

METABOLIC COSTS OF HUMAN BOUNCING

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INTRODUCTION

In running, hopping, or bouncing, humans have been modeled as mass-spring systems, with an associated natural frequency for each task. The passive elasticity of the musculo-tendon complex may store and return energy to the system, decreasing the amount of muscular work required. A simple example of humans exhibiting spring-like activity is bouncing about the ankle joint. We hypothesize that the energetic cost of this bouncing is influenced by two major factors. Energy is expended when muscles perform work, leading to a certain metabolic cost. When muscles contract isometrically, there is no work performed, but there is still an energetic cost, increasing with the average force and potentially inversely with the contraction time. These two factors together may explain the total metabolic cost of bouncing.

METHODS

Four subjects (2 male, 2 female) participated in this study. The subjects bounced vertically using only the ankles over a range of frequencies. Bounce amplitudes were kept small, so the subjects never left the ground. We collected ground reaction force and ankle height data for all trials. Subjects first bounced at seven frequencies (1 – 4 Hz) while we collected electromyographic (EMG) data from the left medial gastrocnemius. Oxygen consumption data was then collected with the subject at rest, and while bouncing at four frequencies (1 – 4 Hz). In each trial, the bounce amplitude was adjusted to keep the positive mechanical work constant across frequencies.

The filtered EMG, ground reaction force, and ankle height data were fit with modified sinusoids. We calculated the gain and phase differences from the EMG to the reaction force and ankle position. These gain and phase values were then fit to a mechanical model representing the action of the ankle plantarflexors (Fig 1, after Bach et al., 1983) by adjusting the model parameters. This model was used to calculate positive muscle work performed on the center of mass at the various frequencies. Metabolic cost was calculated from steady state oxygen consumption data.

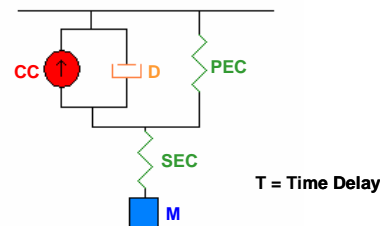


Figure 1: Mechanical model of musculo-tendon system including a contractile component (CC), damper (D), parallel elastic component (PEC), series elastic component (SEC), and time delay (T).

RESULTS AND DISCUSSION

The calculated experimental gains and phases were qualitatively a good fit with the model bode plot for each subject. An example for one subject is shown in Figure 2. Between the four subjects, the average model parameter values were $SEC = 30175 \text{ kg/s}^2$, $PEC = 24202 \text{ kg/s}^2$, $D = 3909 \text{ kg/s}$, and $T = 0.109 \text{ s}$, comparable to values found in earlier studies (Bach et al, 1983).

For each subject, we used the model to calculate the theoretical positive muscle work and total system positive mechanical

work for each frequency. The model parameters were identified from experimental force data and then compared with the corresponding metabolic data. We also calculated the duration of active muscle contraction at each frequency from the fit EMG data. This was used to calculate the average force per contraction time under each condition.

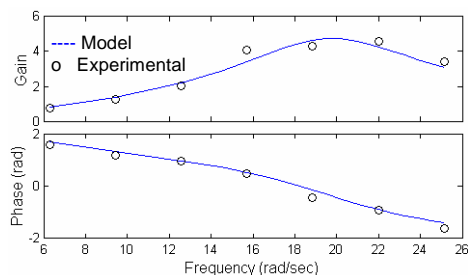


Figure 2: Comparison of experimental and modeled gain and phase data from EMG (input) to ground reaction force (output).

If muscular work is the major determinant of metabolic cost, the expected cost can be calculated by assuming a constant work efficiency of 25% (Hill, 1938). But if the metabolic cost is determined by the rate of force application, as in running (Kram & Taylor, 1990), the expected cost will be proportional to the average force per contraction time. This proportionality was calculated to be 0.183 JN^{-1} in running (Kram and Taylor, 1990), a task similar to bouncing in that the primary cost is supporting body weight.

The theoretical metabolic costs from these two sources were calculated for each frequency and compared with actual metabolic costs (Fig. 3). It appears that if both of these costs are present in bouncing, the cost of doing positive muscle work dominates at low frequencies, while the cost of generating force with a short time course dominates at high frequencies. The theoretical combined metabolic cost is minimized around 3 Hz, the same frequency

at which the subjects' actual metabolic cost was minimized.

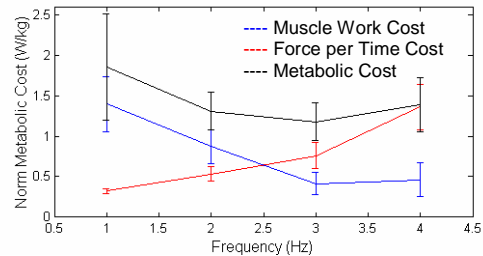


Figure 3: Theoretical costs from positive muscle work, force per contraction time, and actual metabolic cost.

Total mechanical work was kept constant at all frequencies, and therefore does not explain the observed variations in energetic cost. Muscle work alone also does not explain energetic cost, because the calculated efficiency (mechanical power per metabolic power) exceeded 25% at 3 Hz in all subjects. Instead, it is likely that at higher frequencies, the muscle is contracting more isometrically, and the tendon is responsible for much of the positive work (Kubo et al, 2000).

SUMMARY

Humans bouncing about their ankle joint can be treated as a mechanical system, in which the passive dynamics influence the metabolic cost. At low frequencies, the cost of muscular work dominates, while at higher frequencies, the cost of generating force quickly is more important. Metabolic cost is minimized at an intermediate frequency.

ACKNOWLEDGEMENTS

J.C.D. supported in part by a fellowship from the UM Institute of Gerontology.

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