PASSIVE-DYNAMIC MODELS OF HUMAN GAIT

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Introduction

Human motion is controlled by the neuro-muscular system. But bipedal walking, an example of a basic human motion, might be largely understood as a passive mechanical process [3]. For example, Tad McGeer demonstrated, by both computer simulation and physical model construction (both of which we have repeated), that a somewhat anthropomorphic legged mechanism with four moving links can exhibit stable, human-like walking on a range of shallow slopes with *no* actuation and *no* control (energy lost in friction and collisions is recovered from gravity) [1].

So far, our studies focus on two 2D models: a kneed walker, and a simpler 'pointfoot' model. These are linkages made of rigid bars that are connected with hinges. Unlike control-based models, where the controller tries to force a motion on the system, the models' gait cycles (exact sequences of repeated steps) are inherent products of the model parameters.

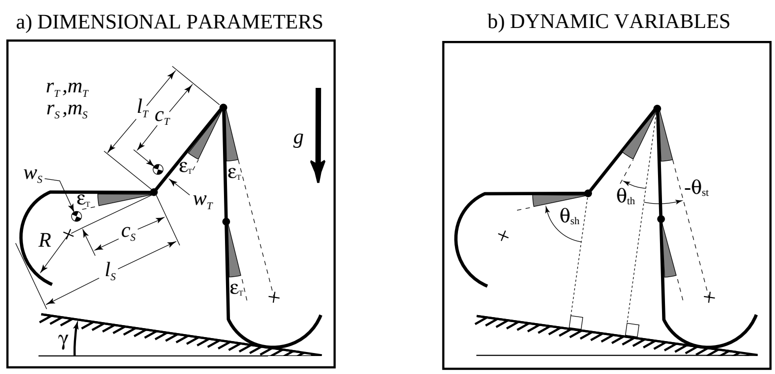

Figure 1: McGeer's kneed walking model.

Kneed Passive Walking Model

Our kneed walker is essentially a copy of McGeer's [2]. It has four links, which represent two thighs and two shanks. Knee stops, modeled by plastic collisions, prevent the shanks from hyperextending relative to the thighs. The shanks are rigidly connected to offset semicircular feet. Mass centers, moments of inertia, foot radius and foot placement relative to the shank are all model parameters. The mechanism is on a ramp of slope γ. Heelstrike is modeled by a plastic (no-slip, no-bounce) collision of the swinging foot with the ramp surface. Double support is instantaneous.

Pointfoot Passive Walking Model

Our 2D pointfoot walker is an extreme special case of McGeer's 2D straight-legged round-foot walker[1]. We study it because of its simplicity. Two massless rigid rods (legs) of length l are connected by a frictionless hinge at the hip. There is a point mass M at the hip and a much smaller point mass m at each foot. The mechanism is on a rigid ramp of slope γ. When the foot hits the ground at heelstrike, it has a plastic collision. During walking, only one foot is in contact with the ground at any time, excepting the instant of double support. The Poincaré section for the pointfoot walker, using the conditions just after heelstrike, turns out to be just two-dimensional. So the stance angle and rate, θ and $\dot{\theta}$, just after heelstrike, determine the subsequent motions of the walker.

Results and Insights from the Models

Using a numerical Newton-Raphson calculation while varying model parameters, we find various gait cycles. Some observations that go beyond the work of McGeer are listed below. These are found from computer and perturbation calculations and, for the most part, have not yet been verified with physical experiments.

1) Suprisingly, solutions exist all the way to downhill slopes of $\gamma = 0^+$ for the point foot walker. The step lengths vanish as the downhill slope goes to zero. Since downhill slope is a measure of inefficiency, the point foot walker is capable of essentially perfectly efficient locomotion. For passive gait cycles to exist at arbitrarily small slopes, the center of mass of each leg must lie on a line connecting the foot center with the hip, a condition automatically fulfilled by our point foot model. We do not yet know whether or not this placement of the center of mass is sufficient to allow the kneed walker to walk at arbitrarily small slopes.

2) Another way to characterize efficiency, one that gives credit to speed, is to use the ratio (average forward kinetic energy)/(energy loss over one step). For the kneed walker, this second measure has a maximum at gait cycles which, although they seem to look the most anthropomorphic with their smooth heel strikes and late knee-strikes, are unstable. Perhaps the human body selects something close to a naturally 'efficient' passive gait mode and stabilizes it at a small control cost.

3) For the point foot walker, walking with small leg angles on small slopes, we found two period-one cycles of interest: a long-period cycle and a short-period cycle, as observed by McGeer in his more general walkers on finite slopes [1]. In these solutions, initial stance angle θ and stance angle rate $\dot{\theta}$ scale according to $C_1\gamma^{1/3} + C_2\gamma + \mathcal{O}(\gamma^{5/3})$. The long-period cycle is stable on downhill slopes less than $\gamma \approx 0.015$ radians.

4) As the long-period-1 cycle becomes unstable at a slope of $\gamma \approx .015$, a stable period-2 (limping) cycle appears. Higher order cycles appear in a period doubling cascade until the stable gait is apparently chaotic (random stumbling) at a downhill slope of $\gamma \approx 0.019$. We have not yet found period 3 (waltzing) solutions.

Further studies of the types we are pursuing may reveal that many human motions are largely natural or quasi-passive and not heavily controlled. In the context of walking, such results might be useful to those studying the active control aspects of walking, to those trying to design anthropomorphic robots, and to those trying to improve prosthetic devices and rehabilitation procedures.

References

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