COMPUTATIONAL MODEL OF MAXIMUM-HEIGHT SINGLE-JOINT JUMPING PREDICTS BOUNCING AS AN OPTIMAL STRATEGY

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INTRODUCTION

Because of its unambiguous objective function, maximum-height jumping is especially well suited to simulation-based investigations of musculoskeletal function and coordination. Previous computational simulations of jumping have increased our understanding of the mechanisms that underlie task performance in a manner that is not always possible using experimental protocols [1]. Multijoint [1] and single joint [2] models of jumping have been employed to study muscle function during maximum-height jumping. Jumping using only the ankles for propulsion has been studied experimentally [2,3] as with simulation [2]. Limiting the task to single joint reduces complexity (eliminating the effects of biarticular muscles, for example) and thereby allows a more focused investigation into the mechanisms of optimal performance. The purposes of this study were to develop a muscle actuated computational simulation of maximum-height, single-joint jumping and to test the model by comparing simulation output with experimental results. This model will be used in future studies to explore the relationship between joint structure and function for various motor tasks.

METHODS

The computational model had two degrees of freedom and consisted of two massless segments (foot and leg) with half body mass positioned atop the leg segment (Fig. 1). The ankle was a revolute joint, as was the connection between the foot and the ground contact, which was located at the position of the MTP joint. Two muscles, a plantarflexor and a dorsiflexor, acted across the ankle joint. Muscles were modeled as Hill-type actuators with first-order activation dynamics. Muscle architecture properties (optimal fiber length, maximum isometric force, tendon stiffness, muscle moment arm) were derived using a least squares curve fitting algorithm that gave the best fit between experimental passive and active isometric joint torque curves from the literature [4,5,6] and model-generated joint torque curves. Maximal height jumping was simulated using a forward dynamic optimization approach in the following objective function [7] was maximized:

\[ J(t_f, u) = y_c(t_f) + \frac{1}{2g}v_c^2(t_f) \]

The 43 optimization parameters were the muscle excitations \( u \) (with 21 nodes for each muscle) and time at takeoff \( t_f \). The vertical position of center of mass is given by \( y_c \). The model was developed using Simulink SimMechanics (MathWorks, Inc.; Natick, MA) and the optimization problem was solved using a combination of gradient- and non-gradient-based algorithms in MATLAB. The jumping strategy used by the model was dictated by setting an upper bound on \( t_f \) such that the model had no time for a countermovement; performed a single counter-movement; or “bounced” by performing several successive countermovements (when \( t_f \) was unbounded).

Figure 1: Computational model (left) and a subject wearing platform shoes and knee braces (right).
Eight healthy male subjects performed maximal height jumps using only their ankles for propulsion. The subjects’ knees were held immobile by braces and each subject was further instructed not to move his hips, trunk, arms, or head. The arms were folded across each subject’s chest. Subjects wore platform shoes (JumpSoles, Metapro; Mountain View, CA) (Fig. 1), which lifted the heel off the ground, allowing the subjects to perform a countermovement (CM) at the ankle. Subjects were instructed to jump as high as possible with no further instruction (CM\textsubscript{FREE}; 5 trials), with instruction to move down initially (CM\textsubscript{DOWN}; 5 trials), and with instruction to try bouncing before jumping up (CM\textsubscript{BOUNCE}; 5 trials). Foot and shank kinematic data were collected to calculate ankle angles and the average peak rise of 4 markers on the pelvis was taken as measure of jump height.

RESULTS AND DISCUSSION

Maximum jump heights were found to be similar between model and experiment (Table 1). The model jumped highest following a series of bounces, and 4 of the 8 subjects also jumped highest when they tried to bounce. For these subjects, the time to takeoff was similar to the time taken by the model and their final bounce was at a similar frequency as the model’s predicted final bounce frequency for maximal performance (Table 1).

Humans are known to jump higher when employing a CM during a multijoint jump [8]. During a single joint CM, tendon energy storage has been shown to be enhanced as the muscle fibers act isometrically, allowing subsequent energy release and enhancement of performance [3]. In the present study, the computer simulation and half of the subjects jumped highest after multiple bounces. With each successive bounce the model exhibited more energy storage in the tendon as muscle fibers generated force isometrically (Fig. 2).

CONCLUSIONS

A computational simulation of single-joint jumping was yielded optimal performance when takeoff was preceded by a series of countermovements, or bouncing. Similar behavior produced the highest jumps in half of the subjects. Simulation output suggests increased elastic energy storage during successive bounces as the mechanism for this performance enhancement. In future studies this computational model will be used to explore how changes in joint structure affect performance in various motor tasks.

REFERENCES


| Table 1: Comparison of model to subjects (n = 4) whose maximum height jumps occurred when bouncing. |
|-----------------------------------------------------|----------------|----------------|----------------|----------------|
| **MODEL**                                           | **SUBJECTS**   | **Mass (kg)** | **Jump height (cm)** | **Time to jump (s)** | **Bounce freq (Hz)** |
| 75.0                                                | 76.3±7.6       | 13.0          | 17.3±5.1          | 1.2              | 2.6±0.4           |

Figure 2: Fiber length and tendon energy versus time to takeoff (top). Plantarflexor excitation \((0 \leq u \leq 1)\) versus time to takeoff (bottom).