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Short communication

Resonance-based oscillations could describe human gait mechanics under various loading conditions

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ABSTRACT

The oscillatory behavior of the center of mass (CoM) and the corresponding ground reaction force (GRF) of human gait for various gait speeds can be accurately described in terms of resonance using a spring–mass bipedal model. Resonance is a mechanical phenomenon that reflects the maximum responsiveness and energetic efficiency of a system. To use resonance to describe human gait, we need to investigate whether resonant mechanics is a common property under multiple walking conditions. Body mass and leg stiffness are determinants of resonance; thus, in this study, we investigated the following questions: (1) whether the estimated leg stiffness increased with inertia, (2) whether a resonance-based CoM oscillation could be sustained during a change in the stiffness, and (3) whether these relationships were consistently observed for different walking speeds. Seven healthy young subjects participated in over-ground walking trials at three different gait speeds with and without a 25-kg backpack. We measured the GRFs and the joint kinematics using three force platforms and a motion capture system. The leg stiffness was incorporated using a stiffness parameter in a compliant bipedal model that best fitted the empirical GRF data. The results showed that the leg stiffness increased with the load such that the resonance-based oscillatory behavior of the CoM was maintained for a given gait speed. The results imply that the resonance-based oscillation of the CoM is a consistent gait property and that resonant mechanics may be useful for modeling human gait.

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1. Introduction

Human walking is known to be determined by mechanics (McGeer, 1990). Gait mechanics has been quantified by investigating the relationship between force and motion using bipedal modeling (McGeer, 1990; Garcia et al., 1998; Kuo, 2001; Geyer et al., 2006; Whittington and Thelen, 2009; Kim and Park, 2011). In recent studies, a spring–mass inverted pendulum model was used to successfully describe the oscillatory motion of the center of mass (CoM) and the associated ground reaction forces (GRFs) (Geyer et al., 2006; Kim and Park, 2011; Hong et al., 2013). Moreover, the empirical GRF data were approximated well by the resonant response calculated using a compliant bipedal model over a broad range of gait speeds and for different age groups (Kim and Park, 2011; Hong et al., 2013). The observed resonant response was produced using a speed-proportional increase in the leg stiffness that resulted in the maximum return of the elastic energy stored in the spring during the double support phase (Kim and Park, 2011). Resonance is a mechanical phenomenon that reflects the maximum responsiveness and energetic efficiency of a system; thus, to describe human gait mechanics in terms of resonance, it is important to determine whether a high correlation between the data and the resonance predicted by the model is consistently observed under different walking conditions.

Body mass is a determinant of resonance, like the leg stiffness; thus, in this study, we investigated whether a resonance-based oscillation could also be used to describe human gait kinetics for various body masses. We investigated the following issues: (1) whether the estimated leg stiffness increased with inertia, (2) whether a resonance-based CoM oscillation could be sustained during a stiffness change, and (3) whether these relationships were consistently observed for different walking speeds. Seven healthy young subjects participated in over-ground walking trials at three different gait speeds with and without a 25-kg backpack. We measured the GRFs and joint kinematics using three force platforms and a motion capture system. Leg stiffness was incorporated using a stiffness parameter in the compliant bipedal model that best fitted the empirical GRF data. To verify the correlation between the model resonance and the data, the resonant period of the model was compared with the duration of the single support phase from the GRF data.

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2. Methods

Seven healthy male subjects (age: 29.28 ± 2.14 years, mass: 75.1 ± 8.6 kg, height: 1.75 ± 0.04 m) were participated in this study. The participants reported no history of gait disorders and signed informed consent forms that were approved by the Institutional Review Board of the Korea Advanced Institute of Science and Technology (KAIST) prior to testing.

The subjects walked on a 12-m-long, 1-m-wide straight walkway, with and without a 25-kg backpack, at three different walking speeds, natural, maximum, and intermediate, which were measured before data collection. The speed for the over-ground walking trials was controlled by cueing the gait frequency corresponding to each gait speed using a metronome. The subjects were allowed to freely choose their step length, and the corresponding gait speeds were calculated from the product of the step frequency and the step length over the two mid-steps of the steady trials. The subjects repeated three gait trials consistently at the same step frequency with an average inter-trial standard deviation of $2 \pm 1.5\%$, showing that the gait frequency controlled the gait speeds reasonably well.

The kinetic and kinematic data were measured using three force platforms (Accugait, AMTI, US) and a motion capture system (Hawk, Motion Analysis, US). Three optical markers were positioned at the sacrum and the malleolus of each foot. Three force plates were placed in the middle of the walkway approximately 5–6 steps after gait initiation to guarantee steady-state gait phase measurements. For each gait frequency, the distance between the force plates was adjusted according to the subjects' step lengths. To prevent the subjects from intentionally stepping on the force plates, the entire walkway was divided into sections of sizes similar to those of the force plates and then covered with the same colored self-adhesive vinyl to conceal the location of force plates. The data were sampled at 200 Hz and filtered using a 5th-order Butterworth low-pass filter with a cutoff frequency of 30 Hz. We used a bipedal compliant walking model with a curved foot (Whittington and Thelen, 2009; Kim and Park, 2011) to quantify the leg stiffness that was used to correlate the GRF with the CoM trajectory (Fig. 1). The compliant walking model consisted of two massless springs and dampers with a lumped point mass m to represent the total body mass, including the backpack load in the loaded trials. To simulate a center of pressure (CoP) excursion during the single support phase, a curved foot of radius $R = 30$ cm was introduced into the model (Adamczyk et al., 2006; Whittington and Thelen, 2009; Kim and Park, 2011). The equations of motion for the single and double support phases are as follows:

$$\begin{bmatrix} mR\sin\theta_1 & m \\ ml_1^2 + 2mRl_1\cos\theta_1 + mR^2 & mR\sin\theta_1 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{l}_1 \end{bmatrix} = \begin{bmatrix} ml_1\dot{\theta}_1^2 - mg\cos\theta_1 + kl_0 - kl_1 - c\dot{l}_1 \\ -2ml_1\dot{l}_1\dot{\theta}_1 - 2mR\dot{l}_1\dot{\theta}_1\cos\theta_1 + mRl_1\dot{\theta}_1^2\sin\theta_1 + mgl_1\sin\theta_1 \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} mR\sin\theta_1 & m \\ ml_1^2 + 2mRl_1\cos\theta_1 + mR^2 & mR\sin\theta_1 \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{l}_1 \end{bmatrix} = \Big[ml_1\dot{\theta}_1^2 - mg\cos\theta_1 + kl_0 - kl_1 - c\dot{l}_1 + (kl_0 - kl_2 - c\dot{l}_2)\left(\frac{l_2\cos(\theta_1-\theta_2) + R\cos\theta_1}{l_2 + R\cos\theta_2}\right) - 2ml_1\dot{l}_1\dot{\theta}_1 - 2mR\dot{l}_1\dot{\theta}_1\cos\theta_1 + mRl_1\dot{\theta}_1^2\sin\theta_1 + mgl_1\sin\theta_1 + (kl_0 - kl_2 - c\dot{l}_2)\left(\frac{Rl_2\sin\theta_2 - l_1l_2\sin(\theta_1-\theta_2) - Rl_1\sin\theta_1}{l_2 + R\cos\theta_2}\right)\Big] \quad (2)$$

where the state variables θ, $\dot{\theta}$, l and $\dot{l}$ are the leg angle, the angular velocity, the leg length, and the rate of change of the leg length, respectively. The resting leg length, which was measured as the subject's leg length, and the gravitational acceleration are denoted by l_0 and g, respectively. The subscripts '1' and '2' indicate the trailing leg and the leading leg, respectively. The simulation began in the single support phase with an initial condition that was estimated from the data. The double support phase began when the leading leg contacted the ground at a pre-determined touchdown angle, which was obtained from the GRF data for each trial. The model parameters, i.e., the stiffness k and the leg damping coefficient c, were determined by matching the model simulation to the data as closely as possible. The parameters were optimized by minimizing the mean square error of the model from the data for the three steps of the GRFs. The average goodness of fit R^2 was defined as $R^2 = 1 - \sum_{i=1}^{n}(f(x_i) - y_i)^2 / \sum_{i=1}^{n}(y_i - \overline{y})^2$, where $f(x)$ denotes the simulated GRF values, y and $\overline{y}$ denote the experimental data and the mean of the data, respectively, and n denotes the number of data points. The details of the equations and the simulation procedures can be found in previously published papers (Kim and Park, 2011; Hong et al., 2013). To investigate whether the estimated leg stiffness for both loading conditions increases similarly with the speed, we performed an ANCOVA test at a significance level of $p < 0.05$. We determined whether the GRF data could be accurately described by the resonant oscillation of the mass–spring bipedal model by comparing the duration of the single support phase τ_s with the resonant period $\tau_0 = 2\pi/\omega_n\sqrt{1-\varsigma^2}$ of the model, where $\omega_n = \sqrt{k/m}$ and $\varsigma = c/2\sqrt{mk}$.

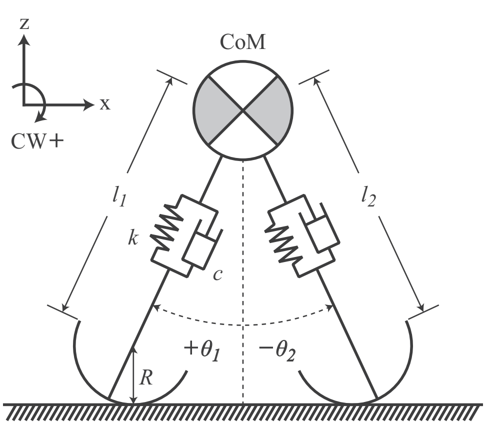

Fig. 1. Schematic of a compliant bipedal model: the model consists of a point mass representing the total body mass (including the weighted backpack in the loaded condition) and two massless legs and curved feet that have point contacts with the ground; the model parameters k, c, R, θ and l denote the leg stiffness, the damping coefficient, the radius of the curved foot, the leg angle with respect to the vertical axis and the leg length, respectively; the subscripts '1' and '2' denote the trailing leg and the leading leg, respectively.

3. Results

The compliant bipedal model reproduced the GRF data reasonably for both loading conditions, with a goodness of fit $R^2 = 0.89 \pm 0.07$ for

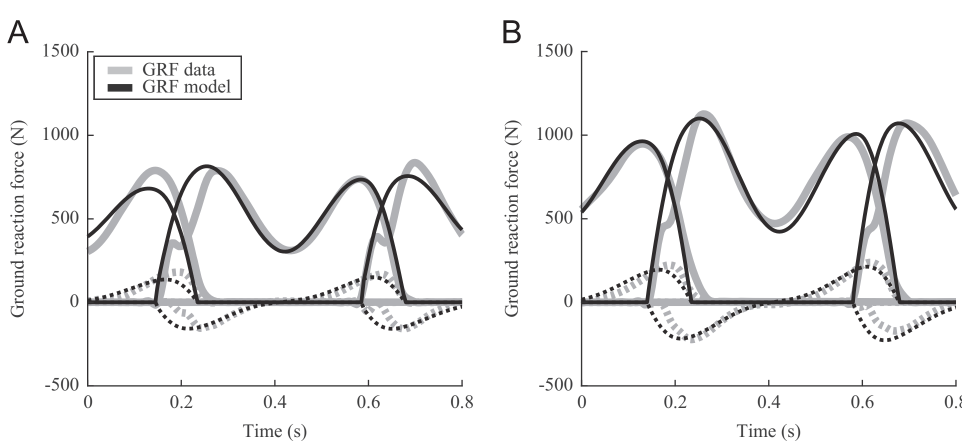

Fig. 2. Empirical GRF data (gray lines) and model simulation (black lines) for (A) unloaded and (B) loaded cases: the vertical and horizontal components of the GRFs are represented by solid and dotted lines, respectively; the spring–damper-loaded bipedal model reasonably reproduces the GRF data with a goodness of fit of $R^2 = 0.87$ (unloaded) and 0.90 (loaded).

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