A limb suspension model to describe leg stiffness change with gait speed

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INTRODUCTION

A limb suspension model describing human steady state walking was developed for quantifying how humans change their lower limb stiffness as walking speed increases. It has been reported that vertical limb stiffness of the double support phase increases with walking speed [1]. However, the change of individual limb stiffness over a complete gait cycle with walking speed has not been quantified by a model, in the view of suspensions dealing with collision. Since one-segment inverted pendulum leg model has limitation describing ground reaction force profiles during gait [2], our model employed compliant leg with spring and damper to reproduce kinematics and kinetics of human’s center of mass (CoM). The results indicated that the limb stiffness increased with gait speed and resulted in increased collision impact. Further examination of the stiffness change with various gait condition and/or subjects will be performed to quantify the gait strategy.

METHODS

Limb suspension model for human walking

![Figure 1: Schematic model of human steady state walking described by feedback control blocks.](image)

Human body was modeled with two massless compliant legs with viscous damper and a concentrated CoM in sagittal plane [3,4]. Passive spring and damper provide suspensions to absorb collision impacts and to control excessive motion of CoM, respectively. A feedback control was used to swing torque generation to stabilize the gait (Fig.1). Hip torque feedback gains and suspension parameters (spring and damping constant) were obtained by optimization (Sequential Quadratic Program) using MATLAB®.

Experiment and data collection

Six healthy young (22.8±1.2 yrs.) subjects with no history of leg injuries participated in this study after signing the consent form approved by the IRB of KAIST.

Auditory gait frequencies ranged from 110-150 bpm (beats per minute) were given to the subject in order to maintain steady state walking by metronome sound. Five different frequencies were selected based on subject’s natural and maximum walking speeds. Secondary size of gait frequency was the averaged self-selected frequency that he preferred in natural walking. The subject was instructed to walk on a straight 12 meter long, 1 meter wide walkway with steady speed guided by metronome’s regular beat. The experiment consisted of total three sets of five randomly ordered gait frequencies. For each trial, ground reaction forces (GRFs) and kinematic data were recorded for 10 seconds using 3 force plates (AMTI, accugait®) and motion capture system (Motion analysis, hawk®), respectively. Velocities and trajectories of CoM were estimated by twice integrating the accelerations obtained from GRFs data [5,6].

RESULTS AND DISCUSSION

Model simulations reproduced the trajectories of CoM and GRFs with the goodness of fit (R²=0.84) for one representative subject.
The vertical stiffness of lower limbs can be roughly calculated during double support phase under the assumption that both legs are considered as one linear spring [7]. CoM displacements decreased as walking speed increased, while mean value of total summed vertical GRFs from both legs significantly increased during the stance phase. By a simple approximation, the lower limbs’ stiffness showed an increasing trend as walking speed increased (Fig.3).

Individual limb stiffness calculated by optimization increased as a function of gait speed. Similar to the lower limb stiffness estimated during the double support, the stiffness of each leg over a complete gait cycle significantly increased with gait speed (p<0.05) (Fig.4).

The subject reduced suspensions with gait speed by increasing individual limb stiffness with the expense of increased collision impact. The change of individual limb stiffness as a function of walking speed could be used to quantify a gait strategy in response to a different walking conditions and/or subject groups.

REFERENCES
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