approx \gamma$. Perfect passive locomotion is obtained when $\eta = 0$. The merit of walking is represented by the Froude number or dimensionless velocity, $\sqrt{V/gl}$, where l is the length of the leg [26]. In this paper, the non-dimensional form of gait parameters are also presented, which allows our results to be compared with other works. The step length is normalized with the walker's leg length, l, the step period is normalized with the term $\sqrt{l/g}$ and the hip velocity with the term $\sqrt{lg}$ to produce a non-dimensional form [26].

4. Results and discussion

The child-sized passive dynamic walker, Dexter MK III, can walk on the treadmill for 1500 steps without falling. Such a passive walker is used for evaluating the effects of various dynamic parameters in the passive gait patterns.

4.1. Ramp–treadmill comparison

To determine the equivalence between testing on a treadmill to testing on a ramp, the resultant gait patterns produced on both test platforms were analyzed. In this analysis, the hip accelerations, inner leg angle phase portrait, step length, step period, and average hip velocity are used to compare the gait patterns. The magnitude of the hip acceleration provides a depiction of the dynamics of the gait in the time domain. The phase portrait of the inner leg angle provides an overall description of the kinematics of the gait. Finally, the step period, step length, and average hip velocity provide a synoptic but quantifiable comparison between the two gait patterns produced.

The acceleration profiles, shown in Fig. 5 and Fig. 6 are the average magnitude of the hip accelerations over one step period, where the start of the x-axis is the start of each step. The acceleration profiles show the timely consistency of the knee lock and of the average step period. The magnitudes of the acceleration profiles, outside of the heel strike region, are quite comparable as well. The treadmill acceleration profile has a slightly higher standard deviation outside of the knee lock and heel strike regions. The increase in standard deviation of the treadmill acceleration profile is most likely due to the vibrations caused by the operation of the treadmill. The phase portrait comparison, shown in Fig. 7, is a plot of the average angular displacement versus angular velocity of the inner leg angle of the same walker on the ramp and the treadmill. The phase portrait illustrates the consistency between the kinematics of the two gaits throughout one gait cycle (two steps). The discontinuities on the phase portrait exist because all of the steps do not start and end with the same inner leg angle position and velocity. The gait parameters determined from the trials on the ramp and the treadmill are in agreement within the standard deviation, as shown in Table 3. The gait parameters determined for the ramp have a higher standard deviation since only a small number of steps could be completed per trial due to the limited ramp length. With a small number of steps, the effects of the initial conditions may not have completely dissipated, introducing variability in the gaits measured. The small difference in kinematics between the gait patterns measured on the two test platforms indicates that testing on a treadmill is equivalent to testing on a ramp.

It is believed that the close kinematics of the biped on two testing platforms is due to the absence of the upper body and the constant treadmill belt speed. On the treadmill, the upper body, if exists, would oscillate about the static upright position,

Table 3
The ramp and treadmill results.

Parameter	Ramp	Treadmill	Difference
Step period (s)	0.591 ± 1.18%	0.597 ± 0.51%	1.02%
Step length (m)	0.2286 ± 2.72%	0.2291 ± 0.44%	0.22%
Hip velocity (m/s)	0.387 ± 3.59%	0.384 ± 0.92%	0.78%
Number of steps	11 trials with 82 steps total	4 trials with 176 steps total	

* ±## is the standard deviation between the trials.

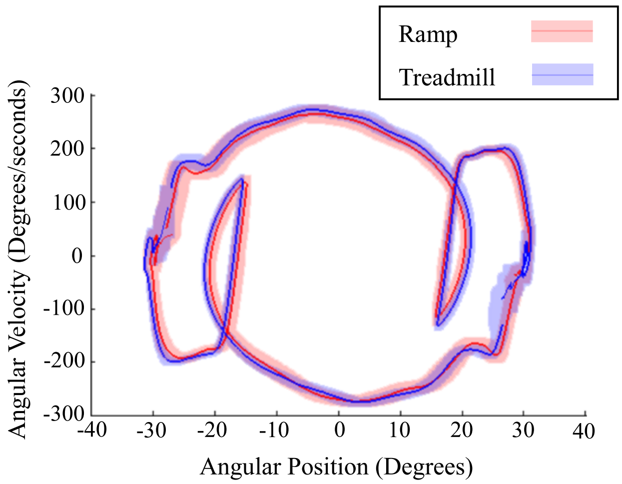

Fig. 7. Phase portrait of the inner leg angle on the ramp and the treadmill.

while on the ramp, the upper body would oscillate about the upright position which is moving forward. Since the ramp and the treadmill are two inertia frames as the treadmill has a constant belt speed, it is not surprising that the kinematics is close on the two testing platforms. However, if there is a massive upper body and the treadmill belt speed cannot remain constant, the treadmill should be used with caution.

4.2. Effects of the treadmill inclination angle

The relationship between the gait parameters and the treadmill inclination angle will be discussed here. To produce steady gait, the range of inclination angles of the treadmill was between 3.29° and 4.21°. Note that the ramp angle was measured using a four foot level and a combination square. This technique takes more vigilance from the measurer, but can attain considerably higher accuracy and better repeatability than commercial digital levels. The accuracy of the measured angle was ±0.05°. The measured and calculated gait parameters are shown in Figs. 8–10, with the gait parameters as the vertical axes and the treadmill inclination angle as the horizontal axes. Dimensional gait parameters are plotted on the left column and dimensionless gait parameters on the right column. From Figs. 8–10, we can see that increasing the treadmill inclination angle has a significant effect on the gait pattern of the passive walker. The step length increases with the treadmill inclination angle as shown in Fig. 8. However the step period decreases with the increased inclination angle, as can be seen in Fig. 9. As a result, the average hip velocity increases, as shown in Fig. 10. Both changes, in the step length and the step period, are significant as standard deviations are low.

The step counts are often reflective of the robustness of the gait. Table 4 shows that at 3.53° and 4.0° inclination angle higher step counts were achieved. The effect of changing the treadmill inclination angle on the step length is similar to the previous research results [24,32]. However, previous simulation results on the effect of the inclination angle on the step period are conflicting. To the best of our knowledge, this is the first experimental results that show that the step period decreases with an increase in the inclination angle of the walking surface. The measurements of the step period are reliable in this experiment and a large number of trials have been conducted.

Less mechanical work is required at lower inclination angles, which indicates a higher walking efficiency. Our experimental results show that lower ramp angles result in a shorter step length, longer step period and lower hip velocity, which results in a lower merit of walking. Since the length of the leg is not changed in this experiment, the walking speed reflects the merit of walking. The conflict between walking efficiency and merit of walking has also been discussed in previous work [2,3,24,32].

4.3. Effects of mass distributions

The mass distribution of the biped was altered to change the location of the mass center of the thigh and the shank. As a result, the static center of mass of the entire passive walker was also changed. In this work, the static center of mass is defined as the center of mass of the whole walker measured from the hip when the knees of the walker are fully extended. The initial static center of mass was 21.47 cm from the hip of the walker. Shown in Table 5, adding weights only on the thigh raised the center of mass towards the hip and adding weights only on the shank lowered the center of mass. Altering the mass distribution also changes the moment of inertia of the legs and the radius of gyration. McGeer [2] suggested that increasing the radius gyration of the legs or moving the center of mass towards the hip keeping the radius of gyration constant have similar effects on the gait parameters. This section will discuss how the merit of walking changes with the change of the location of static center of mass.

In Figs. 11–13 the gait parameters are plotted on the vertical axes and the location of the center of mass is plotted on the

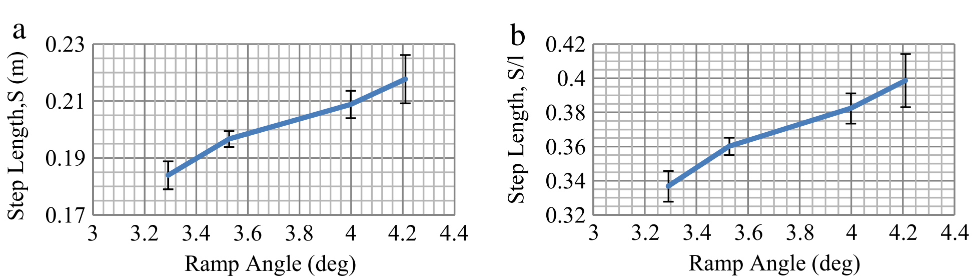

Fig. 8. Step length vs. treadmill inclination angle. (a) Dimensional plot and (b) non dimensional plot.

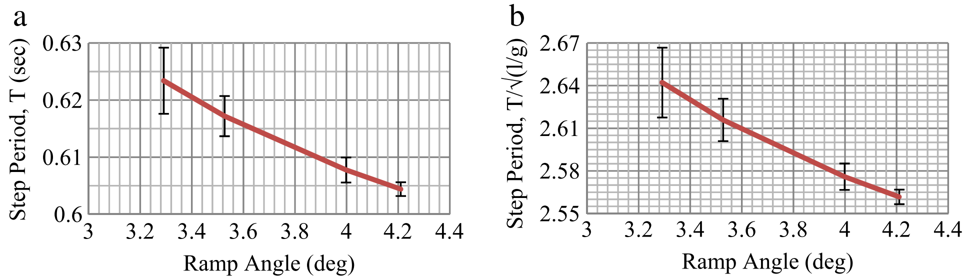

Fig. 9. Step period vs. treadmill inclination angle. (a) Dimensional plot and (b) non dimensional plot.

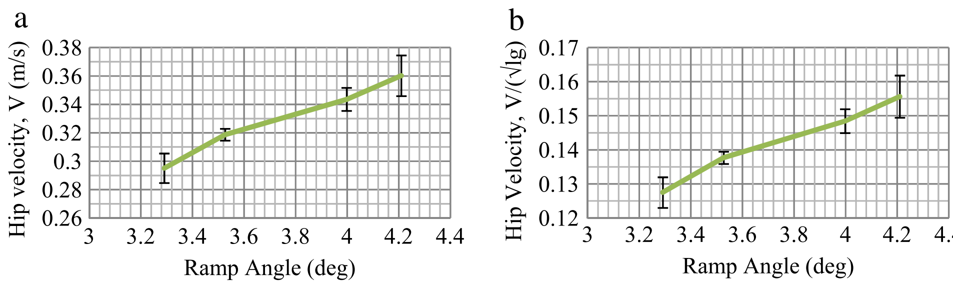

Fig. 10. Hip velocity vs. treadmill inclination angle. (a) Dimensional plot and (b) Non dimensional plot.

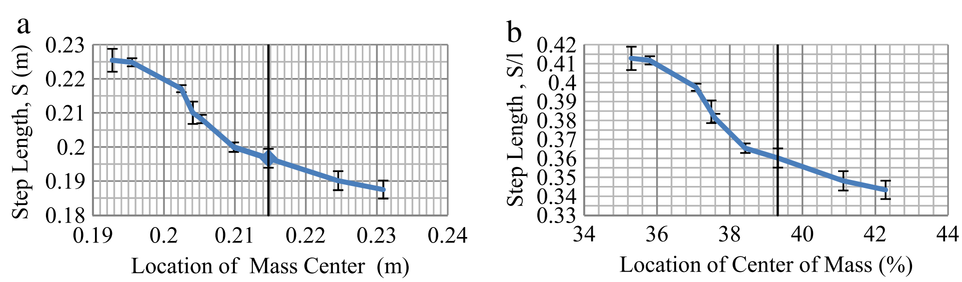

Fig. 11. Step length vs. location of mass center. (a) Dimensional plot and (b) non dimensional plot.

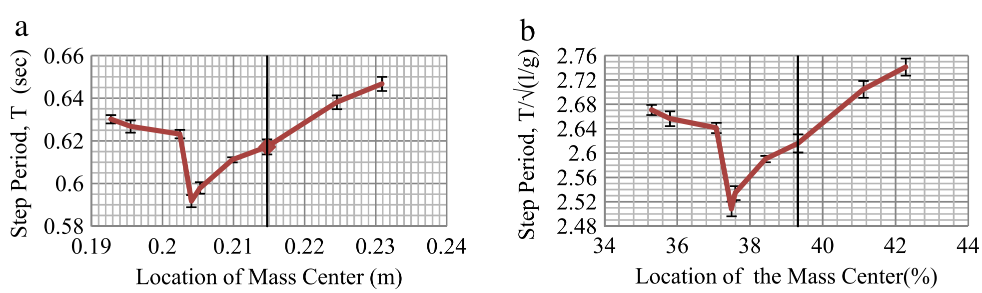

Fig. 12. Step period vs. location of mass center. (a) Dimensional plot and (b) non dimensional plot.

Table 4
Gait parameters with the treadmill inclination angle.

Treadmill inclination (deg)	No. of trials	Avg. steps	Step length		Step period		Hip velocity	
			Avg. (m)	Std. Dev.	Avg. (s)	Std. Dev.	Avg. (m/s)	Std. Dev.
3.29	7	10	0.1839	2.67%	0.6234	0.93%	0.2951	3.52%
3.53	6	14	0.1967	1.41%	0.6172	0.57%	0.3187	1.32%
4.0	7	18	0.2088	2.31%	0.6078	0.36%	0.3436	2.36%
4.21	5	9	0.2177	3.90%	0.6044	0.20%	0.3602	3.98%

horizontal axes. Plots on the left column are dimensional gait parameters and on the right column are the dimensionless gait parameters. A solid vertical line is drawn the passive walker without altering the mass distributions. The two points on the right side of the vertical solid line are the gait parameters when the center of mass is lowered by adding mass on the shank. For the other points on the left side of the solid line, mass was added on different locations on the thigh. The three points on the left end of Figs. 11–13 are the gait parameters when weight was attached to the hip of which the center of mass was raised towards the

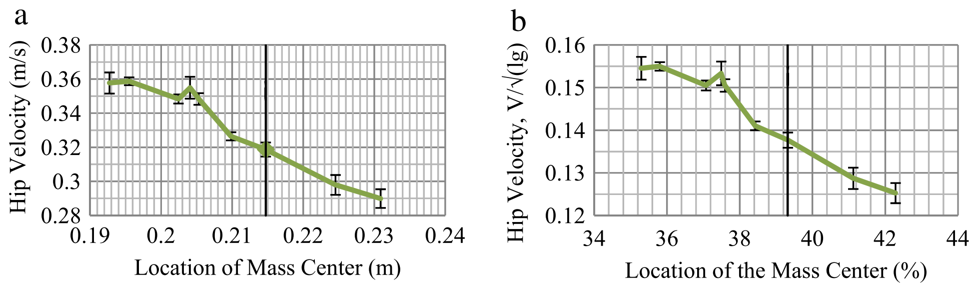

Fig. 13. Hip velocity vs. location of mass center. (a) Dimensional plot and (b) non dimensional plot.

Table 5
Center of mass location with different mass distribution.

	Position of added mass	Location of the center of mass from the hip (cm)
Raised center of mass	Standard	21.47
	152 gm on inside thigh and 160 gm on outside thigh	20.98
	400 gm on inside thigh and 322 gm on outside thigh	20.41
	368 gm on hip and 160 gm on outside thigh	20.25
	528 gm on hip and 320 gm on outside thigh	19.55
	507 gm on hip and 480 gm on outside thigh	19.27
Lowered Center of mass	160 gm on inside shank and 160 gm on outside shank	22.45
	160 gm on inside shank and 320 gm on outside shank	23.09

hip. As the center of mass is raised towards the hip the step length increases, as can be observed in Fig. 11. In this experiment, the hip velocity is dominated by the step length, i.e., raising the static center of mass increases the walking speed. A clear trend is achieved for the step length that is similar to previous work [24,32].

The step period increases when the weight is added to the shank and the step period decreases when mass is added to the thigh, i.e. lowering the static center of mass from the original state increase the step period, while raising the static center of mass decreases the step period. This trend is clearly observed in Fig. 12 except for the three points on the left end where the weight was added to the thigh at the hip. A different trend is visible for adding the weight to the thigh at 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 decrease. Three trials with different mass distributions were conducted and all of the trials provided the same results, which are visible in Fig. 12. When adding weights to a passive walker, there are five dynamic parameters that can be changed: centers of mass of the thigh and shank, radii of gyration of the thigh and 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 center of mass alone. Further research is needed to identify the cause of the change in the trend of the step period when mass is added to the hip.

The step length and the hip velocity have similar trends to those found in previous work [24,32]. In previous experimental work [32] 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 we are able to find a clear trend for the step period with the change of the center of the mass location. We have also found that when the input energy is fixed, i.e. treadmill inclination angle is fixed; raising the center of mass can improve the walking merit as compared to lowering 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 9%. Both the range of 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 dominate parameter that effects the period of motion.

Fig. 14. Flat feet design.

4.4. Effects of length of flat feet

Research with passive walkers has mostly been carried out with arc or semicircular feet. McGeer stated that the semicircular foot was considered for mathematical convenience rather than a physical necessity [1]. Only 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. We intend to explore the relationship between the length of flat feet and the gait parameters. The width of the flat feet was fixed, but lengths of the flat feet were varied. The following three lengths of the foot, 0.086 m, 0.098 m and 0.101 m, have been used, which can lead to periodic gait. The heel was connected to the shank of the walker as shown in Fig. 14.

Three different ramp angles (5.53°, 4.998° and 4.7°) were identified for conducting the experiment. In this section the effects

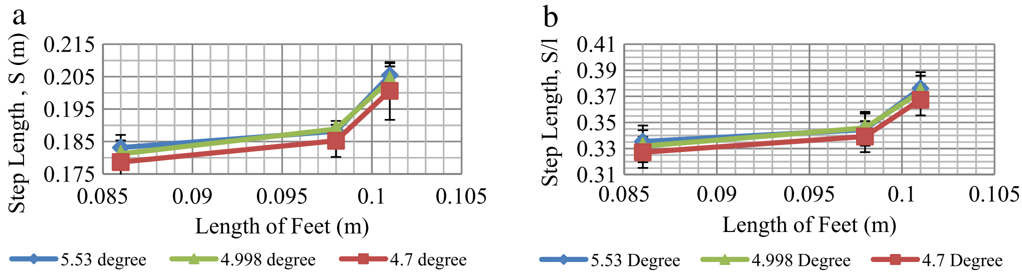

Fig. 15. Step length vs. length of flat feet. (a) Dimensional plot and (b) non dimensional plot.

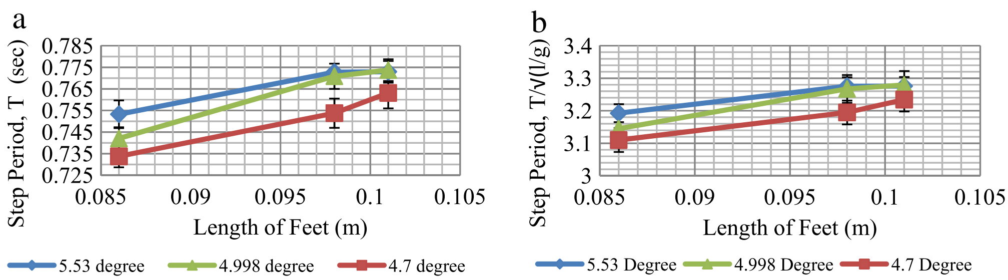

Fig. 16. Step period vs. length of flat feet. (a) Dimensional plot and (b) non dimensional plot.

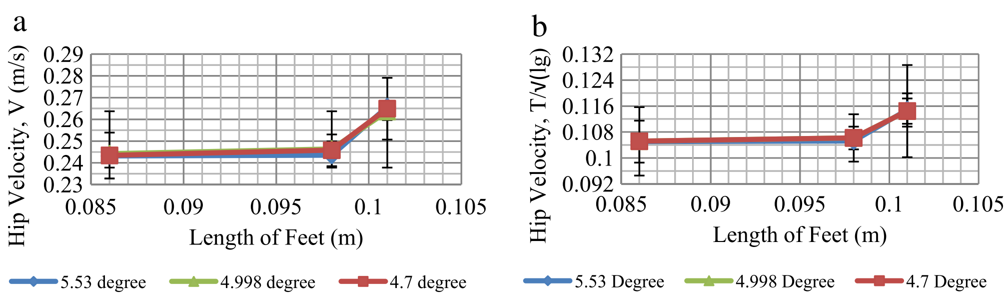

Fig. 17. Hip velocity vs. length of flat feet. (a) Dimensional plot and (b) non dimensional plot.

of the length of the flat feet on the gait parameters of the passive dynamic walker are discussed. Figs. 15–17 shows the relation between the step length, step period and hip velocity with the length of flat feet. The above gait parameters are plotted on the vertical axes and the length of feet on the horizontal axes. Dimensionless gait parameters are also plotted, shown in figures on the right column.

From Fig. 15, we see that the step length of the walker increases with the length of flat feet. This trend is consistent in all inclination angles of the treadmill. The step period, shown in Fig. 16, increases with the increase of the length of flat feet. This is consistent for all three inclination angles. This result of step period, to the best of our knowledge is first documented from this experiment. With the data collected in our experiments, the changes in the hip velocity of the passive walker is not significant as the length of the flat feet increases, as shown in Fig. 17(a). The increase of step period with the increase of the inclination angle is also noticeable from Fig. 16 for the same flat feet, which is contradictory with the results using arc feet. Kinugasa et al. [33] found a similar trend for the step period versus inclination angles. However, in the experiments completed by Kinugasa et al. [33], the leg lengths and the inclination angles were changed simultaneously. Thus, it was hard to conclude that the increase in the step period is due to the effect of the inclination angle or the leg lengths. With the data collected in the fixed flat feet experiments, the changes in the hip velocity of the passive walker are not significant as the inclination angle increases, as shown in Fig. 17. The results indicate that although the flat feet have effects on the step length and the step period, the merit of walking is insensitive to the length of the flat feet and the inclination angles.

From the experiments it was observed that flat feet experienced higher friction and lower impact forces with the walking surface as compared to those experienced by the arc feet. We can see that for the flat feet, higher inclination angles are required than those for the arc feet to make the walker walk steadily, i.e., more energy injection is required. This higher energy is expected as the biped with flat feet requires significant energy to transport the support from the heel to the toe and to rotate the flat feet to initiate the next step. The merit of walking of the walker equipped with flat feet is much lower than the arc feet walker, shown in Table 6. We took the smallest flat feet, 0.086 m to compare it with arc feet. We found with 0.086 m flat feet, 17.65% change in the inclination angle has effects on step period and 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 mechanism of motion of flat feet have consumed most the increased energy, which restricted the increased energy to affect the merit of walking.

It was noticed that the robustness of passive walking with flat feet is low as it was more difficult to launch successful passive walking with flat feet as compared to the one with arc feet. As a result, the standard deviation of the gait parameters was higher than the standard deviation determined for the experiments with

Table 6
Comparison between arc feet and flat feet.

Type of feet	Inclination angle	Step length		Step period		Hip velocity	
		Avg.	Std. Dev.	Avg.	Std. Dev.	Avg.	Std. Dev.
Arc feet	3.53°	0.1967	1.41%	0.6172	0.57%	0.3187	1.32%
Flat feet (0.086 m)	4.7°	0.1786	3.74%	0.7337	0.69%	0.2434	4.33%

the arc feet. In addition, our walker was specially designed and tuned for arc feet. It is recommended here, in future work, to have the biped specifically tuned for flat feet and a more rigid treadmill are required to perform more measurements in order to find the effect of inclination angle on the flat feet passive walker's gait patterns.

5. Conclusions

In this study experimental research has been carried out to evaluate the effects of dynamic and geometric parameters on passive dynamic walking. Firstly, a passive dynamic walker, Dexter Mk III, was designed and built. Dexter Mk III was able to walk on the treadmill for 1500 steps without falling. Secondly, the kinematic equivalence between the passive gait developed on a ramp and on a treadmill was established based on the low errors in the hip acceleration profiles, phase portraits of the inner angle, step period, step length, and average hip velocity. Finally, the above walker and the treadmill were used to evaluate the effects of dynamic and geometric parameters on the passive gait. The dynamic and geometric parameters include the treadmill inclination angle, location of the center of mass, and length of flat feet. The gait parameters compared are the step length, step period, and average hip velocity. The indication of such effects in terms of the walking (in)efficiency and the merit of walking was discussed.

We found that most of the above dynamic and geometric parameters have significant effect on the passive gait pattern. Specifically, increasing the treadmill inclination angle increases the step length, while decreases the step period, which leads to a faster walking speed. The increase in the treadmill inclination angle indicates higher energy input (lower energy efficiency). 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.

Raising the center of mass towards the hip increases the step length, decreases the step period except for the cases when mass was added to the thigh at the hip. As well, the hip velocity increases as the center of mass is raised. The increase of the hip velocity indicates that as the energy input is fixed (fixed inclination angle), the merit of walking can be improved by raising the center of mass. Regarding the change in the step period, when the mass was added to the thigh at the hip, it is speculated that other dynamic parameters, rather than the location of the static center of mass, play a more important role and further research is need.

The angle of inclination was found to have more of an effect on the step length than the step period. The center of mass was found to have substantially more of an effect on the step period than the angle of inclination, which leads to the conclusion that the center of mass is a dominate parameter that effects the period of motion of the passive walker.

The effects of the length of the flat feet on the passive gait were also investigated. Although the trends of the increase in the step length and the step period were observed, the degree of change in the hip velocity was relatively low with a high standard deviation compared to the other cases. Our results of the effects of the inclination angle on the step period with flat feet are contradictory with the arc feet, indicating that the walking mechanism of a passive walker with flat feet and with arc feet may not be the same as suggested in [1]. Further research is required to confirm the findings of the flat feet study. As well, tuning the passive walker specifically for the flat feet and using a more rigid treadmill to reduce vibrations is recommended.

The high sensitivity of our measuring system enabled us to successfully evaluate the effects of dynamic and geometric parameters on passive gait. Evaluation of the dynamic and geometric parameters helps to create a better understanding the passive walking mechanics. The experimental results produce from this study will also help to validate mathematical models of passive biped walkers.

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