

STIFFNESS AND VISCOUS DAMPING OF THE HUMAN LEG

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INTRODUCTION

Mass and spring model has been used in various studies to characterize the biomechanical features of the human leg and body^{1,2}. Since human legs have inherent damping as well as stiffness properties³, the body does not bounce like an undamped spring and mass in many cases. Viscous damping plays an important role in the functioning of the leg and body and helps absorb shocks and maintain stability. Compared with leg stiffness, much less work has been done to study the leg viscous damping property of human subjects. The purpose of this study was to quantify and study the viscous damping as well as stiffness of the leg and body through in vivo experiment on human subjects.

METHODS

Three subjects participated in the study. The subjects stood with both feet on an AMTI force platform. The body center of mass (COM) was moved up and down in small amplitude and random pattern by lifting the trunk through a harness and rope-pulley which flexed the knees, ankles, and hips slightly. The feet were stationary during the body movement. An Optotrak system was used to measure the movement with markers placed at the fifth metatarsal, heel, lateral malleolus, mid-leg, lateral epicondyle of the femur, greater trochanter, ASIS, and the acromion, and they were used to construct the stick figure (Fig. 1(b)). The subjects squatted slightly and the trunk was vertical.

The vertical movement of the marker on the ASIS was taken as the vertical movement of the body COM. Ground reaction force and lifting force were displayed on a computer monitor in real-time to help generate the small-amplitude random vertical movement.

The leg and body were modeled by a spring with stiffness (k), a dashpot with viscous damping (c), and a mass (m) (Fig. 1(a)).

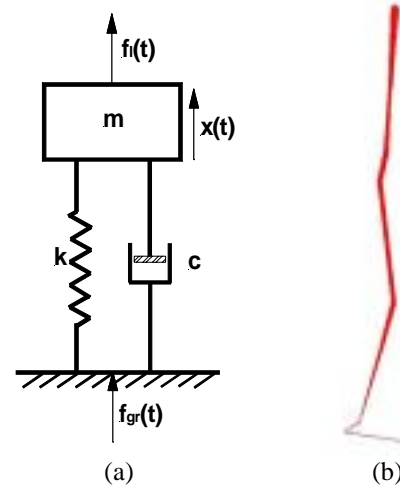


Figure 1: (a) A dashpot (c), spring (k) and mass (m) model of the human leg and body. (b) Stick figure during the COM movement trial.

The system was assumed linear time-invariant during the small-amplitude movement, and the vertical COM displacement $x(t)$ was related to the vertical lifting force $f_l(t)$ as follows:

$$m \frac{d^2 x(t)}{dt^2} + c \frac{dx(t)}{dt} + k \Delta x(t) = \Delta f_l(t) + e(t)$$

where $\Delta x(t)$ and $\Delta f_l(t)$ represented the deviations of the vertical COM displacement and the vertical lifting force from their initial values, respectively. The gravitational

force was assumed constant during the movement and thus did not appear in the above equation. $e(t)$ was the modeling error.

System identification approach was used to estimate the model parameters from the measured body COM displacement and lifting force⁴. Since the body mass (m) could be measured separately, only the stiffness (k) and viscous damping (c) need to be estimated. The estimation was done over every 2-second long data with two consecutive segments overlap by 50%. The estimated parameters were averaged over the multiple segments. The variance accounted for (VAF), defined as $VAF = (1 - \sigma_e^2 / \sigma_s^2) * 100\%$ (σ_s^2 and σ_e^2 were the variances of signal and simulation error respectively), was used to evaluate the modeling result.

RESULTS AND DISCUSSION

For a subject with a body mass of 78 kg, the body COM moved up and down in a range of about 7 mm and the corresponding lifting force varied about 200 N. The estimated viscous damping (c) was 950 N•s/m and the leg stiffness (k) was 28,500 N/m. The simulated and measured forces matched well with a typical VAF of 90%. Stick figure showed that the knee, hip, and ankle joints flexed slightly and contributed to the leg stiffness and viscous damping (Fig. 1(b)).

Viscous damping plays an important role in biomechanical movement. The estimated leg stiffness and viscous damping parameters were used to simulate body COM movement with a step input (a suddenly applied lifting force of 100 N to the body). With the damping ratio $\zeta = d / 2 / \sqrt{mk} = 0.55$, the body COM quickly reached its steady position of about 3.5 mm (Fig. 2). In contrast, with $\zeta = 0$ (no viscous damping), the body COM would oscillate infinitely between 0 and 7.0 mm.

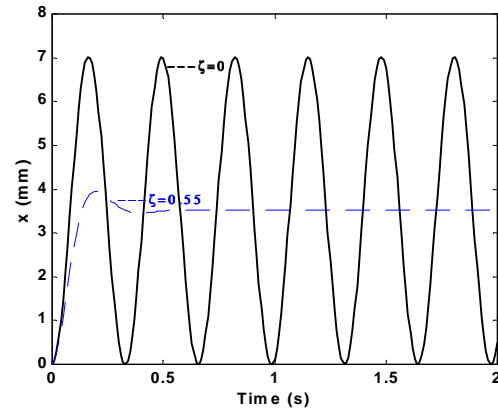


Figure 2: Simulation of COM vertical movement with a suddenly applied lifting force of 100 N (at time=0). Natural undamped frequency $\omega_n = \sqrt{k/m} = 19$ rad/sec and leg stiffness $k = 28,500$ N/m were used.

SUMMARY

Viscous damping helps absorb shock and maintain stability in functional tasks of various biomechanical systems. A better understanding of the viscous damping facilitated by in vivo estimation of the relevant parameters help us to gain insights into the control of biomechanical systems.

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