Leg stiffness increases with gait speed to maximize propulsion energy during push-off
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INTRODUCTION
Compliant walking models have been used to account for the gait dynamics associated with compliant lower limbs [1, 2], and leg compliance has been quantified as a form of vertical lower limb stiffness [3]. However, the vertical stiffness of the lower limb has been defined by the ratio of the force change to the displacement change based on a formulation of $K_{vert} \approx \Delta F/\Delta x$ without considering a full dynamic equation, thus has a limited ability to represent gait dynamics. 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. 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.

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 [1, 2]. 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 examine the energetic benefits of leg stiffness changes as a function of gait speed, the propulsion energy indicating the spring potential energy at the end of single support phase was calculated as a function of leg stiffness and gait speed.

METHODS
Eight subjects walked over-ground at four different gait speeds, ranging from their self-selected speed to their maximum speed [4]. The dynamic leg stiffness was estimated from a damped compliant walking model (Fig.1) that was optimized to best fit the ground reaction force data (Fig.2). To examine the relationship between leg stiffness and gait dynamics in the view of mechanical resonance, the oscillation period of the compliant walking model was calculated from the damped natural frequency and was compared with the duration of the single support phase. To examine the energetic benefits of leg stiffness changes as a function of gait speed, the propulsion energy indicating the spring potential energy at the end of single support phase was calculated as a function of leg stiffness and gait speed.

Figure 1: A compliant walking model. The human body was modeled with two massless, compliant legs with curved feet. The parameters $K_{leg}$, $C_{leg}$, $\theta$, $L$ and $R$ indicate the spring constant, damping constant, leg angle, leg length and curved foot radius, respectively. The subscripts ‘1’ and ‘2’ indicate the trailing leg and the leading leg.

RESULTS AND DISCUSSION
Model simulations reproduced the trajectories of the GRFs with the goodness of fit (r) for all subjects (Fig. 2). Both the leg stiffness and damping ratio calculated by the model optimization significantly increased as a function of gait speed (Fig.3; p<0.05). The averaged slopes of the dimensionless stiffness (normalized by body weight
divided by height) and the damping ratio with respect to a unit speed change were 39.82±12.71 (s/m) and 0.036±0.013 (s/m), respectively (Fig. 3). Damping ratios ranged from 0.03 to 0.08 and were necessary to robustly generate repeated steps that reproduced the human data with various initial conditions.

Figure 2: Model simulations of the GRFs. The solid lines and the dotted lines represent the vertical and horizontal directions, respectively.

Figure 3: The effective leg stiffness as a function of walking speed obtained from the optimization that minimized the data-model fitting error. Leg stiffness was normalized by the subject’s weight divided by height. The solid line indicates the linear regression.

The duration of the single support phase correlated well with the period of the damped natural frequency of the single compliant (Fig. 4), suggesting that CoM oscillations during the single support phase may take advantage of resonance characteristics of the spring-like leg. The theoretical leg stiffness that maximized the elastic energy stored in the compliant leg at the end of the single support phase was approximated by the empirical leg stiffness. This result implies that the CoM momentum change during the double support requires maximum forward propulsion and that an increase in leg stiffness with speed would beneficially increase the propulsion energy.

CONCLUSIONS

Our results suggest that humans emulate spring-like leg mechanics, and modulate the apparent stiffness to optimize gait dynamics and energetic. The effective leg stiffness increased with gait speed to support the greater propulsion energy required before collision during faster gaits.

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