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An experimental study of passive dynamic walking

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SUMMARY

A two-straight-legged walking mechanism with flat feet is designed and built to study the passive dynamic gait. It is shown that the mechanism having flat feet can exhibit passive dynamic walking as those with curved feet, but the walking efficiency is significantly lower. It is also shown that the balancing mass and its orientation are etfective for controlling side-to-side rocking and yaw, which have significant effects on steady walking. The effects of various parameters on the gait patterns are also studied. lt is shown that changes in the ramp angle have the most dominant effect on the gait pattern as compared with the changes in the hip mass, ramp surface friction and size of the flat feet. More specifically, as the ramp angle increases, the step length increases while the range of the side-to side rocking angle decreases and the step length dictates the walking speed and the gravitational power Another finding, is that adding a hip mass improves the walking efficiency by allowing the mechanism to walk on a flatter ramp. This research enables us to gain a better understanding of the mechanics of walking. Such an understanding will have a direct impact on better design of prostheses and on the active control aspects of bipedal robots.

KEYWORDS: Biped; Passive dynamic walking; Gait pattern.

1. INTRODUCTION

Development of bipedal walking machines has attracted long-time interests. The most common approach is to control joint angles to mimic the walking of animals or humans. The disadvantages of this trajectory-control approach include its inefficiency in actuating the bipedal walking and the unnatural looking of the gait. One example is the Honda P3 robot, which weighs 130 kg and uses approximately 2 kW power during walking, more than 20 times the muscle work rate of a walking human of the same size,[1] yet the gait pattern is not natural. Some of the energy cost is due to friction and the impact where the swing foot comes in contact with the ground. However, the major portion of this energy consumption is the consequence of the trajectory-based approach, especially when the desired joint angle profiles are designed without the consideration of energy efficiency. One fundamental problem in the research using the trajectory-control approach is that the importance of the control actuation is over-emphasized, but the role of the mechanic/dynamics of the respective bipedal system is overlooked.

A parsimonious approach to the studies of the mechanics of bipedal gait is to study the passive dynamic walking. McGeer[2] demonstrated through simulations and experiments, that there exists a class of two-legged mechanisms for which walking is a natural dynamic mode. Once started on a shallow slope, these mechanisms will settle into a steady gait quite comparable to human walking without any active control or energy input. Collins *et al.*,[1] Coleman and Ruina,[3] Garcia *et al.*,[4,5] Kuo[6] and Chatterjee and Garcia[7] confirmed McGeer's finding, and further extended the research using two approaches. One is to build various physical mechanisms to demonstrate the existence of passive dynamic walking. For example, Coleman and Ruina[3] built a simple two-leg toy that is statically unstable in all standing positions, yet is stable in walking down a shallow slope. Collins *et al.*[1] built the first three-dimensional, two-legged and kneed passive-dynamic walking machine. Their machine not only preserved features of McGeer's two-dimensional model, including mechanical simplicity, humanlike knee flex, and passive gravitational power from descending a shallow slope, but also added specially curved feet, a compliant heel and mechanically constrained arms to achieve a harmonious and stable gait. One common feature of the above walking mechanisms is that all the feet are either semicircular or curved. In spite of the improvement of the energy efficiency, the reason of using semicircular or curved feet is that passive walking has been inspired by the observations of smooth rolling of wheels along a level surface. However, as correctly pointed out by McGeer[2], the semicircular foot was a mathematical convenience rather than a physical necessity. He speculated that other arrangements, such as a flat foot, should be feasible for a similar passive gait.

The computer simulation method has mainly been used to study the stability and the performance of various passive dynamic walking machines. McGeer[2] studied the effects of parameter variations on the step period and the step length. The varied parameters included the foot radius, hip mass, hip damping, leg inertia, height of the mass center and leg mismatch. Garcia *et al.*[4] used an irreducible simple, uncontrolled, two-dimensional and two-link model to study the stable passive dynamic gait. They found two distinct gait patterns at small ramp angles, of which the longer-step gait is stable at small slopes. They also found that, by increasing the ramp angle, stable cycles of higher periods appear, and the walking-like motion apparently becomes chaotic through a sequence of period doublings. Kuo[6] extended the planar motions to allow tilting side to side (rocking motion) and found that passive walking cycles exist, but the rocking motion is unstable. Kuo could not find passive strategies to stabilise the rocking motion. Chatterjee and Garcia[7] studied the passive dynamic walking using the simulation method. They found that small slopes preclude long steps and that small steps imply low speeds. These investigations provided important insights into the mechanics of bipedal walking. In addition, the computer simulation approach enables one to conduct simulations that are difficult even impossible for physical experiments.

The previous research on passive dynamic walking is intriguing. The results suggest that the mechanical parameters of the biped (e.g. link lengths, mass distributions) have a greater effect on the existence and the quality of gait than is generally recognised. Thus, one needs to also study mechanics, not just activation and control, to fully understand walking.[1,2,6] In the course of this research, the authors noticed that most of the findings related to the parametric effects on the passive dynamic gait patterns have been obtained using simplified computer models where semicircular feet or point feet were used, while the physical models, all with curved feet, have been restricted to the demonstration of the existence of the passive dynamic walking. Limited experimental results of the effects of parameters on the passive gait pattern has only been reported by McGee,[2] where only the changes in the ramp angle and the leg mass center offset were considered. Computer modelling is a powerful method. However, the only study that intended to compare the simulations with the experimental results has shown poor match between the two.[2]

In this paper, we present the design and the construction of a two-straight-legged passive dynamic walker similar to the one described by McGeer[2] except that flat feet are used instead of semicircular or curved feet. Thus, the passive walker reported here can stand still. We further study, using the developed walking device, the effects of parameter variations on the gait patterns. These parameters are the ramp angle, ramp surface friction, hip mass and size of the flat feet. The gait patterns to be compared are: step lengths, step periods, walking speeds, the gravitational power and ranges of side-to-side rocking angles. The overall objective of this work is to gain better understandings of the mechanics of passive dynamic walking. Understandings of the mechanics and the limits imposed by passive dynamic walking will allow us to better design prostheses. They will also have a direct impact on the active control aspects of walking because good controllers take advantages of the natural dynamics of their respective systems. Once passive dynamic walking is better understood, simple control mechanisms with small amounts of power can be introduced to increase the stability of the motion.[1]

The paper is organised as follows: The design of the passive walker is presented in Section 2. The measurement procedure, including the equipment set up, data acquisition and data analysis are also detailed in the same section. The results and their indications are discussed in Section 3, followed by concluding remarks in Section 4.

2. METHODOLOGY

2.1. Design and construction of the walking mechanism

The walking device, as shown in Figure 1, weighs 187.5 grams and stands 21 cm. It consists of two legs with rectangular plastic feet and two arms extending out from the feet with a balancing mass at each end. The following materials were used to build the walking mechanism: a Tinkertoy Classic Junior Builder Set of which all the pieces are made of wood, two pieces of 0.9 cm thick plexi glass (used as feet), two blocks (2.7 cm × 3.3 cm × 4.9 cm) of wood (used as hinges) and wooden balancing masses, which consist of one arm (15.4 cm), one spool (5 cm_diame-

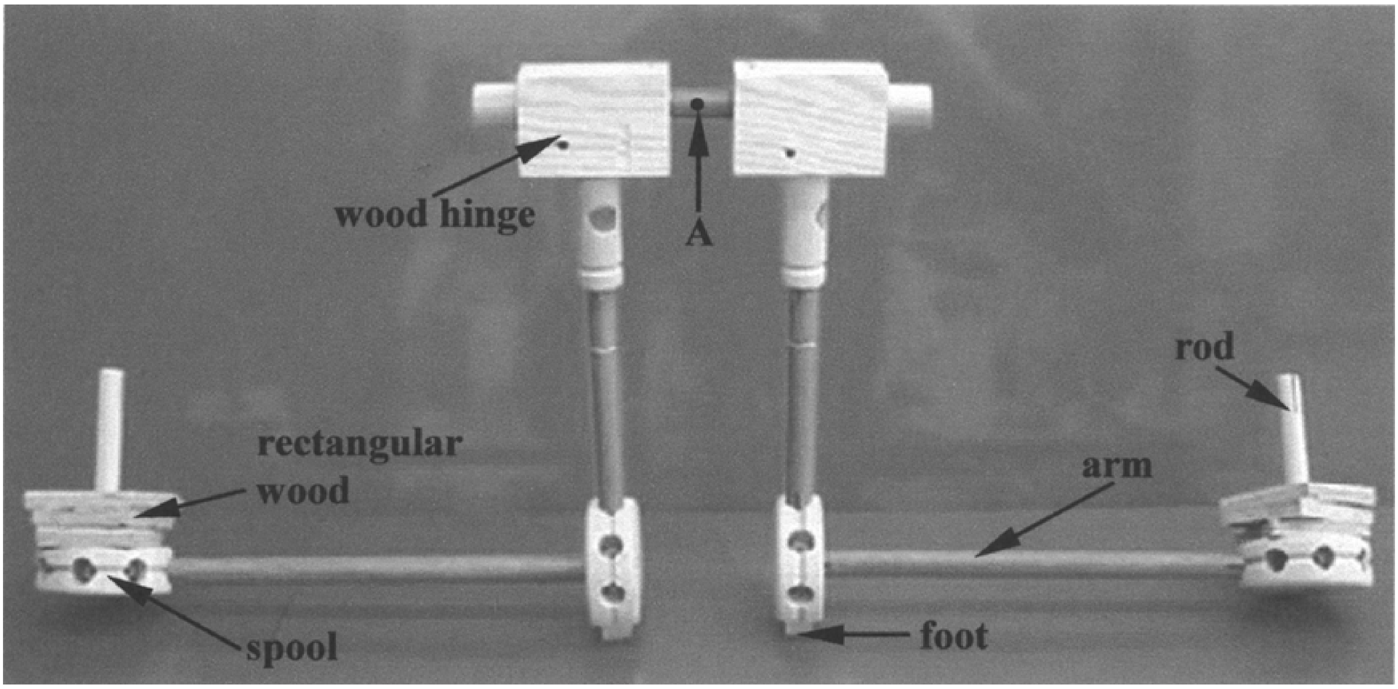

Fig. 1. Picture of the passive dynamic walker.

ter × 1.7 cm_thickness), one rod (5 cm) and three rectangular wood (4.6 cm × 3.7 cm × 0.7 cm). The orientation of the balancing mass can be adjusted by rotating the rod about the arm (see Figure 1 for details).

The two legs were connected to each other at the top of the walker with a pin joint type of mechanism. The two wooden blocks had a hole drilled through them slightly larger than the size of the wooden pin that passed through both blocks. The size of the hole was modified until it reached to a size with minimum friction. All legs and arms were approximately 90° from each other except the balancing mass assembly, where the rod was tilted approximately 25° to 35° angle from the upright direction opposite to the walking direction.

The most challenging part of the assembly is the pin joint at the hip of the walker. It is extremely important that the legs remain perpendicular to the walking surface. For this reason, the joint was required to be both tight enough not to allow any caving of the leg in the frontal plane and also loose enough to allow the pin moving freely in the wooden blocks, which have been made as a pin joint. Many minor refinements were required until the walker met both conditions. All the pieces fit quite tightly together and did not require the use of glue except the plexi glass feet that were glued to the wooden leg spools of the walker.

2.2. Measurement protocol

The method for measuring gait parameters of the walking device is presented in this section. The protocol includes the equipment setup, measurement procedure and data processing. Two camcorders (Samsung SCL310 (NTSC) and Cannon XL1 (NTSC)) were used to record the trials as the passive device walking down the ramp simultaneously. One was facing the frontal plane and another one was facing the sagittal plane. A ruler was set at the center of the measurement field for calibration. The detailed set up is shown in Figure 2.

In each trial, our tested biped was started by hand from the top of a ramp, and after a few steps, it settled into the steady gait appropriate for the slope in use. It is important to note that for each trial the walker undergoes a period known as the transient stage where the gait pattern is not steady. It is up to the operators' discretion as to where this transient stage ends. The video, recording the motion in both sagittal and frontal planes, was then digitised frame by frame. Once all the useful data were extracted, they were inputted into excel spreadsheets where the step length, step period, slope speed and gravitational power were determined as follows:

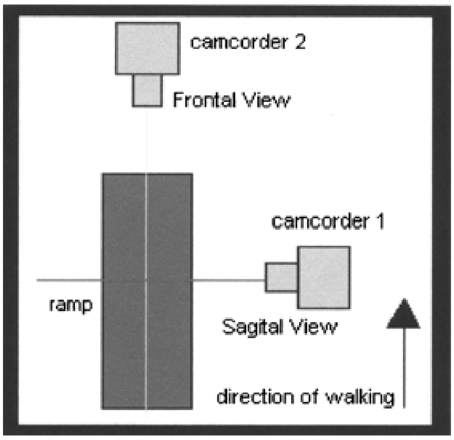

Fig. 2. Experimental set-up.

Step length: To calculate the step length, the distance was measured in which the walker took a given number of steps. This distance was then divided by the number of steps taken to obtain the average step length. With the existing equipment we believe that this method of calculation would result in a lower measurement error than directly measuring each individual step.

Step period: The calculation of the step period is similar to that of the step length. With the camcorders having the frequency of 30 frames per second, the time was noted when the foot was leaving the ramp surface at the first steady step. Once the walker had walked a certain distance, the foot touched the ramp surface and the time at this point was recorded. The difference between the time instants was then divided by the number of steps taken to obtain the average step period.

Gravitational power: Gravitational power has been defined as the rate of work produced by the gravity during passive walking[4]. It can be expressed as $mgV \sin\theta$, where V is the walking speed along the ramp, m is the total mass, g is the gravitational acceleration and θ is the ramp angle.

Walking efficiency: The passive walking efficiency has been defined as $\frac{mechanical\ work}{weight \times distance\ traveled}$[3,5]. For gravity-powered walking, the efficiency is measured by the walking slope, $\sin\theta$, where θ is the ramp angle.

The measurements and data analyses were conducted over all data except those from the first few steps in the transient stage of each trial. For each parameter variation, the experiment was repeated for six trials. All the above variables from six trials were averaged and standard deviations were calculated.

3. RESULTS AND DISCUSSIONS

In this section, we present and discuss the experimental results. The objective is to gain an understanding of the mechanics of bipedal walking.

3.1. Observations

Steady walking was observed from our passive walker. We placed the walker at the top of the ramp faced downhill, tipped the walker to one side and then released it. The walking device rocked side to side, coupled with swinging of the legs and took tiny steps downward the ramp. When the swing foot collided with the ground, support would be transferred impulsively from the heel to the toe at the midstance. We were able to achieve a 70% to 80% successful rate of launches. Our best ramp angle is 4°. After several trials, we reached to 90% successful rate or higher, and the walker seemed more robust in that it was less sensitive to the initial disturbance and it reached to steady walking faster as compared with other ramp angles. The above observations confirmed that a two-legged mechanism with flat feet can exhibit passive dynamic walking like those with semicircular or curved feet. The observed humanlike walking is dictated by the combination of system parameters as its counterpart with curved feet.

Two interesting observations about side-to-side rocking and yaw (rotation about the vertical axis) have been made. Side-to-side rocking provides the ground clearance, which is essential for walking with straight legs. Kuo[6] showed, through computer simulations, that unconstrained side-to-side rocking can lead to instability, but he could not find a passive strategy for stabilization. Kuo's simulation model[6] is similar to our walker without balancing masses. Side-to-side rocking is actuated by the moment resulted from the gravity of the walker about the axis parallel to the walking direction and passing the supporting foot during the single support phase. Since the gravity center is not always on top of such an axis, the tendency of side-to-side rocking always exists, which must be counteracted. In our experiment, we were unable to achieve steady walking without balancing masses. By closely observing the walking motion, we noticed that a number of tipping-over were due to the rapid increase in rocking angles within a short period of time. The large rocking angle often caused the walker to tip over to either side. By adding proper balancing masses, we increased the moment of inertia, *i.e.*, the resistance to rocking, and we were able to manipulate the frequency and the magnitude of side-to-side rocking, which were phase-locked with the swinging motion leading to steady walking. Thus, our assembly of balancing masses can be used as a simple passive strategy for stabilizing side-to-side rocking. Another technique to resist rocking is to use swing arms. For example, Collins *et al.*[1] used two arms to swing freely laterally to enhance the side-to-side rocking stability and Wisse *et al.*[8] suggested a free-side-to-side-swinging mass to balance rocking of the walker. Regardless the techniques, side-to-side rocking is needed for bipedal walking, but it must be controlled carefully. The balancing mass assembly is a simple yet effective passive tool for controlling side-to-side rocking.

It is not surprising that as one leg moves forward, yaw will be generated. This is because as one leg moves forward, the two side-by-side legs will have angular momentum variations about the vertical axis, which induces yaw. Thus, yaw is inherent to bipedal walking, and it is highly undesirable. Our initial trials showed that even if small yaw was present, the walker fell quickly. Thus, the effects of yaw must be counteracted. In our experiment, we found that yaw is sensitive to the orientation of the balancing mass, and to have steady walking possible, the rod of the balancing mass must be tilted in the opposite direction of walking. For the ramp angle of 4°, the optimal orientation of the balancing mass is about 27° from the vertical in the opposite direction of walking, which can almost eliminate yaw effects in our walking device. Thus, the balancing mass and its orientation can be a possible passive control of yaw. Another way to reduce yaw is to use swing arms. For example, in the previous work /two arms were constrained to move fore and aft with the opposite leg to increase the resistance to yaw.

In the course of reducing yaw, we noticed that the dynamic effects from swinging, side-to-side rocking and yaw are highly coupled. The acceptable orientation of the balancing mass for counteracting yaw is sensitive to the frequencies and the magnitudes of side-to-side rocking, as well as swinging. The highly interactive dynamic effects from the above three motions make the understanding of passive dynamic walking challenging.

In summary, we observed steady walking in our straight-legged mechanism with flat feet. Although the dominant swinging motion occurs in the sagittal plane, side-to-side rocking and yaw are inherent to the side-by-side bipedal walking and they have significant effects on the steady gait. The yaw motion should be eliminated since it destabilizes the walker. However, proper controlled side-to-side rocking is needed to enhance stable swinging motion in the sagittal plane and to reduce the destabilizing effect from yaw simultaneously. Thus, side-to-side rocking should be maintained, but carefully controlled. We found that the combination of the amount of mass and the orientation of the balancing mass is a simple but effective passive tool to control side-to-side rocking and to counteract the destabilizing effects from yaw. The above observations of the passive control of side-to-side rocking and yaw indicates the importance of the arm swinging in stability and energy-efficiency of human walking, and such arm-swinging might be just dictated by the system parameters rather than driven by a controller.

3.2. Effects of parametric variations on passive gait patterns

In this section, we present the experimental results on the effects of the ramp angle, hip mass, ramp friction coefficient and size of flat feet on the gait pattern, which includes the step length, step period, slope speed, range of the side-to-side rocking angle and gravitational power.

3.2.1. Benchmark results. We first present the results of the gait patterns of our passive walker with various ramp angles as the benchmark results. The friction coefficient ofthe ramp is 0.24 and the foot-size is 3.1 cm × 0.9 cm. We managed to have our device walking steadily on the ramp with the ramp angle ranging from 3° to 7°. The measured and calculated gait parameters are shown in Table I. From this table, one can observe that, as the ramp angle increases, the step length increases steadily, while the range of the side-to-side rocking angle decreases. However, our measurements do not show a clear trend of changes in the step period. Our calculation shows that the walking speed increases with the ramp angle, the same trend as that of the step length, which indicates that longer step lengths result in higher walking speeds. Thus, our experimental results show that the ramp angle dictates the step length, walking speed and gravitational power.

It is interesting to compare the gait pattern of our walker with flat feet to the previous work where round feet or point feet were used. For example, in McGeer's experimental work[2] as well as other simulation studies,[4,6,7] the step length was also found to increase with the ramp angle, but the step

Table I. Benchmark results.

Ramp angle (deg.)	Step Length (cm)		Step Period (sec.)		Slope Speed (cm/sec.)		Range of Rocking Angle (deg.)		Gravitational Power ($\times 10^{-2}$) (watts)	
	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
3	2.52	0.61	0.24	0.06	10.69	1.18	11.75	0.52	1.00	0.1
3.5	3.29	0.50	0.25	0.02	13.03	1.60	10.92	0.66	1.50	0.2
4	3.89	0.25	0.28	0.01	14.07	1.13	10.26	0.42	1.80	0.1
5	3.81	0.50	0.24	0.01	5.71	1.36	7.50	0.48	2.52	0.2
6	4.70	0.29	0.26	0.03	18.34	2.58	6.94	0.14	3.50	0.5
6.5	4.94	0.30	0.24	0.004	20.64	1.22	7.92	0.20	4.30	0.3
7	5.32	0.30	0.26	0.02	0.60	1.71	6.04	0.10	4.62	0.4

period did not show a clear trend of changes. These previous results are consistent with our findings. However, in the previous work with curved feet or point feet, the ramp angle varied from 0.5° to 2°, while our mechanism walked on a ramp with a larger slope (3° to 7°), which indicates lower walking efficiency, that is higher gravitational power was required to actuate our passive walker. This is expected since rolling is an inherent property to round objects and lower friction is experience, while for our walker with flat feet, not only high friction is experienced, but also higher energy is needed to transfer the support from the heel to the toe and to make the flat foot tipping over in order to initiate the next step. Higher gravitational energy input requires larger drop of the gravity center and consequently needs larger ramp angles. However, in spite of the higher demand for the gravitational energy input, our walker exhibits better stability in terms of standing still and being robust against the larger range of ramp angles. The finding about longer step lengths resulting in higher walking speeds is consistent with previous results[7] based on simulations and a theoretical proof.

3.2.2. Hip mass. We attached a lumped mass at the hip, *i.e.* point A in Figure 1, and repeated the measurements. The lumped mass was increased from 0 gram up to 110 grams. The friction coefficient of the ramp and the foot-size remained unchanged. The capacity of the presented device walking on various ramps was summarised in Table II. During the experiment, we noticed that with a moderate hip mass, it was easier to achieve steady gait as compared with a large hip mass or a low hip mass attached. However, large hip masses enabled the presented mechanism walking on flatter ramps. For example, with a hip mass over 90 grams, we were only able to manage to have our device walking on the ramp at 2.5° and 3° as shown in Table II. On the other hand, with a low hip mass, we were able to achieve steady walking with large ramp angles. For example, with a hip mass below 15 grams, the presented mechanism was able to walk on the ramp ranging from 3° to 6.5°. Thus, a properly added hip mass can enhance steady passive dynamic walking.

The result of the step length vs. the hip mass is shown in Figure 3. Several observations can be made. Firstly, a higher hip mass enables the device walking on a flatter ramp, *i.e.* the added hip mass improves the efficiency of the walking cycle. This finding is consistent with the previous work[2,7] with curved feet used based on simulations. Secondly, it appears that a lower hip mass results in a slightly longer step length. Thirdly, regardless of the hip mass, the step length overall increases as the ramp angle increases, and our results show that the step lengths are more sensitive to the ramp angles than the hip masses.

The result of the step period vs. the hip mass is shown in Figure 4. The step period does not show a clear trend as the hip mass changes. The slope speed vs. the hip mass is shown in Figure 5. The walking speed oscillates with respect to the hip mass for the same ramp angle. However, changes in the ramp angle again show more effects in that the walking speed increases with the ramp angle. This trend of the walking speed is the same as that of the step length. Thus, for the passive dynamic walking with flat feet, longer step lengths result in higher walking speeds regardless of the hip mass.

The result of the range of the rocking angle vs. the hip mass is shown in Figure 6. With a low hip mass up to 20 grams, the range of the rocking angle decreases as the hip mass increases. As the hip masses are higher than 60 grams, it seems that the range of rocking angles is not sensitive to the hip mass, but the range of the rocking angles is overall

Table II. Walking with different hip mass.

Hip mass \ Ramp angle	2.5°	3°	4°	5°	6°	6.5°
0 gram		*	*	*	*	*
5 grams		*	*	*	*	*
10 grams		*	*	*	*	*
15 grams		*	*	*	*	*
20 grams		*	*	*	*	
25 grams		*	*	*	*	
30 grams		*	*	*	*	
35 grams		*	*	*		
40 grams		*	*	*		
50 grams		*	*	*		
60 grams		*	*			
70 grams		*	*			
80 grams		*	*			
90 grams	*	*	*			
100 grams	*	*	*			
110 grams	*					

* – represents the hip mass for which steady walking was achieved.

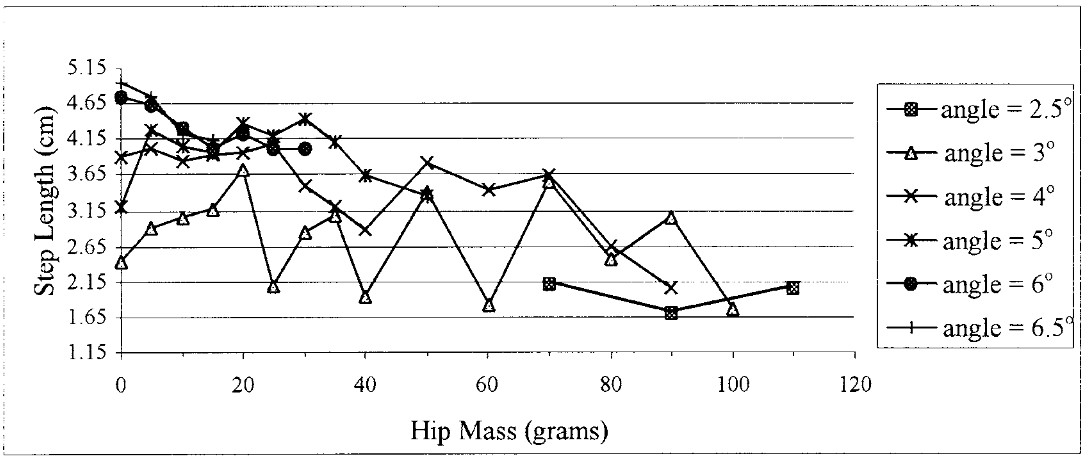

Fig. 3. Step length vs. hip mass for all tested angles.

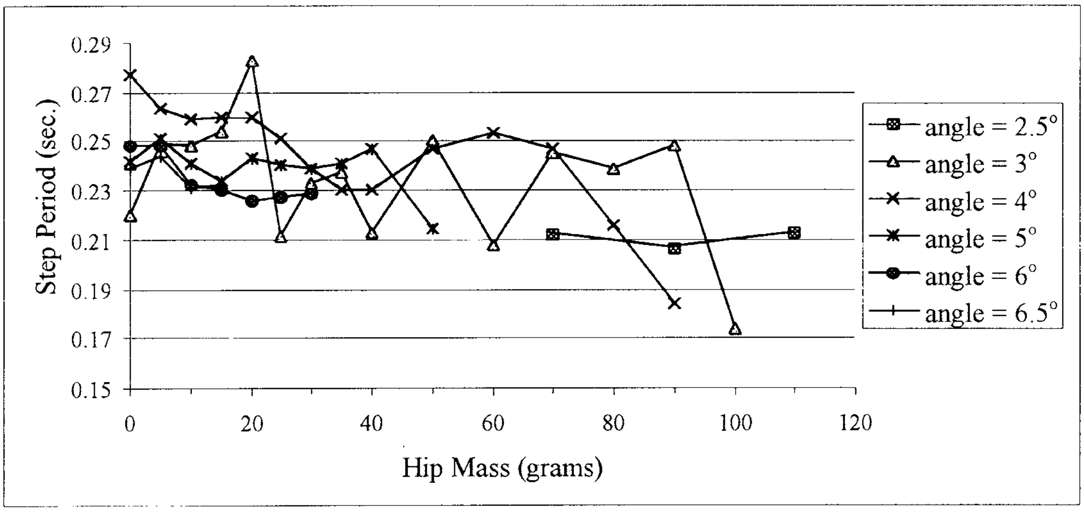

Fig. 4. Step period vs. hip mass for all tested angles.

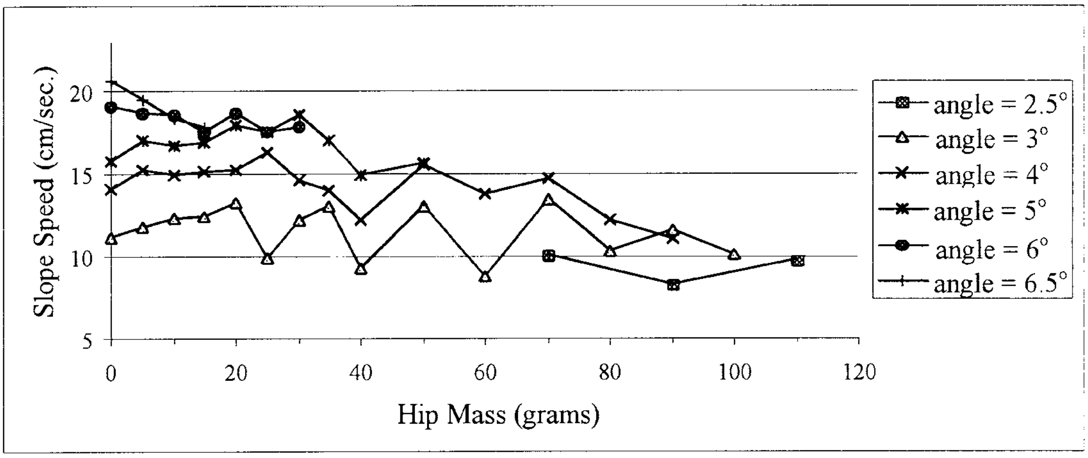

Fig. 5. Slope speed vs. hip mass for all tested angles.

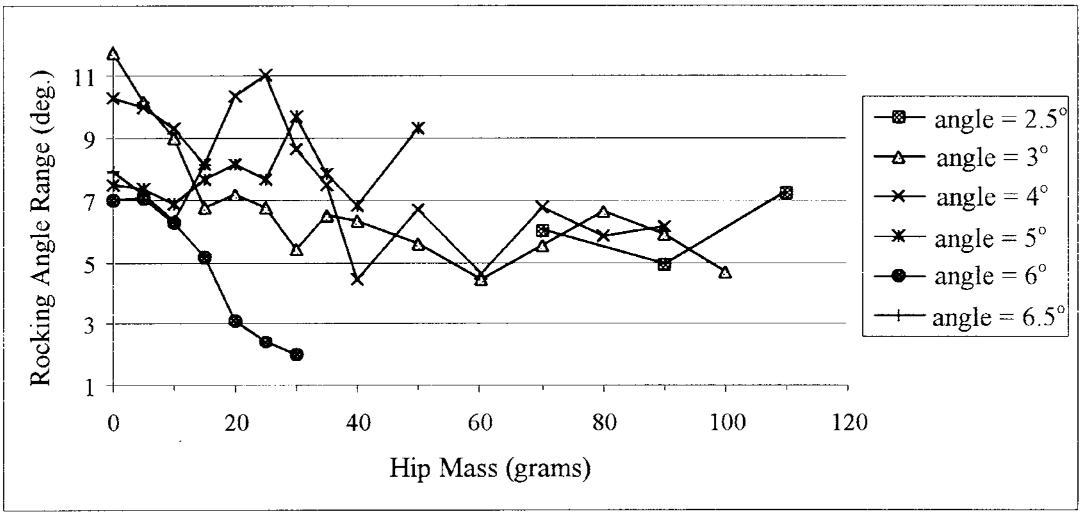

Fig. 6. Range of rocking angle vs. hip mass for all tested angles.

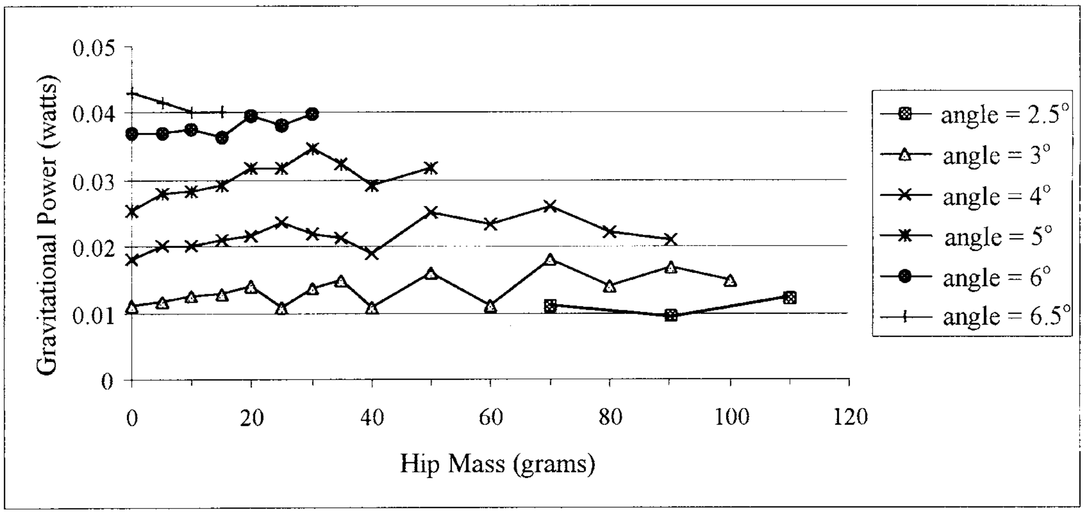

Fig. 7. Gravitational power vs. hip mass for all tested angles.

lower than those with a lower hip mass at the same ramp angle.

The gravitational power (Figure 7) shows a similar pattern as the one of the walking speed in that it increases with the ramp angle. At the same ramp angle, the gravitational power oscillates within a narrow band.

In summary, the important findings of the effects of the added hip mass on passive dynamic walking with flat feet are that the added hip mass improves the efficiency of walking by allowing the device walking on flatter slopes, the gait parameters are more sensitive to the changes in ramp angles as compared to the changes in the added hip mass. Higher ramp angles render longer step lengths, which dictate the walking speeds and the gravitational power.

3.2.3. Friction coefficients. We also studied the effects of friction on passive walking. We used three different surfaces for the ramp with a low friction coefficient (0.24), intermediate friction coefficient (0.33) and high friction coefficient (0.42). The foot-size was 3.1 cm × 0.9 cm and no hip mass was attached. The walking device can walk with a minimum ramp angle of 3° for the ramp with a low friction coefficient. For the intermediate and high friction coefficients, the lowest ramp angle at which the walker is still able to walk is 4°. It is expected that the larger friction coefficient causes higher energy dissipation, thus the walker requires more energy input. Larger ramp angles allow more gravitational energy to be injected to the walker to compensate the energy loss due to the friction.

Referring to Figure 8, the step lengths with various ramp angles for the low friction coefficient ramp are always higher than those with the intermediate and high friction coefficients. For the ramp with intermediate and high friction coefficients, the step lengths increase with the ramp angles, the same as those for the low friction coefficient except for the ramp angle of 4°. Figure 9 shows that the step periods for the ramp with low friction coefficient are the highest as compared with those belonging to the intermediate and high friction coefficients. The step periods do not change significantly with respect to the ramp angles. Referring to Figure 10, the slope speeds for the surface with a low friction coefficient are higher than those with the intermediate and high friction coefficients. The slope speed

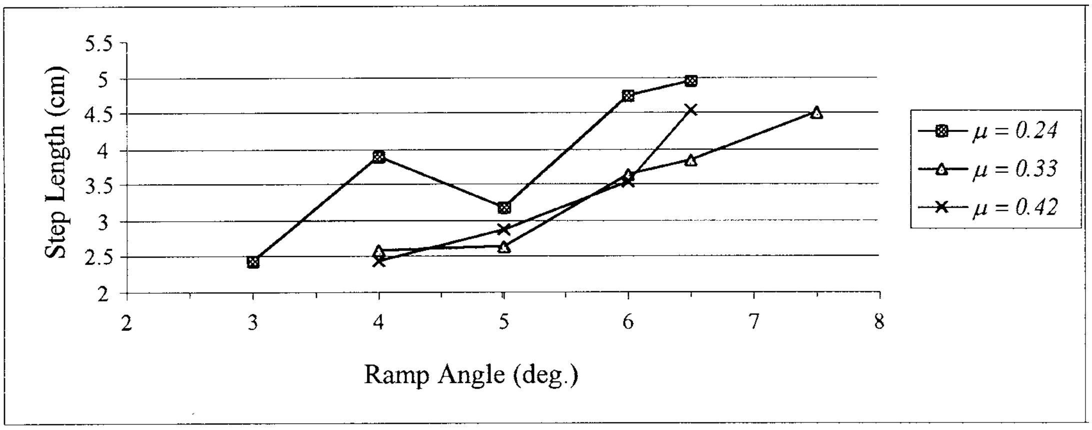

Fig. 8. Step length vs. ramp angle for various friction coefficients.

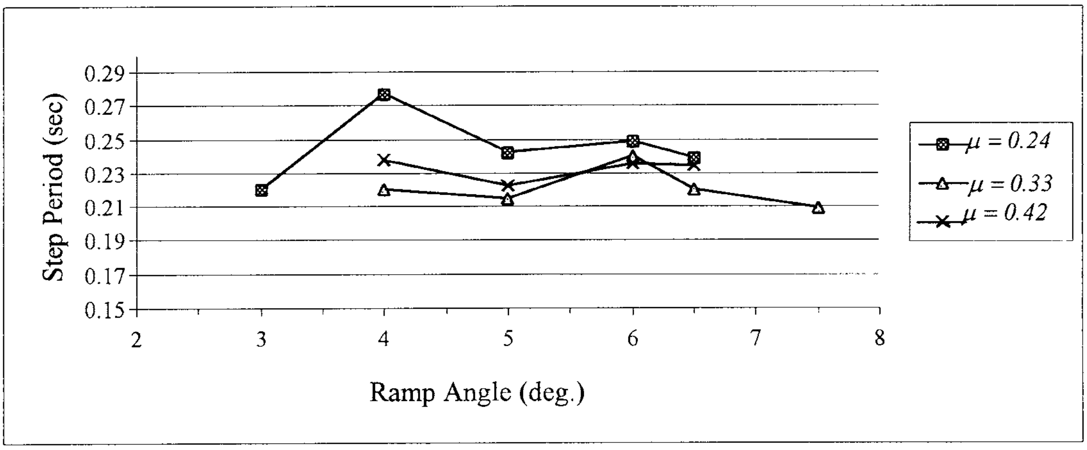

Fig. 9. Step period vs. ramp angle for various friction coefficients.

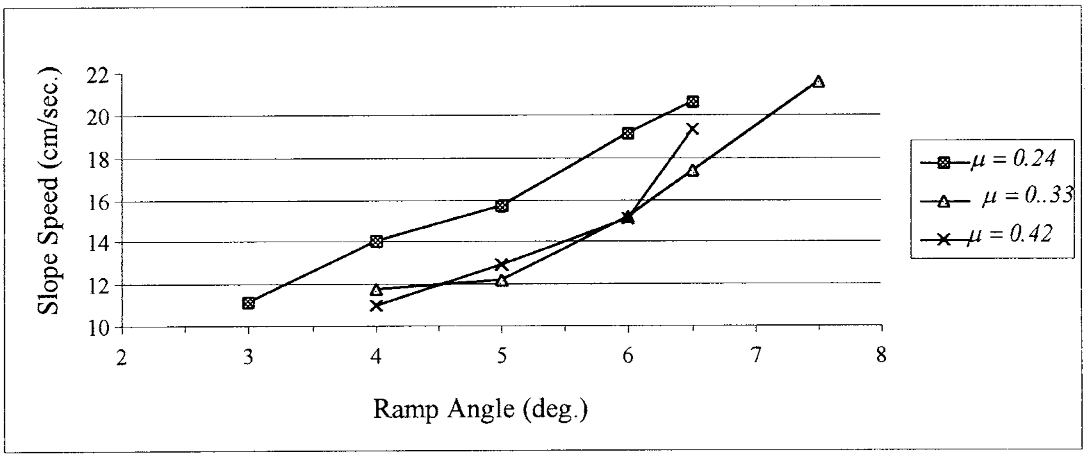

Fig. 10. Slope speed vs. ramp angle for various friction coefficients.

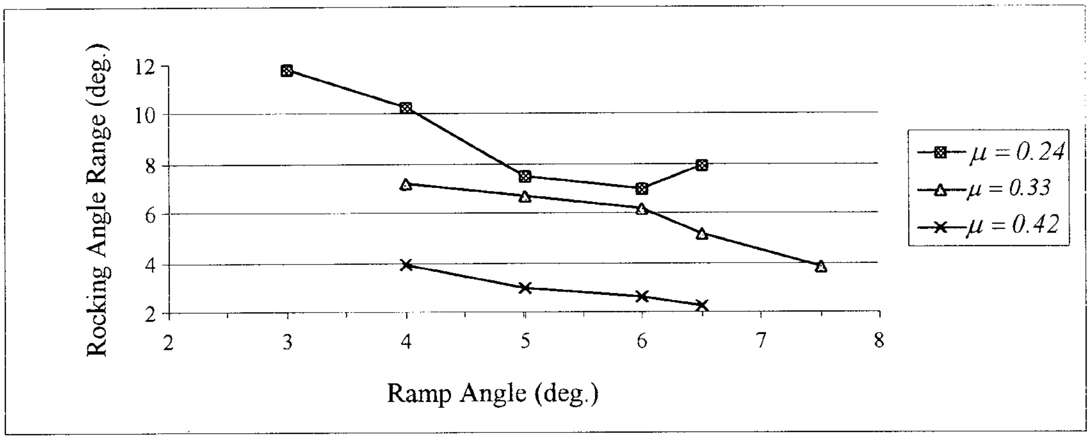

Fig. 11. Range of rocking angle vs. ramp angle for various friction coefficients.

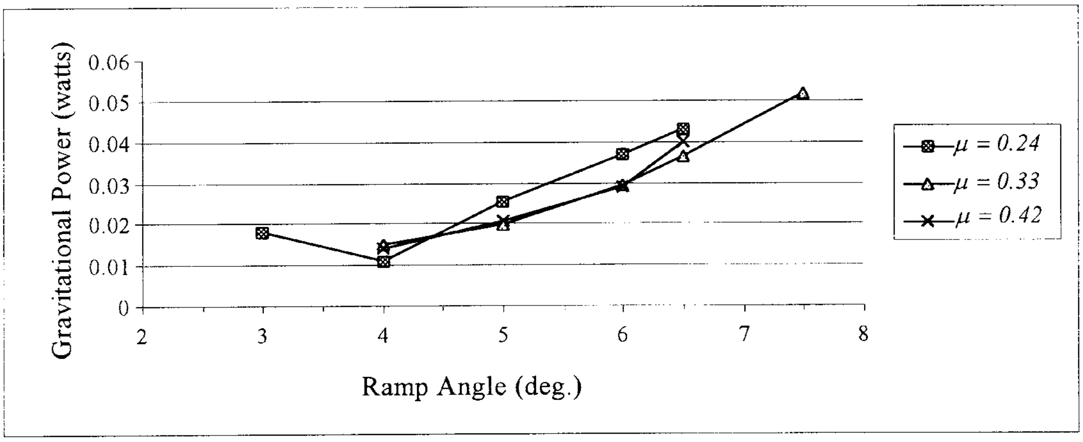

Fig. 12. Gravitational power vs. ramp angle for various friction coefficients.

increases with the increase in the ramp angles regardless of the surface friction coefficient.

The rocking angles for the low friction coefficient are the highest, followed by those with the intermediate and high friction coefficients as shown in Figure 11. The ranges of the rocking angles tend to decrease with the increase in the ramp angles. From Figure 12, we found that although the gravitational power for the ramp with the lowest friction coefficient is slightly higher than those for the ramps with higher coefficients, the gravitational power consistently increases with the ramp angle. This is another evidence that the step lengths dictate walking speeds and the gravitational power.

3.2.4. Foot lengths. We also investigated the effects of the lengths of the flat feet on walking. The friction coefficient of the ramp was 0.24 and no hip mass was attached. The same walking device with various lengths of feet were used (2.2 cm, 2.5 cm, 2.7 cm, 2.8 cm, 3.1 cm and 3.3 cm). The width of the feet remained unchanged (0.9 cm). However, we were only able to make our walking mechanism with the feet lengths of 2.8 cm and 3.1 cm walking steadily. The results of step lengths, step periods, slope speeds, ranges of rocking angles and the gravitational power are shown in Figures 13 to 17. The first observation is that the ranges of rocking angles with shorter feet are significantly higher than those with longer feet. Another observation is that the step length, step period, slope speed, rocking angle range and gravitational power increases with the ramp angle regardless the lengths of feet.

4. CONCLUDING REMARKS

In this work, we constructed a two-straight-legged passive dynamic walker with flat feet. We further studied the effects of changes in the ramp angle, hip mass, friction of the ramp and foot length on the walking patterns systematically. The walking patterns were characterised by the step length, step period, walking speed, side-to-side rocking angle and gravitational power. The purpose was to gain physical insights into the mechanics of passive walking.

We first found that as compared with other passive walking devices with curved feet or point feet, the presented walker with flat feet can not only stand still, but also walk steadily down a ramp with a larger range of ramp angles. However, the presented passive walking device requires significantly higher ramp angles than those with curved feet or point feet, which indicates that the walking efficiency is significantly lower. This is expected because higher energy is needed to transfer the support from the heel to the toe and to make the flat foot tipping over to initiate the next step. Like the passive walkers with curved feet, walking with flat

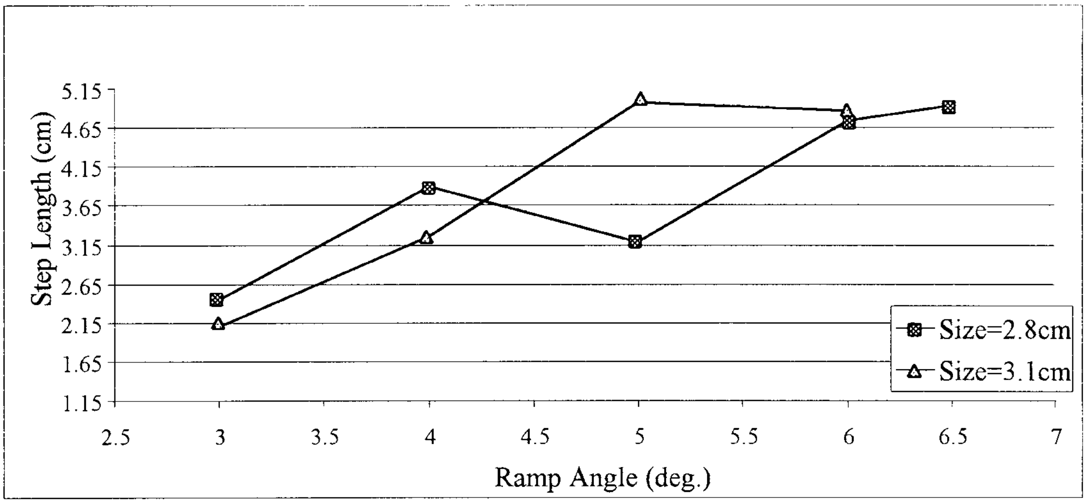

Fig. 13. Step length vs. ramp angle with various foot sizes.

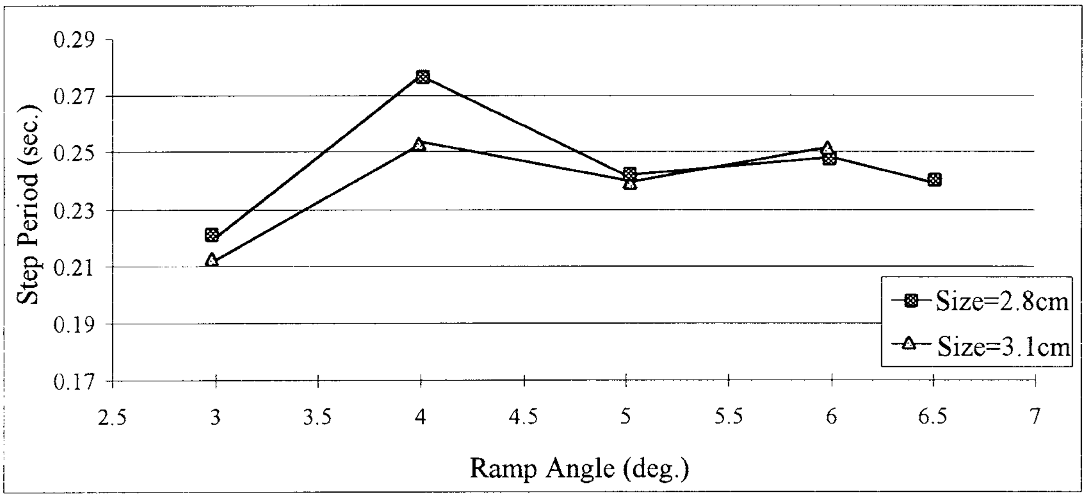

Fig. 14. Step period vs. ramp angle for various foot sizes.

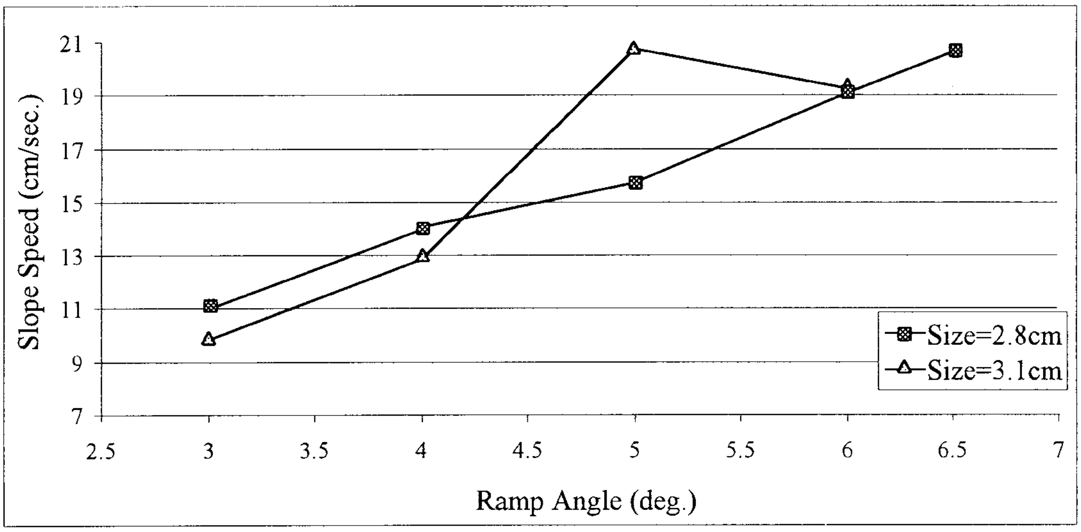

Fig. 15. Slope speed vs. ramp angle for various foot sizes.

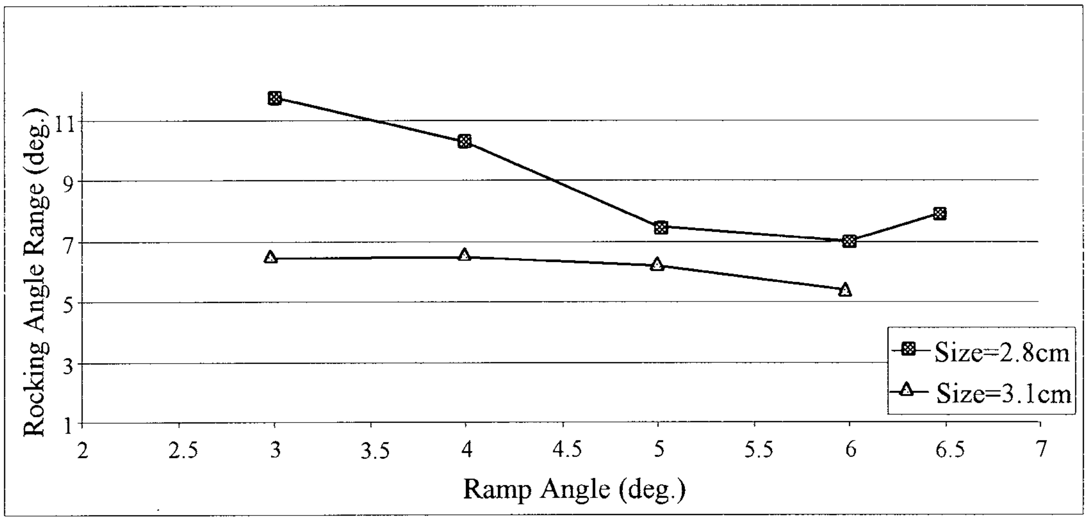

Fig. 16. Range of rocking angle vs. ramp angle with various foot sizes.

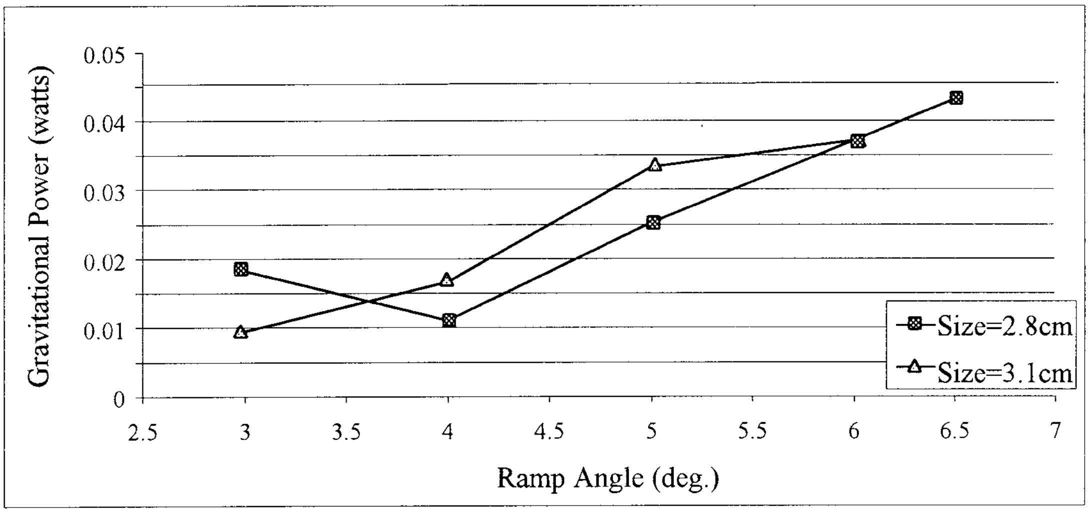

Fig. 17. Gravitation power vs. ramp angle with various foot sizes.

feet is dictated by the combination of dynamic parameters. The fact that the walker can settle in steady walking in spite of the variations in parameters shows the robustness of the passive dynamic walking. We also found that the dynamic effects of the swinging motion, side-to-side rocking and yaw are internally coupled, and yaw is highly undesirable for stable walking. Side-to-side rocking is required for straight-legged walking devices and it may enhance the stability of walking if properly controlled. One of the effective passive tools for controlling side-to-side rocking and yaw is the proper combination of the balancing mass and its orientation. Another passive tool is to use free swing arms. Regardless the techniques, proper control of side-to-side rocking and yaw is essential for steady walking, which indicates the importance of the role of human swinging arms in stable and energy-efficient walking and such a role may be inherent to a machine rather than driven by the central nerve system.

Regarding the effects of parameters, such as the ramp angle, hip mass, ramp friction and foot length on the gait patterns, we found that changes in the ramp angle have the most dominant effects on the gait patterns. More specifically, as the ramp angle increases, the step length increases regardless of the hip mass, friction coefficient and foot size. The step period does not show any clear trends with the increase in the ramp angle. The walking speed and the gravitational power are dictated by the step length, and consequently by the ramp angle. As the ramp angle increases, the range of the rocking angle decreases regardless of the friction coefficient and foot size. Another finding is related to the hip mass. An increase in the hip mass improves the walking efficiency by allowing the mechanism to walk on a flatter ramp. Also, a higher hip mass reduces the step length as well as the rocking angle. The third interesting finding is that 4° is a magic ramp angle for our walking device. It was significantly easier to have our mechanism walking on a ramp of 4° as compared with other ramp angles regardless of hip masses, foot lengths and frictions. The gait parameters associated with 4° ramp, such as the step length, step period and rocking angle, are also distinguished from those with other ramp angles. We also noticed that the successful rate with the ramp angle of 4° is the highest (about 90%) as compared with other ramp angles. It seems that 4° of the ramp angle is an ideal slope for our walker.

Most previous experimental studies on passive dynamic walking have been limited to demonstrating the existence of passive gait for various passive walking mechanisms where curved feet were used. Very few have focused on the detailed walking patterns. Through our experimental study, we not only demonstrated the existence of passive gait for the presented walking device with flat feet, but also investigated the effects of various parameters on the gait patterns. The study is systematic and the results agree with limited available simulation results qualitatively where either semicircular feet or point feet were used. The importance of this research lies within its connection to human gait, as well as to the development of energy-efficient bipedal robots. This work, along with other research on passive dynamic walking, enables us to gain a better understanding on the mechanics of walking. Such an understanding can have positive impact on design of better prostheses and on the active control aspects of walking.

References

1. A. H. Collins, M. Wisse and A. Ruina, "Three-dimensional passive-dynamic walking robot with two legs and knees", *Int. J. Robotics Research* **20**, No. 7, 607–615 (2001).
2. T. McGeer, "Passive dynamic walking", *Int. J. Robotics Research* **9**, No. 2, 62–82 (1990).
3. M. J. Coleman and A.Ruina, "An uncontrolled toy that can walk but cannot stand still", *Physical Review Letters* **80**, No. 16, 3658–3661 (1998).
4. M. Garcia, A. Chatterjee, A. Ruina and M. Coleman, "The simplest walking model: stability, complexity, and scaling", *ASME Journal of Biomechanical Engineering* **120**, No. 2, 281–288 (1998).
5. M. Garcia, A. Chatterjee and A. Ruina, "Efficiency, speed and scaling of two-dimensional passive-dynamic walking", *Dynamics and Stability of Sysfems* **15**, 2, 75–99 (2000).
6. A. D. Kuo, "Stabilization of lateral motion dynamic walking", *Int. J. Robotics Research* **18**, No. 9, 917–930 (1999).
7. A. Chatterjee and M. Garcia, "Small slope implies low speed for McGeer's passive walking machines", *Dynamics and Stability of Systems* **15**, 139–157 (2000).
8. M. Wisse, A. L. Schwab and R. Q. van der Linde, "A 3D passive dynamic biped with yaw and roll compensation", *Robotica* **19**, Part 3, 275–284 (2001).
9. H. Elftman, "The Function of Arms in Walking", *Human Biology* **11**, 529–535 (1939).