Journal of Theoretical Biology 388 (2016) 108–118

Contents lists available at ScienceDirect

Journal of Theoretical Biology

journal homepage: www.elsevier.com/locate/yjtbi

Adding adaptable toe stiffness affects energetic efficiency and dynamic behaviors of bipedal walking

Shiqi Sun [a], Yan Huang [a,b], Qining Wang [a,*]

[a] The Robotics Research Group, College of Engineering, Peking University, Beijing 100871, China
[b] Key Laboratory of Biomimetic Robots and Systems, Beijing Institute of Technology, Ministry of Education, Beijing 100081, China

HIGHLIGHTS

- Human toes play an important role in supporting the body and controlling the motion.
- Adding adaptable compliant toe joints could benefit the stability and energy efficiency.
- Multi-joint foot structure could reduce the energy consumption of ankle joints.
- A proper toe actuation pattern is important for smooth and efficient locomotion.

ARTICLE INFO

Article history:
Received 27 November 2014
Received in revised form
1 August 2015
Accepted 7 October 2015
Available online 28 October 2015

Keywords:
Toe function
Dynamic bipedal walking
Joint stiffness
Energetic efficiency
Walking stability

ABSTRACT

In human walking, toes play an important role in supporting the body and controlling the forward motion. These functions are achieved by muscles and tendons around toe joints. To further understand the importance of toe and how toe muscle functions affect the locomotion, we employ a simple bipedal walking model with compliant joints. The ankle joints and toe joints are modeled as torsional springs and the actuation patterns are similar to that of normal human walking. Experimental results show that adding adaptable compliant toe joints could benefit the stability and energy efficiency. By generating plantar flexion moment after heel-off, the toes contribute to stabilize the body and control the forward motion. In addition, multi-joint foot structure could improve the energy efficiency by reducing the energy consumption of ankle joints. A proper toe actuation pattern could result in a proper toe dorsiflexion and reduce the maximal ankle plantar flexion, leading to a smoother and more efficient locomotion.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

Human foot contributes to supporting body weight and moving body forward with dynamic stabilities during walking (Gage et al., 1996). Though the ankle provides most of the propulsion work, toes also play an important role in bipedal walking (Mann and Hagy, 1979). During propulsion, the toe flexor muscles (flexor halluces longus and flexor digitorum longus) generate an internal plantar flexion moment around the ankle and assist the ankle plantar flexors in generating heel-lift (Stefanyshyn and Nigg, 1977; Goldmann and Bruggemann, 2012). When the heel leaves the ground, the toes become load bearing through the metatarsal heads and distal phalanges. In walking, the toes support between 30 and 40% of the body weight (Mann and Hagy, 1979; Hayafune et al., 1999). In addition to generating heel-lift and supporting the body, the toe flexor muscles help control the forward motion of the COM during propulsion. As propulsion begins, the ankle plantarflexes and the metatarsophalangeal (MTP) joints are passively dorsiflexed as the COM moves anterior to them, causing an external dorsiflexion moment around the MTP joints (Leardini et al., 1999; Oleson et al., 2005; Miyazaki and Yamamoto, 1993). During this phase, the extrinsic and intrinsic digital flexors are active (Mann and Inman 1964), generating plantar flexion moments to balance the external dorsiflexion moment and control the forward falling motion.

These functions of toes are achieved by behaviors of muscles and tendons around toe joints, especially the MTP joints. The mechanical behavior of the muscles and other soft tissues associated with particular joints can be described by joint stiffness (Davis and Deluca, 1996). In general, joint stiffness characterizes the relationship between a joint moment and the associated joint rotation that is either produced or controlled by the joint moment. A number of investigations have used this parameter to quantify

---

* Correspondence author. Tel.: +86-10-62754083; fax: +86-10-627540388.
E-mail address: qiningwang@pku.edu.cn (Q. Wang).

http://dx.doi.org/10.1016/j.jtbi.2015.10.002
0022-5193/© 2015 Elsevier Ltd. All rights reserved.

the mechanical behavior of human joints. Cappozzo et al. (1979) quantified the stiffness of the knee and employed this information in the design of a prosthetic knee for above knee amputees. Davis and Deluca (1995) documented the ankle stiffness during normal ambulation. Oleson et al. (2005) characterized the stiffness of MTP joints during running. However, few studies investigated the MTP joints stiffness in normal walking and it is unclear how the MTP joints stiffness affects the locomotor performance.

Passive dynamic walking model, with high energy efficiency, natural gait and mechanical simplicity, is a useful tool to understand the human walking mechanism (Ruina, 2006). The concept of passive dynamic walking was proposed by McGeer in 1990 (McGeer, 1990). Since then, several kinds of passive dynamic models have been studied in terms of foot shape (Garcia et al., 1998; Adamczyk et al., 2005; Ruina et al., 2005) and actuation mode (Collins et al., 2005; Kuo, 2002; Hobbelen and Wisse, 2008). Kwan and Hubbard (2007) compared several models with point feet, round feet and flat feet. Flat-foot models are more anthropomorphic, and have a good energy efficiency by distributing the energy loss per step over two collisions, “heel-strike” and “toe-strike”. A range of flat foot shapes were also analyzed to determine the significance of foot length and ankle placement. Zelik et al. (2014) employed a flat-foot walking model with compliant ankle joints to investigate how ankle work and series elasticity impact economical locomotion. Passive walking models with toe joints have also been studied by several researchers (Kumar et al., 2009; Huang et al., 2010). However, these studies considered no or constant joint stiffness, without consideration of the active role of toe in bipedal walking. In addition, the investigations of toe joints have been extended to engineering areas. Several studies have added passive toe joints to humanoid robots to improve walking performance (Konno et al., 2002; Ogura et al., 2006; Sellaouti et al., 2007). ROBIAN and WABIAN-2R show more human-like gaits compared to the robots without toe joints. Humanoid robot HRP-2 which has passive toe joints can achieve a faster and smoother walking. Besides, the effects of adding toe joints in transtibial prosthesis have also been studied by some researchers (Zhu et al., 2014a,b). Zhu et al. (2014b) investigated the effects of toe stiffness on ankle kinetics in a robotic trastibial prosthesis. Results showed that adding a toe joint could reduce the ankle output moment and energy consumption. These studies indicate the importance of adding toe joints for human-like and efficient gaits. But how the toe joint stiffness affects walking performance remains a question.

In this study, we use a dynamical model to systematically investigate the impacts of toe joint stiffness on bipedal walking. We add adaptable joint stiffness to the segmented-foot model. The stiffness of ankle and toe joints are modeled as torsional springs. The equilibrium position and stiffness are changed according to current phase, forming a human-like actuation mode. Thus the ankle and toe joints can actuate the walker to travel on level ground. We compared the proposed model with a rigid-foot model under human-like ankle actuation to further understand the importance of toes. A discussion about coordination between toe joints and ankle joints was also performed. Our model provides a tool to understand how toes function in bipedal walking to achieve a stable and efficient gait and help us in building humanoid robots with toe joints.

2. Model

2.1. Bipedal walking model with segmented feet

To obtain further understanding of real human locomotion, we propose a flat-foot limit cycle walker with compliant ankle and toe joints (see Fig. 1). The 2-D model consists of two rigid legs interconnected individually through a hinge. Each leg contains a segmented foot. The mass of each link is distributed averagely. Thus the center of mass (CoM) of each limb is at the middle of the respective stick. The values of mass and length of each limb are described in Table 1. The ratios of leg length to foot length and toe length to foot length are set to match the corresponding approximate properties of human beings (Kwan and Hubbard, 2007).

The segmented foot used in this paper is shown in Fig. 1. Heel and toe tip are the two endpoints of the whole foot. The foot is divided into two parts, hindfoot (from heel to toe joint) and toe (from toe joint to toe tip). The two parts are hinged through the toe joint. Torsional springs are mounted on both ankle joints and toe joints to represent joint stiffness. To simplify the motion, we have several assumptions, including (1) the legs suffer no flexible deformation, (2) the hip joint has no damping or friction, (3) the friction between the walker and the ground is enough to guarantee the flat feet not deform or slip, and (4) strikes are modeled as instantaneous, fully inelastic impacts where no slip and no bounce occurs. The limit cycle walker walks on a level ground.

A typical walking step of our segmented-feet model can be described by several phases, as shown in Fig. 2. The push-off of the model is divided into toe-rotation (Phase *I*) and toe tip-rotation (Phase *II*), during which the foot rotates around toe joint and toe tip respectively. During single-support phase (Phase *III*), the swing leg has no contact with ground and swings freely, and the toe joint returns to the neutral position with a small toe lift. The double stance phase starts when the heel strike of the leading leg occurs (phase *IV*). After the heel strike, the foot of the leading leg rotates around the heel while the whole foot of trailing leg keeps contact with ground (phase *V*). In phase *VI*, the hindfoot of the trailing leg lose contact with ground and rotates around the toe joint, while the foot of the leading leg rotates around the heel. After the foot strike (phase *VII*), the stance leg and the swing leg are swapped and the model moves back to phase A, which means another walking cycle begins. Phase switching is dependent on the information of ground reaction forces (GRF) and the angles of certain links.

Table 1
The mechanical parameter values of the proposed model.

Property	Mass (kg)	Length (m)	Moment of inertia (kg m^2)
Leg	5	0.8	0.2667
Foot	0.5	0.2	0.0017
Toe	0.11	0.044	$1.8 \cdot 10^{-5}$

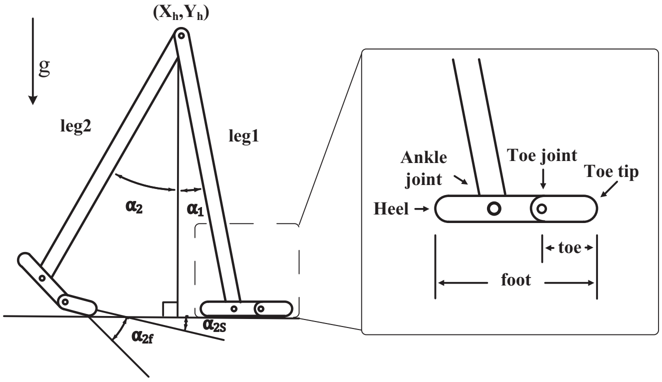

Fig. 1. Passive dynamic walking model with segmented flat feet and compliant joints. Swing angles between vertical coordinates and each leg α_1, α_2, foot angle between horizontal coordinates and each foot α_{1f}, α_{2f} and toe angle between horizontal coordinates and each toe α_{1s}, α_{2s} are shown in the figure.

Download English Version:

https://daneshyari.com/en/article/4495999

Download Persian Version:

https://daneshyari.com/article/4495999

Daneshyari.com