Chapter 1

Introduction

Much of this chapter is taken from material contained in a funding proposal to the National Science Foundation, entitled "Passive Nonlinear-Dynamic Study of Human Gait," NSF# 9806612. The proposal was co-written by Mariano Garcia and Andy Ruina and submitted to the Division of Bioengineering and Environmental Systems under the "Biomedical Engineering And Research To Aid Persons With Disabilities" program in December 1997. The proposal was accepted and funded for three years beginning in Fall 1998.

Most terrestrial multicellular animals, including humans, can walk. Some people also hope for useful walking robots. Increasing our knowledge of walking has a wide range of applications. Since human motion is controlled by the nervous system and powered by muscles, the role of nerves and muscles is obviously of interest. But one way to understand the role of nerves and muscles is to learn how much can be done without them. Human walking, for example, might be modeled for some purposes as an uncontrolled mechanical process. One idea behind this thesis is that the role of the nerves and muscles in walking might be more to gently guide than imposingly control.

The approach here was originally pioneered by McGeer (1989-1993), who demonstrated that a two-dimensional, four-link mechanism, which somewhat resembles human legs, is capable of stable, human-like gait down a shallow slope with no activation (besides gravity) and no control. McGeer's *passive-dynamic* theory of bipedal locomotion describes gait as a natural repetitive motion of a dynamical system or, in the language of nonlinear dynamics, a *limit cycle*.

This thesis describes extensions of McGeer's work using analytic approaches, numerical computer simulation, non-linear dynamics techniques, and physical experiments. This work is addressed at a broad range of general questions about the role of mechanics in animal movement for the special case of walking. What are the limits to the stability and efficiency of passive-dynamic motions? How much of human coordination is governed by the brain and how much is governed by mechanics? To what extent are the physical aspects of biological design dominated by stability and/or efficiency considerations? Do more degrees of freedom limit the possibilities of self-stability? Do the nonholonomic aspects of intermittent contact affect stability? Answers to these and other questions could be useful in the theory of gait synthesis, in diagnosing and treating gait disorders, in prosthetic design, and in robotics.

1.1 A Passive-Dynamic Approach

Although there is no doubt that muscular power is needed for walking, it might be neglected from a certain viewpoint like engine power was neglected for much of the design of early airplanes, as descibed by McGeer (1990a). In this work, a simple energy source (gravity) is substituted for the small but essential muscle use of humans. It is likely that results thus obtained will be relatively insensitive to the particular choice of energy source. However, the use of gravity as an energy source (as opposed to a muscle or motor model) eliminates arbitrariness in control decisions and simplifies simulation and physical experimental verification.

Observation of animals also partially validates passive-dynamic approaches. For example, electromyographic muscle signals (EMG) recorded by Basmajian and Tuttle (1973) show a low level of muscular activity in human and gorilla legs during walking, as compared to other movements. The minimal muscle idea motivated (what seems to be the first) passive-dynamic (or *ballistic*) partial-gait simulations of Mochon and McMahon (1980). Other results which lend some credence to this approach are mentioned in Section 1.3.

McGeer's results with passive dynamic walking machines also suggest that the mechanical parameters of the human body (e.g. lengths, mass distributions) have a greater effect on the existence and quality of gait than is generally recognized. That is, one needs to study mechanics, not just activation and control, to fully understand walking. This observation may have some relevance in the study of elderly and/or child gait, whose mass distributions may differ somewhat from those of typical middle-age experimental subjects, as discussed by Jensen (1993).

The control aspects of muscle use involve small energetic cost, at least in principle. The role of low-energy control actions may be better understood by finding the limits of passive strategies. As seen from a control perspective, this work largely involves investigation of control parameters which are physical properties rather than the traditional active-control parameters (such as feedback gains, neural net parameters, genetic algorithm reward schemes, etc.). While the second extreme –

that of adjusting control algorithms and optimization criteria – is being explored by others, the other extreme – that of adjusting mechanical parameters in uncontrolled theoretical and physical models – remains relatively unexplored.

1.2 Passive Dynamic Walking Machines

The McGeer-like passive-dynamic walking machines consist of hinged rigid bodies with limited ranges of motion that make collisional and rolling contact with a sloped, rigid ground surface. The term "passive" here means that the models have no energy sources other than gravity or self-contained torsional springs, and that they are not controlled with feedback. Note that a wind-up toy or escapement mechanism might be considered to be passive since it fits the above definition.

1.2.1 Taxonomy

A taxonomy of passive-dynamic walking machines is shown in Figure 1.1. The mechanisms of interest in this work are denoted with asterisks. Most machines consist of a *swing leg* (not in contact with the ground) and a *stance leg* (touching the ground), connected by a frictionless hinge at the *hip*. Extra mass is generally added at the hip serving as a crude model of an upper body. For kneed walkers, each leg is composed of a rigid thigh and shank, and the stance knee is locked; the swing knee is a frictionless hinge with a knee-stop preventing hyperextension. The two legs are assumed identical. Straight-legged (kneeless) walkers may be viewed as obtained from kneed walkers by permanently locking the knees. Two-dimensional (2-D) models are constrained to a plane, while three-dimensional (3-D) models can move in three dimensions. More details on the dynamics and modeling assumptions are given in Chapter 2. In the next sections, some results from the earlier models are summarized.

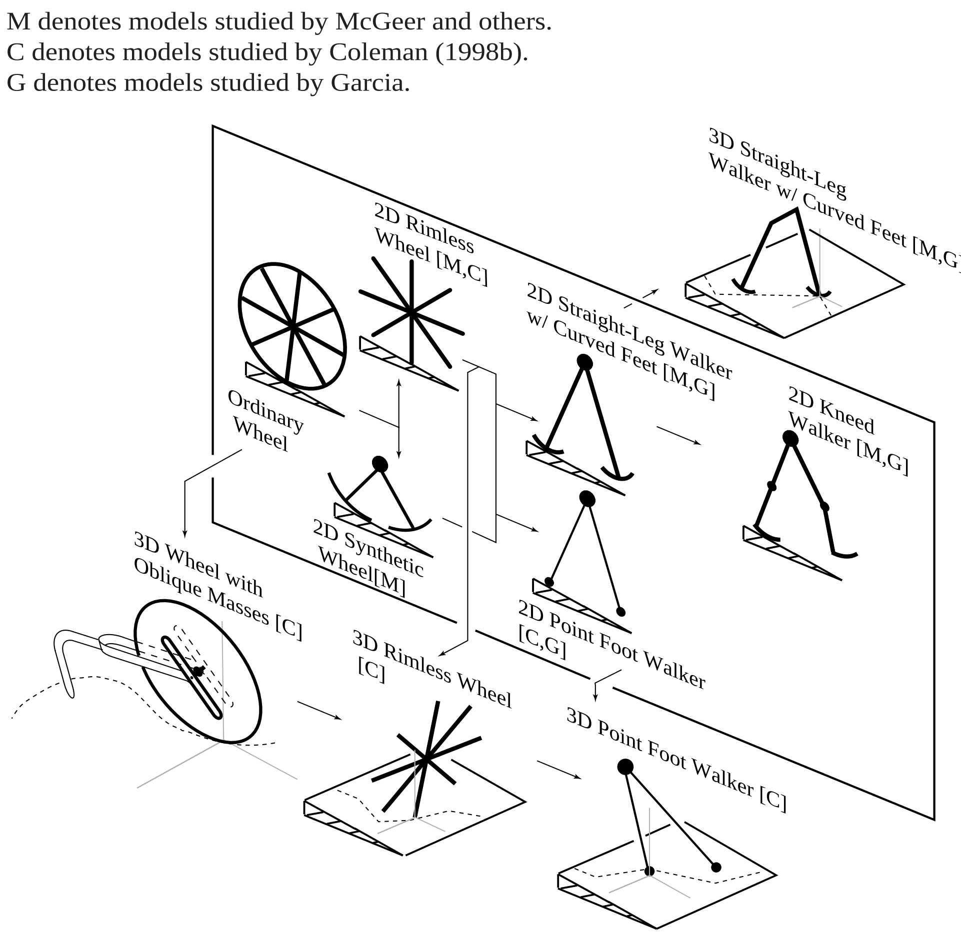

Figure 1.1: Taxonomy of passive-dynamic walking models. The key explains which models were studied in depth by McGeer, Coleman, and/or Garcia. This figure is also used by Coleman (1998b).

1.2.2 Wheels, etc.

Two related ways to support a translating weight over (approximately) level ground are with wheels and with legs. McGeer (1990a) studied two wheel-like devices: the *synthetic wheel*, a non-physical device which the Ruina lab has not investigated, and the spoked but *rimless* wheel which had been studied previously by Margaria (1976) and Rubanovich and Formalskii (1981), and was later used by Alexander (1991) and further studied by Coleman (1998b).

1.2.3 Rimless Wheel In Two And Three Dimensions

A rimless wheel pivots and collides with the ground on rigid spokes instead of rolling smoothly. As with walking, translation occurs by intermittent non-slipping contact. When a spoke collides with the ground, the trailing spoke instantaneously loses contact so that, except at the moment of collision, only one spoke is contact with the ground. As with other models, the spoke collisions are assumed to be instantaneous, no-slip, and perfectly inelastic. The only non-contact force is gravity. Unlike an ideal dissipation-free round wheel, the rimless wheel cannot roll steadily on level ground because it loses energy at each collision.

The speed of a 2-D rimless wheel is regulated by dissipation from collisions (McGeer (1989)). The gravitational energy available per step is independent of speed and proportional to step length, whereas the kinetic energy lost per step in collisions increases with the square of the speed and also (approximately) the square of the spoke spacing (see also Alexander (1995) and Alexander (1991)). Balance of these energies determines the speed of the wheel.

Unlike the 2-D rimless wheel, the 3-D rimless wheel is not constrained from falling down sideways, but still doesn't. Because rolling coins, wheels, disks, etc. don't fall over, the stability of the rimless wheel might not seem surprising. However, rolling flat disks are only neutrally stable against lean perturbations (small, wobbling-type perturbations never decay), whereas Coleman et al. (1997) found that the 3-D rimless wheel can be asymptotically stable (small wobbling-type perturbations decay). Coleman's discovery that intermittent contact augments side-to-side stability in rolling raises the possibility that similar passive processes might contribute to human side-to-side balance.

1.2.4 Straight-Legged Walkers In 3-D

Toys which exhibit walking characteristics are hardly new inventions. For example, the patents of Fallis (1888) and Bechstein and Uhlig (1912) describe walking toys which provide for swing foot clearance with cleverly-shaped feet. Martijn Wisse (visiting Cornell in Fall 1998 from TU Delft) is currently constructing a kneed model which uses the aforementioned patent ideas to provide for 3-D stability. All such walking toys known to the author can stand up when they are not walking; thus their stability is not so surprising.

Although the asymptotic stability of the rimless wheel (above) inspires some hope, it has gyroscopic terms to help with stabilization that walking models cannot access. However, work on skateboards by Hubbard (1979) as well as previous work with bicycles (by Hand (1988)) and boats (by Bennet and Cardanha (1991)) shows that passive balance stability does not necessarily depend on gyroscopic terms.

McGeer (1991) was the first to simulate passive walking in three dimensions. His model was similar to a two-dimensional straight-legged walker, but with disk feet and hip spacing. He found that, like the two-dimensional models, the three-dimensional models also exhibited two gaits, a short period gait and a long period gait. Both gaits were unstable; the dominant instability was caused by out-of-plane falling. McGeer varied the hip spacing while searching for stable gaits; a plot of his results is shown in Figure 5.5.

Fowble and Kuo (1996) also simulated a three-dimensional model similar to

McGeer's, but constrained the model to not steer (yaw). Swing leg clearance was provided by side-to-side rocking motions (about the lean axis). This model also proved to be unstable despite a search for stable parameters; the instability was in the out-of-plane direction, as in McGeer's work. Fowble and Kuo (1996) showed that for small disturbances, the walker could be stabilized by a feedback control system which sensed only lean motions.

Shortly afterwards, Coleman (1998b) attempted to simulate stable walking in a model with point-feet and zero hip width. Inspired by a simple stable bicycle model, Coleman's strategy was to vary the off-diagonal elements in the moment of inertia tensors of the legs. Coleman discovered (or perhaps re-discovered) two strategies for minimizing the amount of instability in each step. The first strategy was to use parameters which resembled an out-of-plane balance bar such as those used by circus tightrope walkers. This slowed the out-of plane falling motions and minimized the out-of-plane dynamics. The second strategy was to take very small steps and thus minimize the step period and the time spent falling sideways. Both of the strategies focused on limiting the out-of-plane instability (per step).

Although Coleman (1998b) (see also Coleman and Ruina (1998)) was unable to find parameters which led to a stable walking machine, he met with a curious success. While building a small Tinkertoy® model to demonstrate the aforementioned balance-bar mass distribution, he found that with some "non-quantifiable tinkering," the model was able to walk, apparently stably and consistently, down a shallow slope. The appeal of this model is that it cannot stand still in any configuration whatsoever and is thus distinguished from all other walking toys. This Tinkertoy® mechanism has also been replicated and validated by several other researchers. Although the mass distribution in this physical model is not anthropomorphic, its success hints at a possible role for passive dynamics in side-to-side balance as well as fore-aft balance.

To finish this short discussion of passive walking machines in three dimensions, we mention the work of Adolfsson et al. (1998). They are simulating a three-dimensional machine with knees. Their model is similar to the kneed machines previously mentioned, but it has a line contact at the feet to minimize out-of-plane motions. Their model is able to walk stably down a ramp but can also stand upright without falling. Adolfsson's strategy is to minimize the out-of-plane dynamics with contact constraints, as opposed to using control (like Kuo) or dynamics and mass distribution (like Coleman).

1.2.5 Notable Features Of These Machines

Pure passive-dynamic models are built (theoretically or physically) from passive elements (rigid bodies, springs, dashpots, hinges, frictional and rolling contact) with power coming only from gravity. As elaborated in Chapter 4, three interesting features of these models are the following:

- These mechanisms can actually walk; that is, they resemble human legs not only in design but also in function.
- These machines are very efficient; they can walk at very shallow slopes.
- For certain parameters, the gaits are dynamically stable.

1.3 Other Relevant Walking Research

Because the nervous system controls, and the muscles power walking, most gait simulations incorporate varying amounts and types of joint-angle or model-muscle control in an effort to mimic human gait, like those of Pandy and Berme (1988a), Taga (1995), and Hurmuzlu (1987a)). Some theoretical gait-synthesis models use sophisticated control strategies and generator patterns, such as the neural networks of Taga (1991).

Zajac and Winters (1990) provides a good summary of many of the issues involved in modelling bipedal gait; as an example, they include results from Yamaguchi and Zajac (1990), where a 3-D multi-degree-of-freedom model was combined with a minimum-energy optimization to investigate the feasibility of Functional Neuromuscular Stimulation, or FNS. Although this simulation does not include heelstrike, it hints at the relatively small amount of control and actuation necessary to produce one step in a biped model.

Non-linear dynamics approaches, similar in some ways to what is described in this thesis, have also been used by Hurmuzlu and Moskowitz (1986), Beletskii (1990), and others. Katoh and Mori (1984) was one of the first to control a biped robot by explicitly utilizing stable limit cycles (in the control sense); they treated the single and double support phases as different control problems and hopped from one trajectory to the other to produce stable controlled walking in simulation and experiment. They also specified some mass distribution criteria for linearizability and stability. Miura and Shimoyama (1984) used feedforward control for their biped robot, approximating its dynamics as an inverted pendulum, and seem to have been one of the first to treat the entire gait cycle as a function and sample once per step for feedback control. Their models are similar to those studied here in that they are essentially statically unstable pendula but have dynamically stable limit cycles. The same is true of the well-known hopping robots of Raibert (1986). Hurmuzlu and Moskowitz (1986) formalized the approach of treating the forward integration of one step, combined with the heelstrike at the end of the step (and perhaps kneestrike in the middle) as one Poincaré map, which McGeer (1990a) called the "stride function". Grishin and Formalskii (1990) and others have used similar approaches.

One moral of the work of Hurmuzlu was the importance of including heelstrike in the model, as also evidenced by McGeer (1990a), Hatze (1989), and Rubanovich and Formalskii (1981). Hurmuzlu and Moskowitz (1986) found that in a similar, controlled double-pendulum model, ground impacts were a major contributor to dynamic walking stability, presumably because of the sudden reduction of volume in phase space they cause. A drawback of some previous theoretical muscle-control gait models, is that they only study a part of a step (e.g., Pandy and Berme (1988b), Yamaguchi and Zajac (1990), Ju and Mansour (1988)).

Alexander (1995) reviews several cases where simple models give greater insight into human motion than more complicated models. The videos of the recently publicized 4000 watt, multimillion Honda Humanoid Robot (about which little is officially known) provide insight into the extreme cost, difficulty, and inefficiency of attempting control-based walking in complicated models (for both robots and humans, presumably). It seems likely that the human body's design and control scheme(s) amount to finding and operating near passive motions, and then adding small amounts of actuation.

There is some evidence that passive-dynamic strategies lead to simple, stable, and efficient gait actuation strategies. For instance, Grishin and Formalskii (1990) showed that a biped robot could be controlled by a series of impulsive stimuli. McGeer (1993b) also descibed simple control strategies for walking on level ground and uphill. Camp (1997) added a simple actuation strategy to a stable passive walker to simulate stable powered gait on level ground; a physical model based on his simulation is being built at Cornell. Finally, Pandy and Berme (1989) argue that biped locomotion must be primarily open-loop because of the feedback delays in the human nervous system.

1.4 Potential Impact And Biomedical Relevance

Use of passive or crudely controlled theoretical and physical models to gain understanding of locomotion may lead to other long term applications in rehabilitation and orthotics.

- **Pathological Gait.** There may be some correlation between parameter effects in passive or simply powered theoretical walking models, and in some cases of pathological gait where the causes are mechanical (and not neurological) in nature.

- **Fundamental Questions About Efficiency And Stability.** The results from theoretical walking models raises a fundamental theoretical question. Is it possible to have an asymptotically stable locomotion mechanism that is also perfectly efficient? The theory of Hamiltonian systems does not apply to walking machines because, by virtue of their intermittent contact, they are non-holonomic Ruina (1998). Studies of bicycle stability and the like show that non-holonomic systems can have asymptotic stability even without dissipation. Can legged mechanisms also be made stable without dissipation?

Although this is partially a question in pure mechanics it also pertains to humans. Efficiency and stability might be design trade-offs, but this does *not* appear to be a fundamental restriction. Insight into these issues is relevant to understanding healthy humans and also to prosthetic corrections.

The results of this research could be useful in the theory of gait synthesis, in diagnosing gait disorders, in prosthetic design, and in robotics. Specific applied problems that could gain from this research, for example, are those in functional neuromuscular stimulation (FNS), where minimizing muscle usage is a key strategy, and prosthetic design, where actuators with complex controls are expensive and difficult to maintain.

- **Gait Synthesis And Functional Neuromuscular Stimulation.** Study of passive-dynamic models can provide clues about the design of the human body and the brain's underlying strategies for motion synthesis. One of the more direct applications of this work could be in the area of Functional Neuromuscular Stimulation (FNS). FNS offers a way to restore some motion to paraplegic patients by applying external electrical stimulation to muscles which, because of injury or other reasons, have become paralyzed. In addition, FNS can improve limb range of motion, muscle strength, and bone mineralization, according to Kobetic et al. (1977).

  Some drawbacks to FNS, from Yamaguchi and Zajac (1990), include the following: **a)** the low strength of electrically-stimulated muscle, **b)** the difficulty in fine-tuning resulting muscle forces, **c)** a heavy reliance on orthotics for balance, and **d)** a lack of knowledge regarding the mechanics of the muscles, joints, and body.

The approach described in this work addresses these issues as follows:

a) Research in prosthetic design by Bach et al. (1994) and Donn et al. (1989) has shown, as might be expected, that the mass distribution of a prosthesis has an effect on the oxygen consumption of the user and on their gait. Operating near a passive gait cycle is energetically efficient as compared to other control strategies. If parameters in the legs are tuned properly as in Garcia et al. (1997) passive gait cycles can exist with arbitrarily low energy demand. These cycles might be used as a basis for FNS using smaller muscle forces and reducing muscle fatigue.

b) Passive gait cycles can be asymptotically stable; that is, small disturbances decay over time. Simple powering schemes on level ground will produce stable gait as well, as shown by McGeer (1993b), Camp (1997). With this type of control, minor variations in muscle force or duration will not destabilize the gait. Thus both the size of muscle force needed for balancing purposes and the fineness with which it needs to be controlled might be reduced using passive-dynamic strategies.

c) Use of passive-dynamic stability could potentially reduce the need for awkward balancing paraphernalia. In the future, one might see clinical use of dynamically stable, 3-D, anthropomorphic theoretical models, adjusted to the subject's parameters. Prostheses and braces would then be designed using the theoretical model so as to gain efficient and stable motions as easily as possible. Similarly, prosthetic designs could be better tuned, by using the passive dynamic approach, to provide stability with a minimum of awkward hardware.

d) Stable passive-dynamic models remain stable when mechanical parameters are only changed slightly. Thus designs based on very stable limit cycles may make less demand on exact knowledge of system parameters.

- **Educational Issues.** The view of coordination as being neuro-muscular is deeply implanted in the consciousness of the medical community. Results from passive-dynamic models can have an impact on a variety of medical practicioners and researchers. This work, well communicated, could have a positive effect by contributing to a change in the way therapists, doctors, and medical researchers think about coordination and locomotion. Some of the methods used here are applicable to powered and controlled prosthetic designs as well.

  The nonlinear-dynamic parametric-design approach provides a systematic way to tune control parameters. As researchers come to understand the approach used here (but claimed as original), it will augment (and possibly replace) real-time continuous feedback controls in both robotics and human gait synthesis. Many researchers doing numerical simulations of human motion, for example, are not yet aware of the utility of the non-linear dynamics tools to help them find stable motions (such as the interpretation of a limit cycle as a fixed point, and linearization of the fixed point as a measure stability).

1.4.1 Critique Of Passive Walkers As Human Models

Of course, there are some drawbacks to using passive walkers as human models. In humans, double-support (two feet on the ground at once) accounts for about 20% of a gait cycle. In the theoretical and physical models presented here, double-support is an instant. Without adding more complexity to the models, the details of the propulsion from ankle flex in double support cannot be addressed, though this may not be a critical flaw, as argued by Townshend and Tsai (1991).

Another theoretical modeling approximation is the locking of the stance leg with kneed models. Experimental data of Winter (1987) shows that the stance leg flexes slightly at mid-swing (as careful inspection of 4.3g reveals).

The kneed model is only two-dimensional and lacks all upper body parts. The physical model of the two-dimensional kneed walker uses four legs to keep side-to-side balance. However, a straight-legged model in 3-D is also studied, and work with kneed 3-D models is in progress by Adolfsson et al. (1998).

The most obvious critique of the models is that they lack muscles. However, if the models are inherently stable and robust, they are most likely insensitive to the particular choice and details of the energy input. In any case, as noted previously, it is of interest to see how much the legs might be able to do *without* muscles and control.

1.5 Outline Of This Thesis

Chapter 2 contains an overview of a parameter-varying recipe used by McGeer, which is a useful technique for these and similar studies.

Chapter 3 attempts to answer the question, "What is the simplest model that can mimic human walking?" It contains an analysis of what is believed to be the simplest walker in two dimensions that is capable of falling down, and yet retains the essential flavor of biped locomotion. This model is a useful starting point for the following reasons:

- It has a special mass distribution that simplifies the underlying mathematics and mechanics.
- It is a limiting case of other models that have been previously studied by McGeer McGeer (1990a) and Goswami Goswami et al. (1997), and it is a deterministic version of Alexander's "minimal biped" Alexander (1995).
- It has no free design parameters.
- It allows some analytical study of its behavior, which can be correllated with numerical results.
- It behaves according to certain scaling rules which can be extended to more complicated models.

This walker can have stable walking solutions at arbitrarily small slopes.

In Chapter 4, the previous results are extended to more complicated (and more realistic) models. with general mass distribution, knees, and/or circular feet. We attempt there to answer the question, "How does mass distribution affect walking efficiency?", and as a partial answer we present necessary conditions on the mass distribution to allow stable walking at arbitrarily small slopes.

Lastly, in Chapter 5, an attempt is made to answer the question, "Can stable walking exist in a statically-unstable three-dimensional model like that of McGeer?" The model used includes other parameters not used by McGeer or Coleman, such as torsional springs and dampers. A gradient-search method is presented which has uncovered the presence of a local minima in six parameters, but has thus far failed to yield stable walking.