Journal of Biomechanics 44 (2011) 1253–1258

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Leg stiffness increases with speed to modulate gait frequency and propulsion energy

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ARTICLE INFO

Article history:
Accepted 17 February 2011

Keywords:
Leg stiffness
Compliant walking model
Elastic energy
Human walking
Gait speed

ABSTRACT

Bipedal walking models with compliant legs have been employed to represent the ground reaction forces (GRFs) observed in human subjects. Quantification of the leg stiffness at varying gait speeds, therefore, would improve our understanding of the contributions of spring-like leg behavior to gait dynamics. In this study, we tuned a model of bipedal walking with damped compliant legs to match human GRFs at different gait speeds. Eight subjects walked at four different gait speeds, ranging from their self-selected speed to their maximum speed, in a random order. To examine the correlation between leg stiffness and the oscillatory behavior of the center of mass (CoM) during the single support phase, the damped natural frequency of the single compliant leg was compared with the duration of the single support phase. We observed that leg stiffness increased with speed and that the damping ratio was low and increased slightly with speed. The duration of the single support phase correlated well with the oscillation period of the damped complaint walking model, suggesting that CoM oscillations during single support may take advantage of resonance characteristics of the spring-like leg. The theoretical leg stiffness that maximizes the elastic energy stored in the compliant leg at the end of the single support phase is approximated by the empirical leg stiffness used to match model GRFs to human GRFs. This result implies that the CoM momentum change during the double support phase requires maximum forward propulsion and that an increase in leg stiffness with speed would beneficially increase the propulsion energy. Our results suggest that humans emulate, and may benefit from, spring-like leg mechanics.

1. Introduction

Bipedal walking models with compliant legs have been employed to describe gait dynamics that are a function of the compliant properties of the leg, such as 'M-shaped' vertical ground reaction forces (GRFs) (Blickhan, 1989; Geyer et al., 2005, 2006; Whittington and Thelen, 2009). As a system parameter, the stiffness of a compliant walking model determines the system characteristics, such as the gait cycle period and the amplitude ratio of center of mass (CoM) oscillations to an external force. For example, the stiffness and the total system energy differentiate the domains of walking and running (Geyer et al., 2006). Therefore, quantification of the leg stiffness of a compliant walking model and the change in stiffness at different gait speeds would allow a better understanding of the contributions of spring-like leg behavior to gait dynamics. Previous studies have reported leg compliance as a form of vertical lower limb stiffness (Farley and Gonzalez, 1996; Holt et al., 2000; Holt et al., 2003; Rebula et al., 2009), which was defined as the ratio of the GRF to the CoM displacement. However, leg stiffness determines system dynamics; therefore, determining the lower limb stiffness using full dynamic equations would more directly quantify the contribution of leg stiffness to gait dynamics. In addition, using this method to determine the lower limb stiffness allows changes in leg stiffness to be interpreted from a system dynamics perspective.

In this study, we calculated the effective leg stiffness of human subjects walking at four different speeds by simulating a damped compliant walking model that was slightly modified from existing compliant walking models (Geyer et al., 2006; Whittington and Thelen, 2009). The stiffness and damping ratios were determined using model simulations that best matched human GRF data. To examine correlations between leg stiffness and the oscillatory behavior of the CoM during the single support phase, the damped natural frequency of the single compliant leg was compared with the duration of the single support phase. To interpret the change in leg stiffness with gait speed from an energetic perspective, the theoretical leg stiffness that maximized the elastic energy stored in the compliant leg at the end of the single support phase was calculated as a function of leg stiffness and gait speed and was then compared with human leg stiffness data.

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doi:10.1016/j.jbiomech.2011.02.072