MECHANICAL IMPEDANCE IDENTIFICATION OF THE HUMAN LOCOMOTOR SYSTEM DURING ABLE-BODIED WALKING

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INTRODUCTION

A simple mass-spring-viscous damping model has been used by investigators mainly to model human bouncing (Zhang et al., 2000) and running (McMahon and Greene, 1979). Our laboratory has investigated a rocker-based inverted pendulum of walking without shock absorption on even terrain (Gard and Childress, 2001). The purpose of this investigation is to determine the impedance characteristics of the human locomotor system, based on a spring and viscous damper element added to the previous model of walking, as shown in Figure 1.

METHODS

Three able-bodied persons walked at different walking speeds ranging from 0.8-2.2 m/s. Kinematic and kinetic gait analysis data were collected. Since the vertical displacement of the Body Center of Mass (BCOM) during steady-state walking is approximately a sinusoid we decided to use steady-state sinusoidal analysis. Furthermore, because of the small vertical excursion of the BCOM we decided to assume a linear model. Thus, walking in the context of vertical shock absorption was modeled as a modified 2[nd] order linear vibration system (Figure 1). The terrain in Figure 1 is the approximate trajectory of the rocker-based inverted pendulum which we model by the trajectory's first harmonic.

For the proposed model we write the equations of a sinusoidal system (equations 1-4):

$$w_d = \sqrt{1-z^2} \cdot w_n \qquad (1)$$

where ω_d is the damped frequency of oscillation and can be derived from the walking cadence. ω_n is the natural frequency of oscillation and ζ is the damping ratio. We assume that the human is able to make neuromuscular adaptations of damping and stiffness parameters so that the frequency of stepping (cadence) is close to the damped frequency of oscillation ω_d. ($w = 2 \cdot p \cdot f_{cadence} \cong w_d$). If k is the stiffness and B is the viscous damping, then:

$$k = w_n^2 \cdot M_e \quad (2)$$

$$B = 2 \cdot M_e \cdot w_n \cdot z \quad (3)$$

where M_e is the effective mass during the stance phase of walking and is equal to 0.88M since the standing leg acts like a spring having a distributed mass (Stokey, 2002).

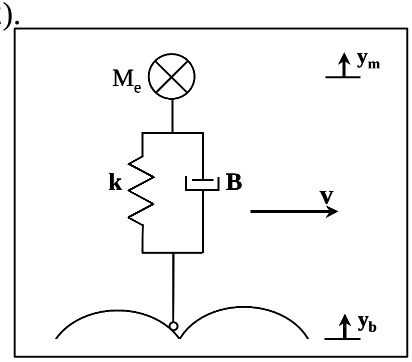

Figure 1: Able-bodied human walking was modeled with a 2[nd] order mechanical vibration system.

The equation of motion in the Laplace domain for the proposed mechanical model of walking (Figure 1) is:

$$\frac{y_m(s)}{y_b(s)} = \frac{\frac{B}{M_e}\left(s + \frac{k}{B}\right)}{s^2 + \frac{B}{M_e}s + \frac{k}{M_e}} \quad (4a)$$

Since $y_m(s)$ is measured and $y_b(s)$ is approximated to a sinusoid with known minimums (heel-strike events) we can derive:

$$\text{Phase of} \left(\frac{y_m(jw_d)}{y_b(jw_d)} \right)$$

$$= \text{phase of} \left(\frac{\frac{k}{M_e} + \frac{B}{M_e} jw_d}{-w_d^2 + \frac{k}{M_e} + \frac{B}{M_e} jw_d} \right) \quad (4b)$$

We then have a system of 4 equations (1-4) with 4 unknowns: ζ, k , B, ω_n. By solving this system of equations we can estimate the damping ratio ζ, stiffness k and damping B.

RESULTS AND DISCUSSION

Our results support the theory that the damping ratio $\zeta = [B/2(M_e k)^{1/2}]$ is fairly constant (ζ = 0.5-0.8) across different walking speeds of walking (Figure 2). Stiffness k appears to increase linearly with walking speed *V*, being around 15 kN/m at 1.2 m/s (Figure 3).

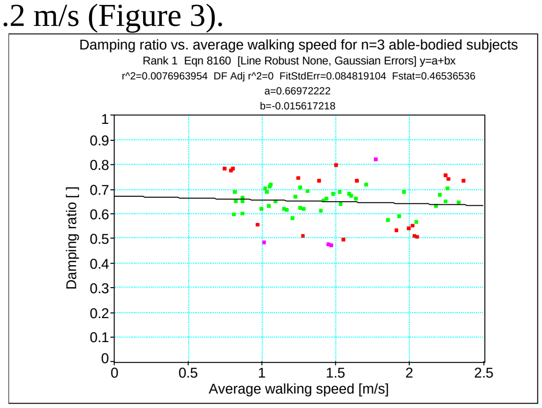

Figure 2: Estimated damping ratio ζ vs. *V*.

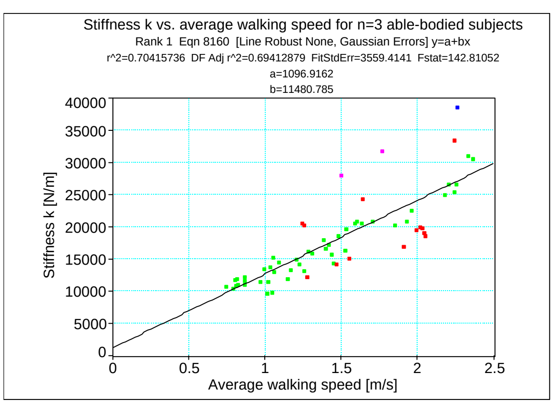

Figure 3: Estimated stiffness k vs. *V*.

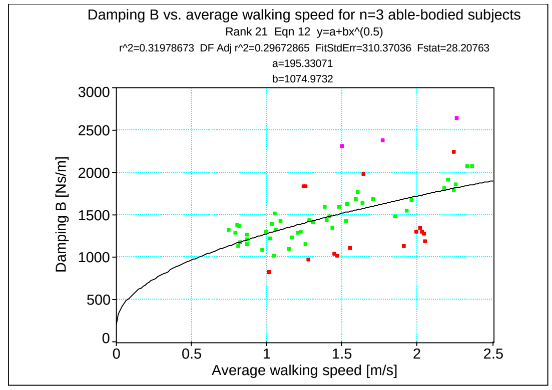

Figure 4: Estimated damping B vs. *V*.

Damping B appears to increase with the square root of walking speed, $\sqrt{V}$ (Figure 4). During able-bodied walking the system appears to be underdamped (0<ζ<1) having a high performance from a control theory standpoint with ζ between 0.5 and 0.8.

SUMMARY

Based on the proposed model the damping ratio of the locomotor system is maintained relatively constant, near high performance values (ζ = 0.5-0.8), with increasing walking speed *V*. The stiffness k and damping B vary with walking speed *V* in such a way that the damping ratio ζ remains in the ζ = 0.5-0.8 optimal value range.

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