Fall 2020 ME751 Final Project Report
University of Wisconsin-Madison

Simulation of a Passive Dynamic Walker in Chrono

Katherine Heidi Fehr

December 12, 2020

Abstract

A classic method to simulate gait is using a gravity based passive dynamic model. In this report I describe two dynamic simulations of passive walkers using Project Chrono. One of these "walkers" is simple, without knees and the other has knee joints. The simple simulation was able to generate three steps but did not reach stability due to improper initial conditions and issues with the swing leg scuffing against the floor. While the kneed walker was created to solve the scuffing issue it also did not reach stability. Future work includes improving these simulations and modifying them to mimic different in-lab experiments.

Git repo: https://github.com/kheidi/simEngine3D/tree/main/pyChrono_Walker

Contents

1. General information

1. Your home department: Mechanical Engineering
2. Current status: PhD student
3. Individuals working on the Final Project:
   - Katherine Heidi Fehr
4. I release the ME751 Final Project code as open source and under a BSD3 license for unfettered use of it by any interested party.

2. Problem statement

My initial project proposal included stated my objective as simulating amputee gait and non-amputee gait in Chrono and extracting the resulting kinematics for comparison against experimental results. After performing a more in-depth literature search and experimenting with Chrono I decided to shift my project to a more fundamental project. In this project **I seek to perform two dynamic simulations of passive walkers using Chrono, one with knees and one without**. The method of passive dynamic walking was initially described by McGeer [1][2] and models gait as two compass-like legs with a point mass connecting them at the hip representing the torso that travel down a slope. Due to the walker's descent down a ramp all movement can be attributed to the force of gravity.

As a biomechanics researcher I mainly focus on natural gait, amputee gait and the differences between the two. A basic dynamic simulation of gait can be further modified to mimic different experiments and scenarios, as will be discussed in the future work section of this report.

3. Solution description

My first step in simulating my walkers was becoming familiar with Chrono and very simple simulations like spheres dropping and rolling down an incline (practice_sphereRoll.py). To create the simple walker (no knees) I attempted various model set-ups from literature. The basic structure of the simpleWalker is the following:

1. Create chrono system
2. Create environment and contact material
3. Create walker body in initial condition position
4. Add constraints
5. Start simulation
6. Use updated position information within simulation loop to enable and disable collision.

The final set-up implemented was based off of work by Cao et al. [3] who created their dynamic simulation in ADAMS. Figure 1 shows the initial condition of the simple walker discussed in this report and key parameters are described in Table 1. The initial angle parameters (θ_1, θ_2) were mainly found via trial-and-error. Both of the walker's legs are the same length (L_{Leg}) and both feet have the same radius (r_{Foot}). Of all the components, the only bodies with collision enabled were the floor and the feet. To simplify the creation of the model, instead of tilting the floor to be an incline, Cao et al. suggests altering the system's gravitational acceleration. After attempting the simulation with an inclined floor unsuccessfully I modified my model to reflect the virtual gravity. In the case presented the systems gravitational acceleration is set to the following, here γ is the virtual incline of the floor:

$$\boldsymbol{g} = [-9.81 * \sin\gamma, -9.81 * \cos\gamma, 0]$$

Five constraints were used in this simulation, summarized in **Table 2**. The first constraint fizes the z-axis of the stance leg parallel to the z-axis ground. This is to ensure that the walker does not tip over on its side. The second and third constraints make revolute joints between the top of the leg to the torso. It is possible to set limits to the revolute angle (to prevent the walker from doing the splits, for example), however I found that these made my simulation worse. The last 2 constraints simply fix/weld the feet to the legs.

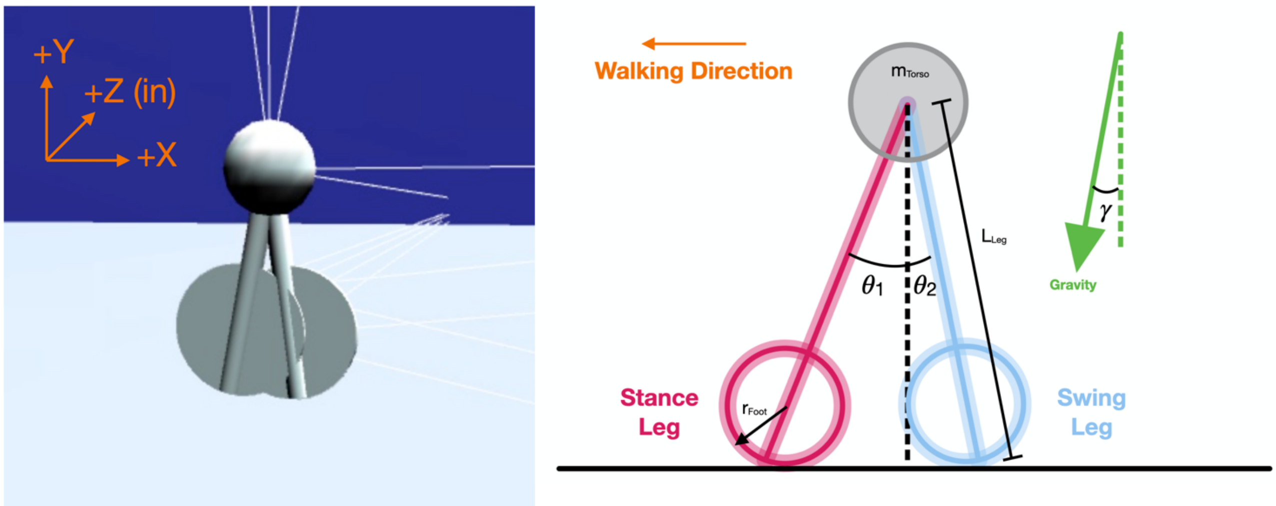

Figure 1. Initial position of simple walker.

Table 1. Key parameters for simple walker.

Parameter	m_{Torso} (kg)	m_{Leg} (kg)	m_{Foot} (kg)	L_{Leg} (m)	r_{Foot} (m)	Gravity (m/s^2)	θ_1 (°)	θ_1 (°)	γ (°)
Value	10	0.01	0.0133	0.1	0.03	9.810	11.5	7	1

Table 2. Summary of key constraints.

Constraint Name	Constraint Type	Body 1	Body 2
zParallel	ChLinkMateParallel	Stance Leg	Floor
hipJoint_stance	ChLinkLockRevolute	Stance Leg	Torso
hipJoint_swing	ChLinkLockRevolute	Swing Leg	Torso
ankleJoint_stance	ChLinkMateFix	Stance Leg	Stance Foot
ankleJoint_swing	ChLinkMateFix	Swing Leg	Swing Foot

A common issue with passive dynamic walkers is floor scuffing. When humans walk, they use their knees and ankles to lift their toes. During my simulations I encountered this issue, when the back leg would line up with the front leg, the fact that the back leg scuffed the ground caused the walker to lose its momentum and it would stop and fall forward. My attempt to solve this included enabling and disabling the collision parameter on the feet. This way when the back leg would swing forward and cross the front leg collision would be disabled and there would be no collision with the ground. When the angle between both legs would equal 40 degrees the collision setting would toggle as shown in Figure 2. In the code submitted collision is enabled for both feet for the first 0.15 seconds.

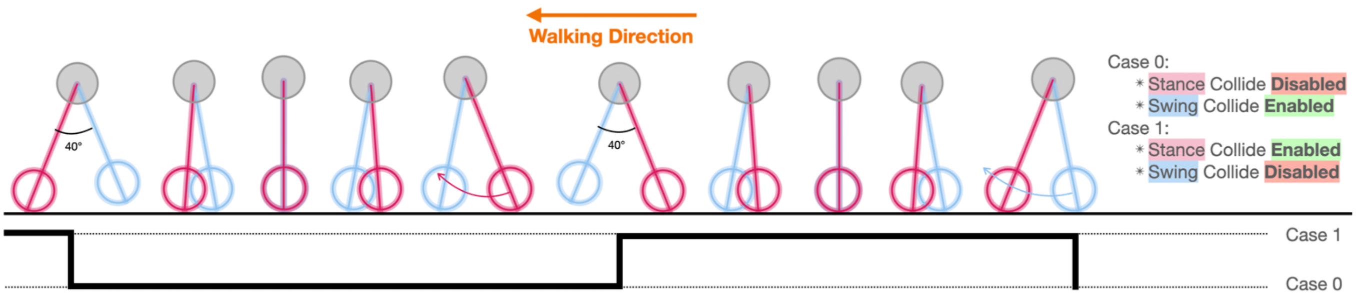

Figure 2. Collision toggle to avoid foot scuffing.

In addition to the simple walker, I initiated the formulation of a kneed walker in attempts to solve the scuffing issue. Due to time constraints I was unable to optimize its initial conditions.

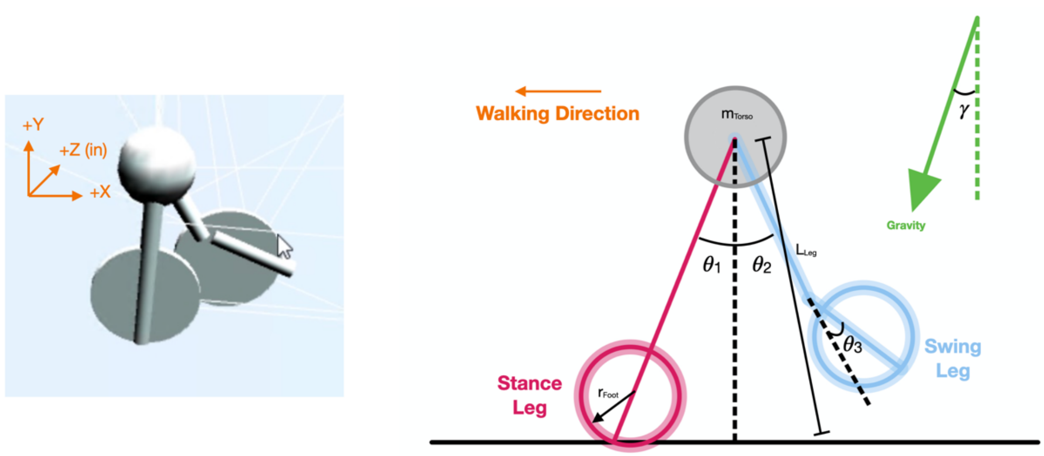

Figure 3. Kneed walker set-up

7. Overview of results. Demonstration of your project

My simple walker (no knees) was able to take a couple steps before flipping over (video: https://go.wisc.edu/tovtw9). This shows that while it was able to demonstrate the idea of passive walking it did not reach stability. This can be due to a number of factors, but I believe it's mainly due to poorly selected initial conditions and perhaps a poor selection of the angle at which the foot scuffing toggle switches. As you can see in the video linked, the walker appears to be skipping due to the collision being

activated while the foot is already penetrating the floor, as can be seen in Figure 4. Once the collision is enabled the solver overcompensates and pushes the foot upwards out of the ground. The collision toggle mechanism worked as coded, switching when the angle between the legs was at 40 degrees.
Figure 5 shows the angle between the stance and swing legs and how they correspond to the collision toggle.

My walker with knees was not able to take any steps (video: https://go.wisc.edu/tbtr5a). Aside from correcting the initial conditions, more changes need to be implemented in the timing of different constraints to account for knees. The paper by Zhang et al. describes a four stage gait that involves locking and unlocking the knee at various points in the gait cycle [4].

Chrono also gives the ability to evaluate various kinematic results which would provide useful information in the case of a steady passive dynamic walker. I'm including a few results figures as a demonstration of the information that can be gleaned by a similar simulation. The first, Figure 6, shows ground reaction force over time. This is a very commonly used metric in biomechanics as it can offer insight into gait symmetry and injuries. In my research I've used the shape of the temporal ground reaction force to predict ambulation mode (ramp/stair ascent/descent). Figures Figure 6 and Figure 7 show the reaction forces and torques at the hip joint. Analysis of the joint mechanics can explain the contribution of different muscles to the gait cycle and can assist in the understanding of pathological gait.

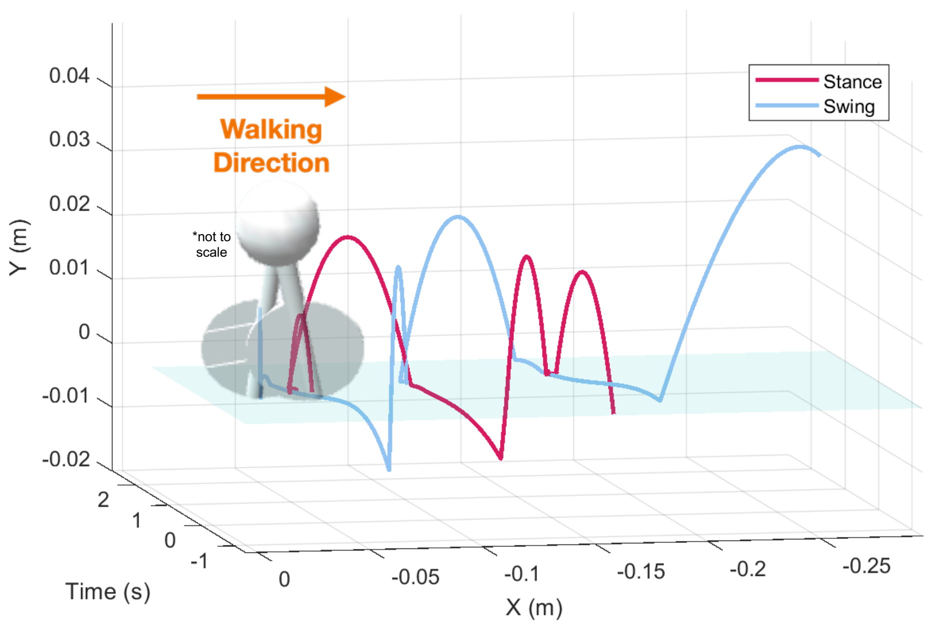

Figure 4. X-Y position of the bottom of the walker's feet over time.

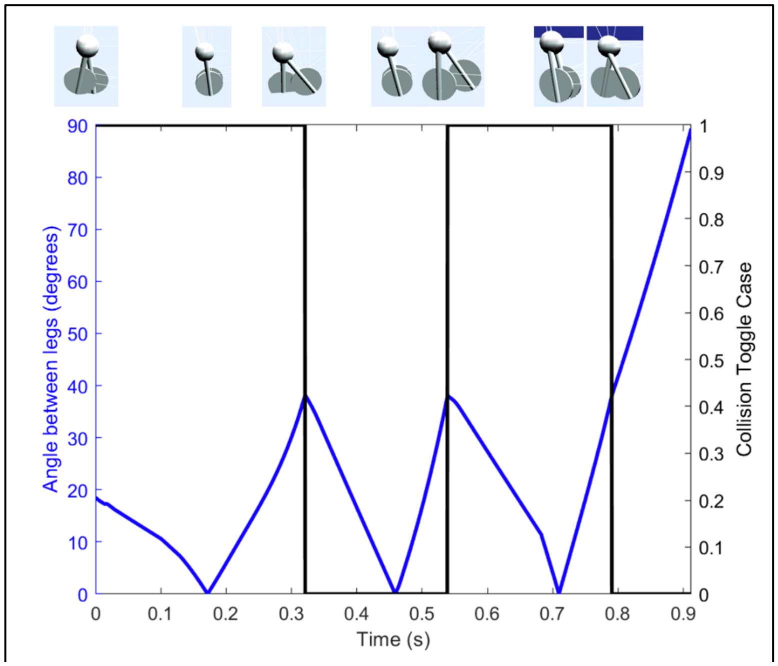

Figure 5. Angle between stance and swing leg in degrees over time (left axis, blue) and value of the collision toggle over time (right axis, black).

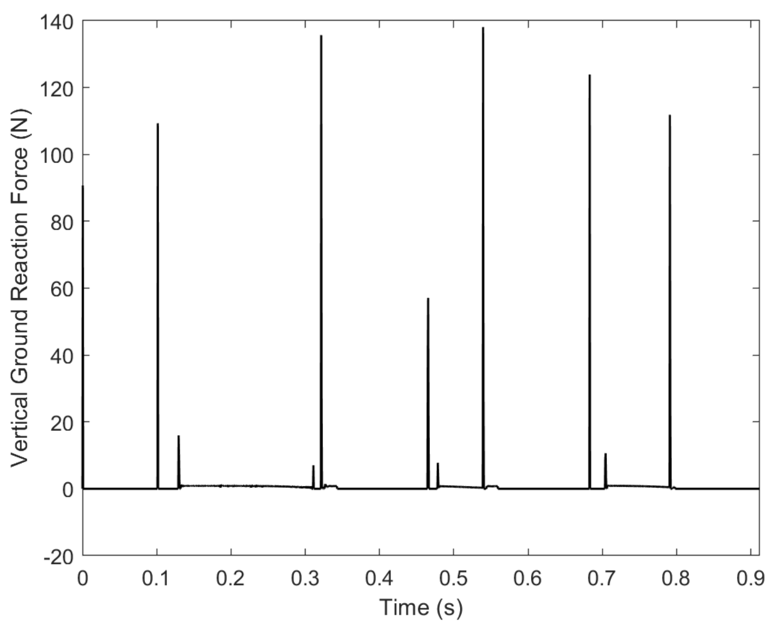

Figure 6. Vertical ground reaction force caused by the simple walker's gait.

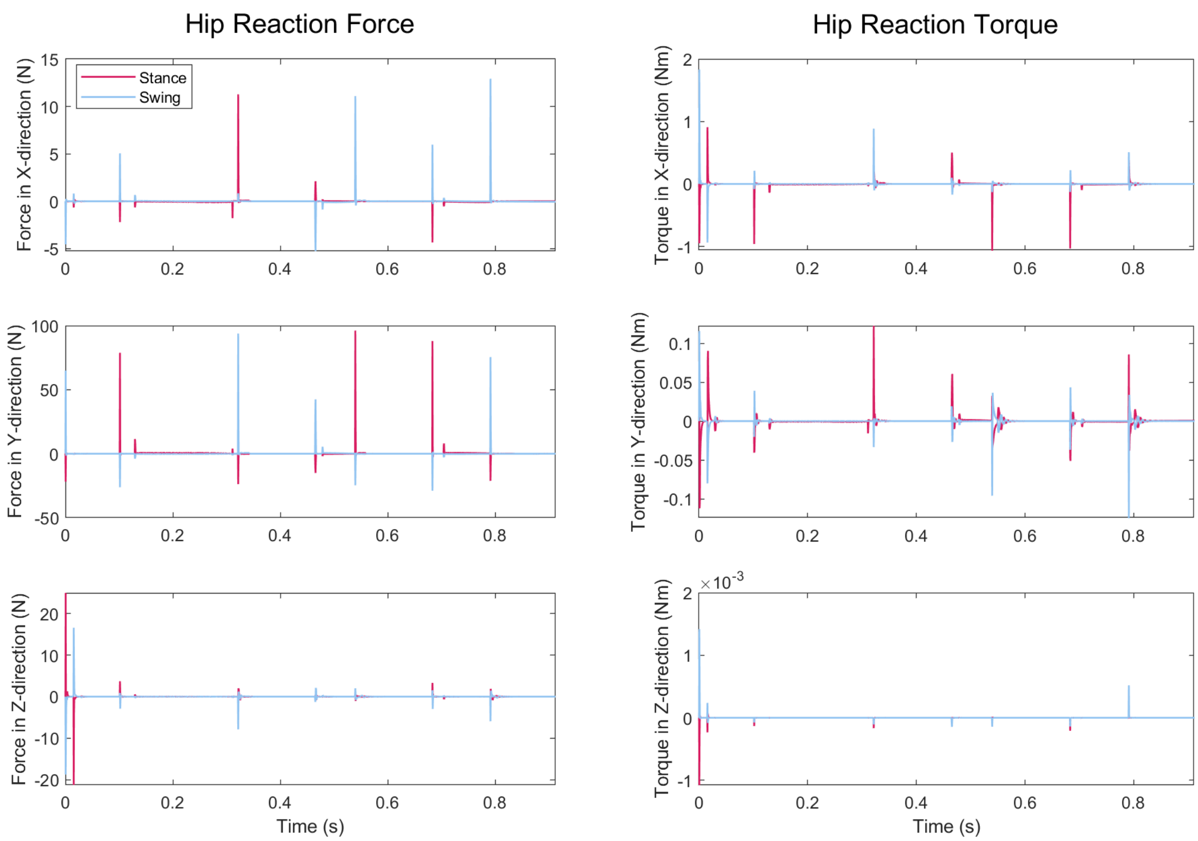

Figure 7. Hip reaction force and torque over time in the three dimensions.

8. Deliverables:

1. This report can be found in Canvas.
2. Git repo:
    a. simpleWalker.py
        i. This is the simple walker without knees
    b. KneedWalker.py
        i. This is the modified simple walker that has knee joints
    c. checkResults.m
        i. Code used to generate graphs shown in this report
    d. practice_sphereRoll.py
        i. Simple chrono script used to familiarize myself with chrono
3. How to run: Simply run the desired python code on a machine that has Chrono and Irrlicht installed.

9. Conclusions and Future Work:

This project was a great opportunity to familiarize myself with Chrono and learn more about passive dynamic walking. In the future I would like to improve the initial conditions of my simulations in order to reach stability either in the simple walker or the kneed walker.

The next step for my project is to use a similar simulation to further understand the effect of trunk lean on walking, a study currently active in my lab [5]. This would involve changing the shape of my walker's torso and running simulations at with the torso at different angles. In turn we would analyze the ankle power over each stride.

References

[1] T. McGeer, “Passive dynamic walking,” *Int. J. Robot. Res.*, vol. 9, no. 2, p. 62, 1990.

[2] T. McGeer, “Passive walking with knees,” in *IEEE International Conference on Robotics and Automation Proceedings*, May 1990, pp. 1640–1645 vol.3, doi: 10.1109/ROBOT.1990.126245.

[3] H. Cao, Y. Wang, J. Zhu, and Z. Ling, “Dynamic Simulation of Passive Walker Based on Virtual Gravity Theory,” in *Intelligent Robotics and Applications*, Berlin, Heidelberg, 2009, pp. 1237–1245, doi: 10.1007/978-3-642-10817-4_124.

[4] P. Zhang, Y. Tian, and Z. Liu, “Gait Analysis of the Passive Dynamic Walker with Knees,” in *Intelligent Robotics and Applications*, Berlin, Heidelberg, 2008, pp. 992–1002, doi: 10.1007/978-3-540-88513-9_106.

[5] R. A. Roembke, “Mechanical and Metabolic Consequences of Trunk Lean Angle in Walking,” presented at the 2019 International Society of Biomechanics, Calgary, Alberta, Canada, [Online]. Available: https://uwbadgerlab.engr.wisc.edu/wp-content/uploads/sites/727/2019/07/Roembke-ISB2019_Abstract_Final.pdf.