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# Countermovement strategy changes with vertical jump height to accommodate feasible force constraints

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ABSTRACT

In this study, we developed a curve-fit model of countermovement dynamics and examined whether the characteristics of a countermovement jump can be quantified using the model parameter and its scaling; we expected that the model-based analysis would facilitate an understanding of the basic mechanisms of force reduction and propulsion with a simplified framework of the center of mass (CoM) mechanics. Ten healthy young subjects jumped straight up to five different levels ranging from approximately 10% to 35% of their body heights. The kinematic and kinetic data on the CoM were measured using a force plate system synchronized with motion capture cameras. All subjects generated larger vertical forces compared with their body weights from the countermovement and sufficiently lowered their CoM position to support the work performed by push-off as the vertical elevations became more challenging. The model simulation reasonably reproduced the trajectories of vertical force during the countermovement, and the model parameters were replaced by linear and polynomial regression functions in terms of the vertical jump height. Gradual scaling trends of the individual model parameters were observed as a function of the vertical jump height with different degrees of scaling, depending on the subject. The results imply that the subjects may be aware of the jumping dynamics when subjected to various vertical jump heights and may select their countermovement strategies to effectively accommodate biomechanical constraints, i.e., limited force generation for the standing vertical jump.

## 1. Introduction

In the standing vertical jump, a countermovement is a preliminary downward action that flexes the knees and hips before shortening the muscles for upward motion (Linthorne, 2001). As reported previously, subjects are generally able to jump higher with the countermovement than without any counter action (e.g., squat jump) (Bobbert et al., 1996; Linthorne, 2001). The mechanisms responsible for the greater jump height have been widely discussed by various research groups in terms of simple kinematics and muscle physiology. Some authors argue that pre-stretching before muscle shortening allows the muscles to build up a high level active state, resulting in greater joint moments at the start of push-off (Bobbert et al., 1996; Van Schenau et al., 1997), while others suggest that the countermovement enables elastic energy storage and reutilization in the muscles and/or tendons for extra work (Anderson and Pandy, 1993; Komi, 2000; Svantesson et al., 1991). However, the exact cause of the force advantage of the countermovement remains to be clarified.

To better understand the comparative advantages of countermovement in terms of mechanics, the countermovement jump was directly compared with the squat jump (Linthorne, 2001; McLellan et al., 2011), which does not employ a preliminary downward phase and begins from a stationary semi-squatted posture instead of an upright standing posture. The force (i.e., ground reaction force)–displacement (i.e., displacement of center of mass) curves corresponding to the countermovement jump and the squat jump were plotted on the same graph and compared in terms of the work performed by the ground reaction force, which suggested that in the countermovement jump, the leg muscles attain a higher amount of vertical force across a wide range of vertical displacements before they begin to shorten.

Multiple approaches have been used in modeling studies of vertical jumping to understand the vertical jump strategy in terms of muscle coordination, muscle strength, and arm swing. The effects of ankle restriction (Arakawa et al., 2013) and trunk inclination (Vanrenterghem et al., 2008) on the coordination of vertical jumping were investigated in terms of the mechanical outputs, such as the maximum power and work. The role of the rate of force development on a vertical jump was tested during a countermovement jump to determine the relationship between the peak force and the vertical jump displacement (McLellan et al., 2011). The energetics and

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benefits of the arm swing (Lees et al., 2006) and squat depth (Domire and Challis, 2007) in a maximal vertical jump were also investigated in terms of energy build-up and dissipation mechanisms.

Although several attempts have been made within a mechanical framework similar to the ones described above, to date, the countermovement dynamics have not been quantitatively explored using a descriptive mathematical model to understand the basic mechanisms of force reduction and propulsion while considering biomechanical constraints, i.e., the feasible force and the rate of force constraints.

There have been many recent studies concerning biomechanical constraints and postural strategies that have suggested that human movements, such as postural responses to external perturbations, are inevitably affected by biomechanical constraints. For example, the postural strategy changes from an ankle strategy to a hip strategy with increasing perturbation magnitudes of support translation (Horak and Nashner, 1986; Park et al., 2004) and forward push (Kim et al., 2012). Specifically, the hip joint torque increases with perturbation, while the ankle joint torque is more limited because of the maximum allowable joint torque. These continuous changes in postural responses have suggested that the central nervous system (CNS) uses a continuous representation of biomechanical constraints (Park et al., 2004).

In this study, we developed a curve-fit model of the countermovement dynamics and examined whether the characteristics of the countermovement jump can be quantified by the model parameter and its scaling. The trajectories of the vertical force were curve-fitted with a combination of a semi-sinusoidal waveform and a linear increase, and the model parameters were then examined as a function of the vertical jump height to study the change in jump strategies. This model-based analysis would facilitate an understanding of the basic mechanisms of force reduction and propulsion that concern the biomechanical constraints and jump strategies with a simplified framework of center of mass (CoM) mechanics and will allow the development of a realistic framework for multi-joint dynamics and/or muscle physiology.

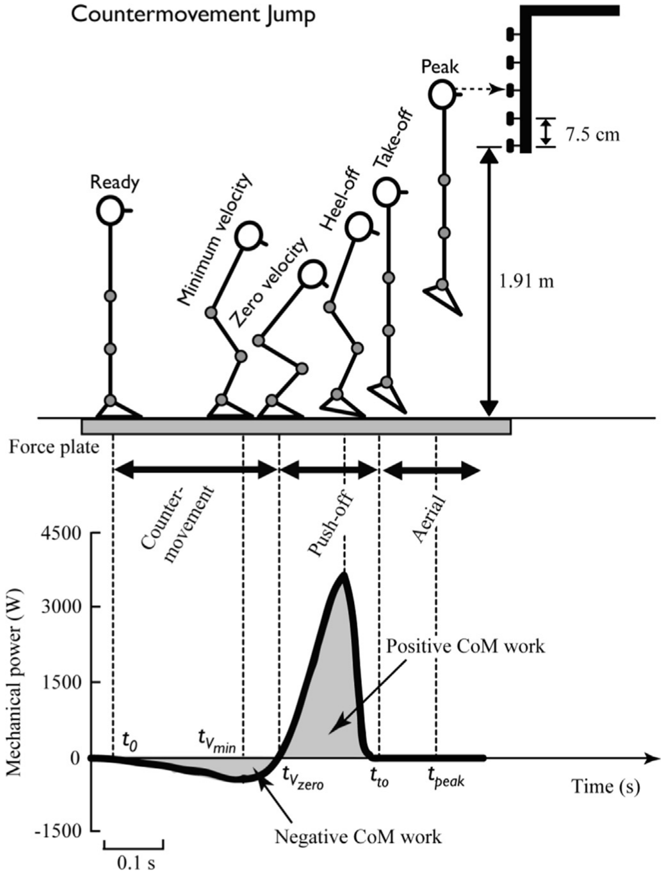

**Fig. 1.** Simplified steps in vertical jumping with countermovement. The countermovement jump (CMJ) consists of four sequential steps, including the countermovement, push-off, aerial, and landing (not shown in the figure). Negative CoM work is performed during the countermovement because of the lowering motion from standing upright to the zero velocity position, and positive work is performed during the push-off. The subjects were instructed to jump straight up to the five different levels marked on a ceiling pole, keeping their hands on their hips.

## 2. Methods

### 2.1. Experimental procedures

The kinematic and kinetic data (i.e., force–displacement curves) obtained from regular experimental trials (i.e., countermovement jumps) with ten healthy young subjects (10 males, mean age: 28 ± 2 yrs, mean height: 177 ± 5 cm, mean body mass: 70 ± 6 kg) who volunteered in this experiment were similar to one another and were categorized into two general types of countermovement jumps, depending on the curve shape (see the trajectories of subject-A and subject-B in figures; see details in the Appendix). In addition, the fundamental trajectory shapes were similar to the trajectory from a previously published paper (Linthorne, 2001); therefore, two representative samples (subject-A and subject-B) were selected and discussed throughout the paper (see averaged data for all subjects in the Appendix).

All the young subjects, including subject-A (male, age: 28 yr, height: 170 cm, body mass: 60 kg) and subject-B (male, age: 30 yr, height: 180 cm, body mass: 76 kg) with no leg injuries or history of balance disorder, participated in this study, after signing an informed consent form approved by the Institutional Review Board of the Korea Advanced Institute of Science and Technology (KAIST). The subjects were instructed to stand upright with their hands on their hips and to jump straight up to five different levels ranging from approximately 10% to 35% of their body heights. The highest level was nearly 92% of their maximum vertical jump heights, and the other levels were placed at equally spaced intervals of 7.5 cm. Black markers attached to a ceiling pole were used for vertical height guidance (Fig. 1). Each subject conducted five sets of five randomly ordered vertical elevations with a 1 min rest between each set. Before the data collection, the subjects rehearsed many pilot trials to become accustomed to reaching the target elevation.

### 2.2. Measurements

For each trial, the optical marker position, located at the sacrum (L5), and the ground reaction forces (GRFs) were recorded at a sampling rate of 200 Hz using motion capture cameras (Hawk®, Motion Analysis, US) and a forceplate (AccuGait®, AMTI, US). The vertical GRFs ($F_{ver}$) were integrated to estimate the velocity and position of the center of mass (CoM), with the sacral marker used to determine the integral constants (Kim and Park, 2011; Linthorne, 2001). The impulse-momentum method was then employed to calculate the take-off velocity of the CoM ($V_{to}$; Fig. 1; Eq. (1)) to estimate the vertical jump height ($H_{peak}$; Fig. 1; Eq. (2)) (Linthorne, 2001)

$$V_{to} = \frac{1}{M}\int_{t_0}^{t_{to}} (F_{ver} - Mg)\,\mathrm{d}t \qquad (1)$$

$$H_{peak} = V_{to}(t_{peak} - t_{to}) - \frac{1}{2}g(t_{peak} - t_{to})^2 + CoM_{ver}(t_{to}) - CoM_{ver}(t_0) \qquad (2)$$

where $M$, $F_{ver}$, $g$, and $CoM_{ver}$ represent the body mass, vertical force, gravity, and vertical CoM displacement measured from the sacral marker, respectively. To ensure that the vertical jump heights were estimated accurately, the motion capture data were used to reconfirm the peak values as follows:

$$H_{peak} = CoM_{ver}(t_{peak}) - CoM_{ver}(t_0) \qquad (3)$$

The optical marker positions and the GRFs were 5th-order Butterworth low-pass filtered with cut-off frequencies of 10 Hz for the motion capture data and 30 Hz for the forceplate data.

### 2.3. Fitting models to experimental data

To quantitatively understand the vertical force generation during the countermovement (i.e., while performing the negative work shown in Fig. 1) (Zelik and Kuo, 2012), the vertical force ($F_{ver}$) trajectories were curve-fitted using a combination of a semi-sinusoidal waveform (only the negative part of the sinusoidal wave)