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Dynamic Stability of Passive Bipedal Walking on Rough Terrain: A Preliminary Simulation Study

Parsa Nassiri Afshar[1], **Lei Ren**[1,2]

1. *School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester M*13 9*PL*, UK
2. *Key Laboratory of Bionic Engineering* (*Ministry of Education, China*), *Jilin University*, *Changchun* 130022, *P.R. China*

Abstract

A simplified 2D passive dynamic model was simulated to walk down on a rough slope surface defined by deterministic profiles to investigate how the walking stability changes with increasing surface roughness. Our results show that the passive walker can walk on rough surfaces subject to surface roughness up to approximately 0.1% of its leg length. This indicates that bipedal walkers based on passive dynamics may possess some intrinsic stability to adapt to rough terrains although the maximum roughness they can tolerate is small. Orbital stability method was used to quantify the walking stability before the walker started to fall over. It was found that the average maximum Floquet multiplier increases with surface roughness in a non-linear form. Although the passive walker remained orbitally stable for all the simulation cases, the results suggest that the possibility of the bipedal model moving away from its limit cycle increases with the surface roughness if subjected to additional perturbations. The number of consecutive steps before falling was used to measure the walking stability after the passive walker started to fall over. The results show that the number of steps before falling decreases exponentially with the increase in surface roughness. When the roughness magnitude approached to 0.73% of the walker's leg length, it fell down to the ground as soon as it entered into the uneven terrain. It was also found that shifting the phase angle of the surface profile has apparent affect on the system stability. This is probably because point contact was used to simulate the heel strikes and the resulted variations in system states at heel strikes may have pronounced impact on the passive gaits, which have narrow basins of attraction. These results would provide insight into how the dynamic stability of passive bipedal walkers evolves with increasing surface roughness.

Keywords: bipedal walking, rough terrain, dynamic stability, human locomotion

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Nomenclatures

a	Distance between the leg tip and the leg point mass m
b	Distance between the leg point mass m and the hip joint
l	Leg length
g	Gravitational acceleration
ϕ	Angle of slope
m	Leg point mass
M	Hip point mass
θ	Angle of the stance leg with respect to the vertical direction
γ	Angle of the swing leg with respect to the vertical direction
$\boldsymbol{M}(\boldsymbol{q})$	Inertia matrix
$\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$	Coriolis and centrifugal matrix
$\boldsymbol{G}(\boldsymbol{q})$	Gravity vector
$\boldsymbol{q}$	Vector of generalized coordinates $[\gamma\ \theta]^{\mathrm{T}}$
α	Half-inter-leg angle during phase transition
$\boldsymbol{Q}$	2×2 angular momenta matrix
$\boldsymbol{x}$	4 dimensional state vector $[\gamma\ \theta\ \dot{\gamma}\ \dot{\theta}]^{\mathrm{T}}$
S	Stride function (step-to-step function)
$\boldsymbol{x}^*$	Fixed point
$\boldsymbol{J}$	Jacobean matrix
φ	Phase angle of the rough surface function
A	Amplitude of the rough surface function
ω	Wave frequency of rough surface function

Corresponding author: Lei Ren
E-mail: lei.ren@manchester.ac.uk

1 Introduction

Humanoid walking robots have attracted intensive researches in the past few decades due to their apparent advantages over the wheeled robots[1–3]. Biological bipedal walking is versatile, flexible and perfectly adapted to the natural environment. This makes bipedal robots potentially useful in many areas, e.g. hazard exploration, transportation over rough terrains, prosthetics or exskeleton development and entertainment *etc*. However, the seemingly simple bipedal walking motion is mechanically very complicated. On one hand, static stability is out of the question since only one leg is in contact with the ground over most of the walking cycle. On the other hand, this stability challenge will be aggravated when moving on irregular surfaces. Despite the tremendous technical difficulties, there are a number of bipedal walking robot projects ongoing in the world. Some notable biped robots are ASIMO, AIBO, QRIO, WABIAN family *etc*.[2,4,5]. Although many astonishing capabilities have been demonstrated by those robots, they are still incomparable to their biological counterpart, human being, in terms of energy efficiency and motion agility, probably due to the complicated controllers, sensors and actuators employed. For example, the latest ASIMO robot drains its battery source in just one hour, which constitutes one ninth of its total body weight[2].

To address these issues, passive dynamic walkers were proposed as a new design and control scheme[6–12]. Passive dynamic walkers are a type of robots with simple mechanical devices normally composed of solid parts connected by joints. They have no actuators or controllers, but can have remarkably human like motions when moving down a slope. In contrast to the conventional bipedal robots, which actively control every joint angle at all times, passive dynamic walkers do not control any joint angle at any time[6,7,10–12]. The idea behind this type of two-legged walking machine was to use natural dynamics of the robot for walking. Exploiting the intrinsic dynamics of the system rather than using controllers or actuators has made these walkers very energy efficient. Although they are over simplified compare to the conventional bipedal robots, they show very human-like gait[6,7,12]. Based on the simplest passive dynamic walkers, more body components can be added to make the robots walking more like human being, e.g. knee mechanism, ankle springs, curved feet and upper body with counter-swinging arms[12–16]. Very recently three robots were constructed by driving the passive dynamic walkers successfully moving on level ground with simple actuations[9]. This suggests that human-like properties of passive dynamic walkers are not dependent on gravitational powers. These model systems have also been proven very useful in elucidating some fundamental mechanisms underlying bipedal walking [3,17,18].

However, in the absence of active stabilising control mechanism, passive dynamic walkers exhibit very narrow basins of attraction, indicating that they probably cannot tolerate very large external perturbations[6,19,20]. This suggests that passive dynamic walkers may have difficulty walking on rough surfaces, which is one of the most important advantages of legged robots. Currently, very few studies have been conducted to examine the dynamic stability of passive dynamic walkers on rough terrain and how they change gradually from being locally stable to being globally unstable. Very recently, the simplest passive walking model was simulated to walk on stochastically varying rough surface with the purpose to examine the effect of surface variability on locomotor variability and stability[21]. The objective of this study is to examine the effect of the roughness of uneven surfaces on dynamic stability of passive dynamic walking. A slightly more complicated passive walking model is used, of which the simplicity allows us to gain insight into the mechanical and dynamic nature of the system. The investigation is mainly focused on the effect of surface roughness on walking stability of the bipedal model. Thus, uniform wave uneven surfaces, rather than random profiles, are used as the ground base for walking. Here, the dynamic walking stability is quantified using the method of Floquet multiplier[22–25]. Multiple simulations of 150 consecutive strides of walking were generated at each combination of different surface amplitudes and different wave phase angles. The evolution of walking stability with increasing surface roughness (amplitude) was examined by considering the average trend of all simulated wave phase angles.

2 Methods

2.1 Dynamic equations

In this study, we use a modified simplest passive dynamic model, which has two legs connected by a frictionless hinge joint at hip (see Fig. 1). The model has no upper body, and the legs are straight without knee or ankle joints. There is a point mass M attached at hip joint. Each leg is assumed to have a point mass m between the hip and the tip of the leg, of which the position is determined by a/b (see Fig. 1). The simplest passive dynamic model[19,21] is a special case of this model when a/b approaches to zero. The foot scraping is neglected during forward swinging of the legs. For physical passive walkers, this problem can be resolved by infini-