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Maximum height and minimum time vertical jumping

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ABSTRACT

The performance criterion in maximum vertical jumping has typically been assumed to simply raise the center of mass as high as possible. In many sporting activities minimizing movement time during the jump is likely also critical to successful performance. The purpose of this study was to examine maximum height jumps performed while minimizing jump time. A direct dynamics model was used to examine squat jump performance, with dual performance criteria: maximize jump height and minimize jump time. The muscle model had activation dynamics, force–length, force–velocity properties, and a series of elastic component representing the tendon. The simulations were run in two modes. In Mode 1 the model was placed in a fixed initial position. In Mode 2 the simulation model selected the initial squat configuration as well as the sequence of muscle activations. The inclusion of time as a factor in Mode 1 simulations resulted in a small decrease in jump height and moderate time savings. The improvement in time was mostly accomplished by taking off from a less extended position. In Mode 2 simulations, more substantial time savings could be achieved by beginning the jump in a more upright posture. However, when time was weighted more heavily in these simulations, there was a more substantial reduction in jump height. Future work is needed to examine the implications for countermovement jumping and to examine the possibility of minimizing movement time as part of the control scheme even when the task is to jump maximally.

1. Introduction

Maximum vertical jumping has been examined experimentally and through simulation models. These studies have revealed, for example, the high power output during jumping (e.g., Davies and Rennie, 1968), the potential role of bi-articular muscles (Van Soest et al., 1993), and the contribution of the arm swing to a maximum jump height (Domire and Challis, 2010). Maximum vertical jumping is particularly amenable to biomechanical analysis because the performance criterion has typically been assumed to be clear: raise the center of mass as high as possible.

For the simulation of many human movements the performance criterion is not as clearly defined as it is for maximum height jumping. In many movements it is feasible that multiple performance criteria are at play simultaneously (Winters and Zajac, 1990). For example, during gait a subject with an injured knee may try to balance the metabolic cost of locomotion and the load on the joint of the injured knee. Identifying such simultaneously applied criteria is difficult and once they are identified the relative weighting of the criteria is potentially even harder to ascertain.

Simulation models of vertical jumps have ranged from simple where only one joint is modeled with a single muscle represented (e.g., Alexander, 1990; Challis, 1998) to complex where multiple joints and muscles are represented (e.g., Anderson and Pandy, 1993; Nagano et al., 2007; Domire and Challis, 2007). In these models optimal controls are identified which at the instant of take-off maximizes the height of the center of mass and the velocity of the center of mass. Typically these optimal controls are a set of activations sent to the muscle models crossing the joints of the model. In many sporting activities jumping is a fundamental skill, for example in basketball and volleyball. During these sports, a jump which results in a largest displacement of the center of mass, may not always lead to success if within the context of play the timing of the skill is not appropriate. Many jumps in basketball and volleyball are not executed with a countermovement as this makes the total movement time too long, so athletes are often in an initial squat position ready to jump. Even though an initial squat may reduce movement time, to get to the ball first a jump may need to be high but also not take too long to execute the jump otherwise another athlete might arrive at the ball first, or the opportunity to intercept the ball may be missed. Therefore in the case of vertical jumping in some sports there are two criteria at

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play: jump as high as possible while also minimizing movement time. Under such conditions to minimize time to intercept the ball requires a high take-off velocity and a low time to generate the jump. To date no studies have examined maximum vertical jumping under movement time constraints.

The purpose of this study was to examine maximum height jumps performed while minimizing the jump time, here jump time refers to the time used to produce the jump while the subject is in contact with the ground. It is anticipated that as the jump time decreases so will the jump height, but the precise nature of the change in jump height is not clear. In addition the factors that dictate the changes in the jump height with constraints on the jump time have yet to be determined. With experimental subjects it would be impossible to control their performance so that the dual criteria of vertical jump performance could be thoroughly investigated; therefore these jumps were examined in a simulation environment.

2. Methods

2.1. Overview

A direct dynamics muscle model driven simulation of human vertical jumping was used to examine vertical jump performance, with dual performance criteria: maximize jump height and minimize jump time (Fig. 1). Initial simulations did not minimize jump time they only maximized jump height, then subsequent simulations sought a balance between these two aspects of performance. The model was evaluated by comparing the model performance for maximum height jumps with no time constraint with that of experimental subjects performing the same task.

2.2. The model

The model consisted of four rigid links (foot, shank, thigh, and a combined head, arms, and trunk) connected by frictionless hinge joints, where the lower limb segments were paired (left and right sides) assuming bi-lateral symmetry and modeling sagittal plane motion. The inertial properties of the segments, Table 1, were based on the data from a group of experimental subjects used for model evaluations. For these subjects their segmental inertial properties were determined by modeling their segments as series of geometric solids (Challis et al., 2012). The equations of motion of the model relate the moments at the models joints, generated by the muscle models, to the angular acceleration of the joints,

$$\ddot{\theta} = M(\theta)^{-1}\left(T_J - v(\theta, \dot{\theta}) - G(\theta)\right) \quad (1)$$

where

$\ddot{\theta}$ – vector of joint angular accelerations,
$M(\theta)$ – inertia matrix,
T_J – vector of muscular moments generated at the joints,
$v(\theta, \dot{\theta})$ – vector of centrifugal and Coriolis terms,
and $G(\theta)$ is the vector of gravity terms.

The major muscles of the lower limb were represented by eight Hill-type muscle models. The muscle model had activation dynamics, force–length, force–velocity properties, and a series of elastic component representing the tendon. The muscle model has been described previously (Gallucci and Challis, 2002; Domire and Challis, 2007). The parameters for the muscle models (Table 2) were based on the data presented by Friederich and Brand (1990), and scaled to the physique of a typical experimental subject from Domire and Challis (2007). The parameters describing the force velocity relationship of the muscle models are from Faulkner et al. (1986). The lengths and moment arms of these muscles were determined using the equations of Visser et al. (1990) for muscles crossing the knee joint, Grieve et al. (1978) for muscles crossing the ankle joint, and Hawkins and Hull (1990) for muscles crossing the hip joint.

The simulations were run in two modes. In Mode 1 the model was placed in an initial position which mimicked the initial squat position of the experimental subjects (see next sub-section). These simulations represent jumps that a subject might perform in a sporting context where in an initial squat they have to jump to intercept a ball where there is a potential for variation in the ball's location. In Mode 2 the simulation model selected the initial squat configuration as well as the

Table 1
Body segment inertial parameters used in the model.

	Foot	Shank	Thigh	HAT
Length (m)	0.150	0.420	0.415	0.757
Center of mass location (%)	45.8	42.3	43.9	62.3
Mass (kg)	1.14	3.31	9.17	46.8
Moment of Inertia (kg m^2)	0.01	0.10	0.27	2.01

HAT refers to a single segment, the head, arms, and trunk. Center of mass locations are expressed as a percentage of segment length from the proximal joint. Masses for the foot, shank, and thigh are for one side of the body. The total mass of the body is 74 kg. Moments of inertia are about a transverse axis through the segment's center of mass.

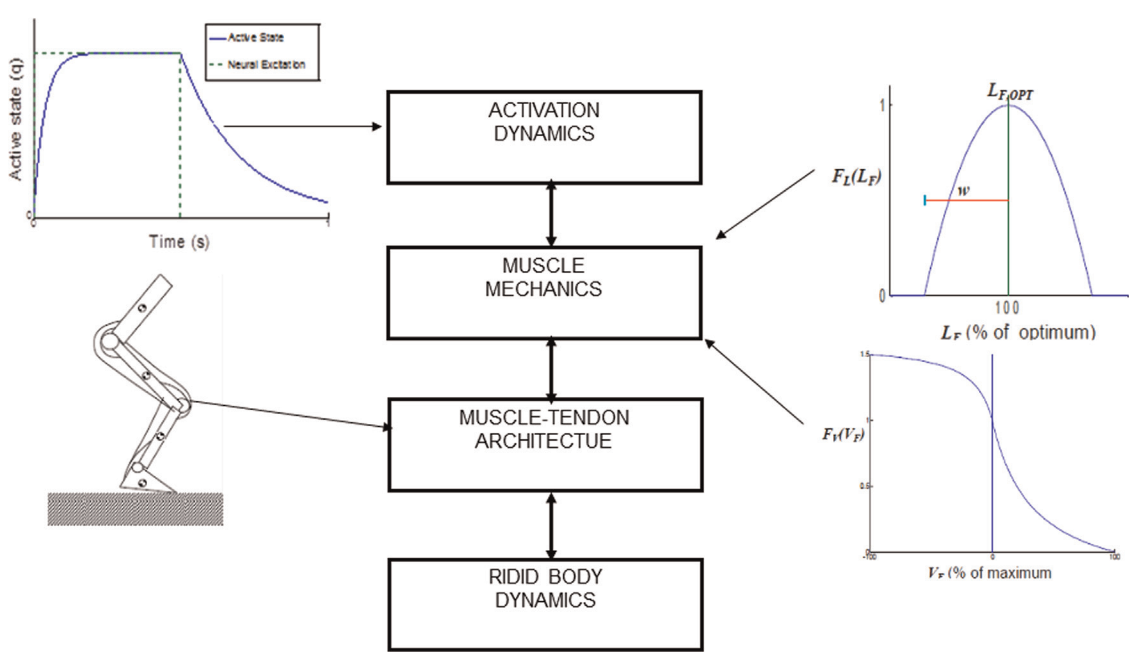

Fig. 1. Schematic representation of the model, and its components.