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Experimental studies on passive dynamic bipedal walking

Kazi Rushdi, Derek Koop, Christine Q. Wu *

Department of Mechanical and Manufacturing Engineering, University of Manitoba, Winnipeg, MB, Canada R3T 5V6

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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

* Corresponding author. Tel.: +1 204 474 8843.
E-mail addresses: cwu@cc.umanitoba.ca, Christine.WU@ad.umanitoba.ca (C.Q. Wu).

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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.

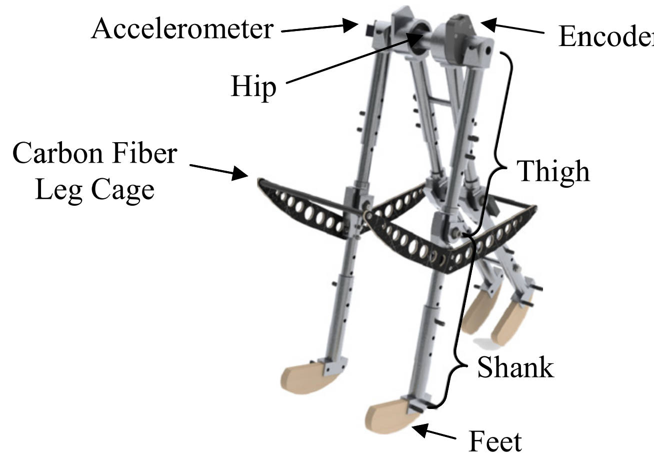

Fig. 1. Dexter MK III.

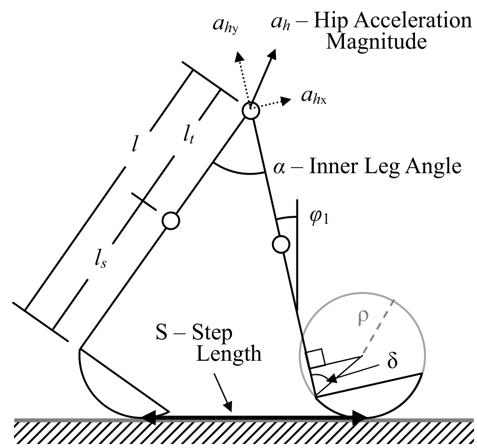

Fig. 2. Diagram of system parameters.

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.