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Mechanical work-canceling strategy modulates initial push-off force depending on vertical jump height †

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Abstract

In this study, we examined how jumping strategy changes with increasing vertical jump height from the viewpoint of mechanical work performed on center of mass (CoM) by individual sources (e.g., ground reaction force and gravity) during the countermovement period; we expected that intensity of the countermovement action would change with increasing jump height in a certain manner (e.g., linear relationship), which could be reflected in the changes of the outcome force and/or the work done by each of the individual sources through the countermovement. Six healthy young subjects were instructed to stand upright with both hands on their hips (*akimbo* posture) and to jump straight up to five different height levels, guided by black markers attached on a ceiling pole. The lowest and highest markers were located at 191 cm and 221 cm from the ground level, respectively. Kinematic and kinetic data obtained from the regular trials were used to estimate mechanical power and work, which were then analyzed to understand the change of the countermovement jump strategy with increasing vertical jump height. We found that 1) mechanical work-canceling strategy modulates initial push-off force depending on the vertical jump height, 2) the initial push-off force was directly determined by asymmetric momentum transformation, and 3) the momentum transformation may be conducted under consideration of accommodating biomechanical constraints.

Keywords: Countermovement jump; Jumping strategy; Mechanical work-canceling; Momentum transformation; Initial push-off force

1. Introduction

Humans could get benefits from countermovement action for larger push-off when jumping vertically compared with squat jump [1, 2]. From a kinematic viewpoint, the squat jump is the exact latter half of the countermovement jump, which is the sequential combination of the preliminary downward and explosive upward motions [3-6]. However, despite their similarity (e.g., sharing the kinematic motion), the countermovement jump has been reported to be significantly advantageous for the jumpers to obtain higher elevations than the squat jump [1, 7, 8]. As mentioned, the countermovement is the preliminary downward action by flexing the lower limb joints (e.g., ankle, knee, and hip), wherein the positive vertical acceleration is created to help jumpers prepare for the larger push-off at the end of the countermovement. Therefore, jumpers could start lifting their center of mass (CoM) upward with supportive vertical forces [2]. In contrast, jumpers could not obtain any supportive acceleration in the squat jump because they should start extending the lower limb joints from the static posture, having no additive acceleration (i.e., no larger vertical forces than their body weight). From a physiological viewpoint, some authors insisted that pre-stretching before muscle shortening plays a major role of allowing the muscles to build up a high-level active state [7, 9], whereas others suggested that the countermovement action enables elastic energy storage and release in the muscle and/or tendons for the enhanced work [10-12].

While investigating some of the positive effects of the countermovement on vertical jumping as shown above, various distinctive features of the countermovement jump have also been investigated across many research fields via model-based and/or human experimental study. A twenty-degree freedom neuro-musculoskeletal model was developed to investigate muscle force, work, and power output of the major lower limb muscles during the countermovement motion [13]. Multiple sets of empirical data describing peak joint torques and powers, concentric knee extension rate of torque, and jumping technique, were analyzed to understand the contribution of kinematic and kinetic parameters to inter-individual variation in countermovement jump performance [14]. Lower limb joint work, energy transport, and intra-subject variation of the joint dynamics were examined to characterize the countermovement jump between different age groups [15]. These distinctive features of the countermovement jump have been greatly

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helpful to understand comparative advantages or fundamental mechanisms of the countermovement action itself. However, not many studies have been conducted to understand how jumping strategy could be defined, and how it changes with increasing vertical jump height for countermovement.

A recent study suggested that the boundary point on the force–displacement curve can be a possible candidate to describe the countermovement strategy and its change [2]. The boundary points, as the outcomes of total work performed during the countermovement period, seem quite appropriate to describe the strategy change with increasing vertical jump height. However, the exact cause of the strategy change of the countermovement remains to be clarified.

In this study, we examined how jumping strategy changes with increasing vertical jump height from the viewpoint of mechanical work performed on CoM by individual sources (e.g., ground reaction force and gravity) during the countermovement period; we hypothesized that intensity of the countermovement action would change with increasing jump height in a certain manner (e.g., linear relationship), which could be reflected in the changes of the outcome force and/or the work done by each of the individual sources through the countermovement. According to the work-energy theorem saying that the work done on an object by a net force equals the change in kinetic energy of the object, total mechanical work performed by external forces would be cancelled out at the end of the countermovement, but the amount of the work performed by each individual source could be changed with increasing vertical jump height, possibly in a linear manner. First, kinematic and kinetic data obtained from the regular trials were used to estimate the mechanical power and work based on the lumped mass (CoM) mechanics. Second, the empirical data were then analyzed for work-canceling strategy to understand the change of the countermovement jump strategy with increasing vertical jump height. This lumped mass model-based approach would facilitate an understanding of how humans would modulate initial push-off force depending on the vertical jump height to take advantage of the countermovement action.

2. Methods

2.1 Subjects

Ten healthy young volunteers (10 males; mean age, 28±2 years; mean height, 177±5 cm; mean body mass, 70±6 kg), who reported no history of balance disorder or major lower limb injuries, participated in this study. All of the subjects signed an informed consent form before the test, which was approved by the Institutional Review Board of the Korea Advanced Institute of Science and Technology (KAIST).

2.2 Experimental procedures

All subjects jumped five different height levels, guided by black markers attached to a ceiling pole (Fig. 1). The subjects

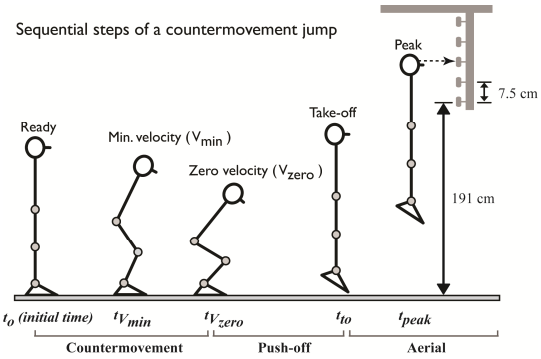

Fig. 1. Sequential steps of a countermovement jump with both hands on hips. The steps are as follows: Countermovement, push-off, aerial, and landing (not shown in the figure). The countermovement action starts from an upright standing position and ends at the lowest position with zero velocity for center of mass (CoM) kinematics. The push-off, the second step, starts at the end of the countermovement without delay and continues to move the CoM upward until its take-off. During the aerial phase, the third step, the subjects focus their sight at one of the black markers attached to a ceiling pole at their peak as requested to reach a certain amount of vertical elevation.

were instructed to stand upright with both hands on their hips (*akimbo* posture) and to jump straight up to a certain height when required to reach one of the five markers, which were used for vertical height guidance. The lowest marker was located at 191 cm vertically from the ground level, and other four markers were placed at equally spaced intervals of 7.5 cm. The five different levels corresponding to each black marker ranged from approximately 10 % to 35 % of their body heights. Each subject conducted five sets of five randomly ordered vertical elevations after rehearsing 15-20 min pilot tests to get accustomed to closely reaching the target. During the regular trials, they wore lightweight workout clothes with their bare feet, and each subject was given a 1-min break time between each set. The details of the experimental procedure have been presented previously [2].

2.3 Measurements

Kinematic and kinetic data were measured by using motion capture cameras (Hawk®, Motion Analysis, US) and a force plate (AccuGait®, AMTI, US), respectively. The reflective marker position, located at the sacrum (L5), and ground reaction forces (GRFs) were recorded at a 200-Hz sampling rate and were 5th-order Butterworth low-pass filtered with 10-Hz and 30-Hz cut-off frequencies for the motion capture and force plate data, respectively. The cut-off frequencies that decoupled white noise from the raw data by minimizing the sum of residual error were determined by a residual analysis [16-19].

The vertical GRFs (F_{ver}) and gravity force ($-M{\cdot}g$) were used to estimate the velocity and position of CoM, with the sacral marker used to determine the integral constants [1, 2, 20]. The take-off velocity of the CoM (V_{to}; Fig. 1; Eq. (1)) calculated by the impulse–momentum method was then used to

estimate the vertical jump height (H_{peak}; Fig. 1; Eq. (2)) [1, 2]:

$$V_{to} = \frac{1}{M} \cdot \int_{t_0}^{t_{to}} (F_{ver} - M \cdot g) dt \quad (1)$$

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

where M, F_{ver}, g, CoM_{ver}, t_o, t_{to} and t_{peak} represent the body mass, vertical GRFs, gravity, vertical CoM displacement measured from the sacral marker, initial time, take-off time, and elapsed time to reach the peak height (H_{peak}), respectively. The body mass was measured directly from the force plate in every single trial, but the mass variation was negligible for the same subject. The motion capture data were used to reconfirm the peak values as follows to ensure that the vertical jump heights were estimated accurately:

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

2.4 Estimation of mechanical power and work performed by GRFs and gravity on the CoM

Mechanical power was calculated by the dot product of CoM velocity and external force in vertical direction, and work performed on the CoM was estimated by the time integral of the power trajectory. The external forces, used to calculate the power, were GRFs (F_{ver}), gravity force (-Mg), and total external forces (GRFs-Mg), and were time integrated with the CoM velocity during both countermovement and push-off phase (Eqs. (4)-(6); Figs. 2 and 3):

$$W_{grf} = \int F_{ver} \cdot CoMvel_{ver} dt \quad (4)$$

$$W_g = \int (-M \cdot g) \cdot CoMvel_{ver} dt \quad (5)$$

$$W_{tot} = \int (F_{ver} - M \cdot g) \cdot CoMvel_{ver} dt \quad (6)$$

where M, g, F_{ver}, $CoMvel_{ver}$, W_{grf}, W_g and W_{tot} represent the body mass, gravity, vertical GRFs, vertical CoM velocity, work by GRFs, work by gravity, and total work performed on CoM, respectively. Time integrals were performed during t_0–t_{Vzero} and t_{Vzero}–t_{to} for countermovement work and push-off work, respectively (Figs. 1-3).

2.5 Data analysis with statistics

First, the mean CoM displacement (Fig. 2(a)), CoM velocity (Fig. 2(b)), GRFs (Fig. 2(c)) of all subjects were plotted on time domain, and the outcomes of countermovement action were extracted from those trajectories to see the change of the countermovement strategy (Figs. 2(a) and (c) insets). The outcomes were the CoM displacement and amount of the GRFs at the end of the countermovement phase (i.e., when t_{Vzero} in Fig. 1), and were tested with linear regression model to

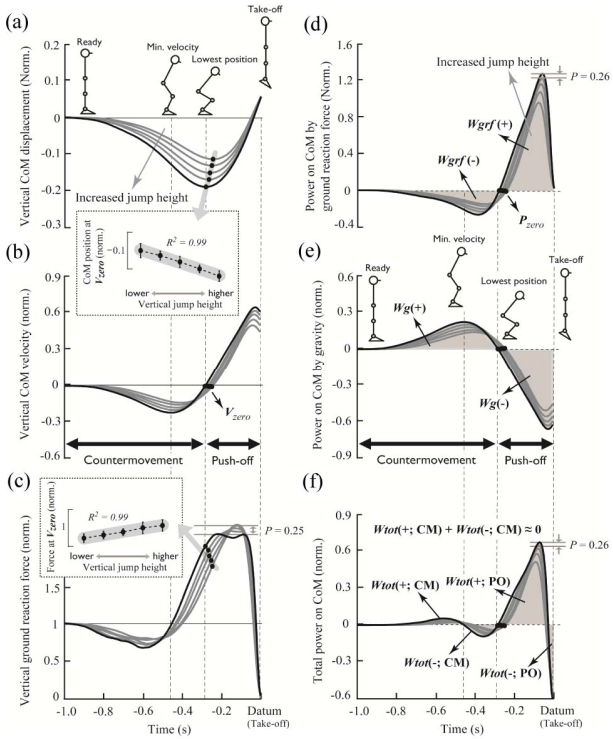

Fig. 2. The mean experimental data of all subjects during the countermovement jump: (a) Vertical CoM displacement; (b) vertical CoM velocity; (c) vertical ground reaction force (GRFs); (d) power on CoM by GRFs; (e) power on CoM by gravity; (f) total power on CoM by all external forces. The thick black solid lines represent the highest vertical jump, whereas the gray lines represent the 1st to 4th vertical jump heights. Each trajectory was shifted leftward based on the take-off time (Datum), and aligned to visibly compare with each other. The insets in (a) and (c) shows how the lowest CoM position and the amount of GRFs at zero velocity (V_{zero} in Fig. 1) change with increasing vertical jump height, where the error bars indicate standard deviations. The shaded areas in (d)-(f) indicate the time integrals of the corresponding power trajectories, i.e., work performed on CoM. The normalization methods are described in the Methods section.

see their changing trends with increasing vertical jump height. Second, the mean power of all subjects were also plotted on time domain (Figs. 2(d)-(f)) and by integrating those power trajectories, CoM work corresponding to GRFs, gravity, and total external forces were plotted with increasing vertical jump height and tested with linear regression model for both countermovement (Fig. 3(a)) and push-off (Fig. 3(b)).

To obtain the mean of the data, we normalized the CoM displacement and vertical jump height data by the body height (m), CoM velocity data by the square root of the body height multiplied by the gravitational acceleration (m/s), force data by the body weight (N), power data by the product of the body weight and the square root of the body height multiplied by the gravitational acceleration (W), and work data by the product of the body weight and body height (N·m). The differences in parameters (i.e., lowest CoM position, initial push-off force, peak vertical force, and peak power on CoM) corresponding to each vertical jump height were analyzed by using a two-

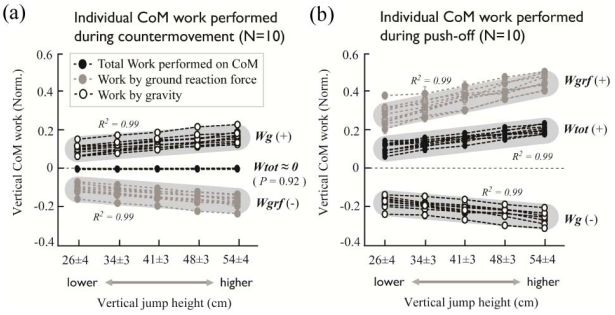

Fig. 3. Mechanical work performed on CoM during (a) countermovement; (b) push-off. Black, gray, and white circles represent total work performed on CoM (W_{tot}), work by GRFs (W_{grf}), and work by gravity (W_g), respectively. No significant difference was found in the magnitudes between W_{grf} and W_g during the countermovement (P = 0.92), regardless of vertical jump height. The thick gray-colored solid lines indicate the linear regression slopes for the average data, with the goodness-of-fit values. Error bars indicate standard deviations.

sample t-test with a significance level of $P < 0.05$. The significance of each of the reported trends from the parameter study was also tested by using regression analysis with a significance level of $P < 0.05$.

3. Results

3.1 Kinematic and kinetic data during countermovement jump

Lower CoM positions were observed in higher vertical jump ($P < 0.05$) (Fig. 2(a), inset). The subjects lowered their CoM position from "ready" to "lowest position" during the countermovement phase and again lifted up their CoM position from the "lowest position" to "take-off" during the push-off phase (Fig. 2(a)). The beginning and ending velocities of the countermovement action were inherently zero, and in-between larger downward momentum was created when jumping higher, resulting in the lower CoM position (Figs. 2(a) and (b)), indicating larger joint deviations. Sequentially, take-off velocities were necessarily linearly proportional to vertical jump height (Fig. 2(b)).

The amount of the GRFs at the lowest CoM position (i.e., at the end of the countermovement) was larger in higher vertical jump ($P < 0.05$) (Fig. 2(c), inset), whereas positive peak forces during the push-off were not significantly different regardless of the vertical jump height (P = 0.25) (Fig. 2(c)). The magnitude of the GRFs decreased below the body weight in the early part of the countermovement and abruptly increased up to about 75 % of their peak values in the last part of the same phase. The peak GRFs of the highest jump seem to be a bit lesser than those of the lowest jump, but no significant differences were found (P = 0.25).

3.2 Mechanical power and work performed on the CoM

The total mechanical power on CoM showed the sinusoidal waveforms that cross the zero line during the countermovement phase (Fig. 2(f)). The first and second half of the cycle were positive and negative, respectively, based on the minimum velocity point (i.e., when t_{Vmin} in Fig. 1; maximum downward momentum point) because the GRFs are directed opposite the CoM motion, whereas the gravity is in the same direction during the countermovement. The positive peak values of the total mechanical power on CoM were gradually saturated with increasing vertical jump height (P = 0.26) (Fig. 2(f)) mainly due to the saturation of the power on CoM by GRFs (Fig. 2(d)).

The total work performed on CoM during the countermovement were nearly zero regardless of the vertical jump height (P = 0.92) because the work performed by GRFs was equal in magnitude, but opposite in sign to that performed by gravity (Fig. 3(a)). In other words, the individual work magnitude (i.e., work by either GRFs or gravity) increased with vertical jump height, but cancelled out to compensate for one another.

Naturally, the total work performed on CoM during the push-off increased with vertical jump height (Fig. 3(b)) because the energy produced by the push-off directly determines the take-off velocity based on either energy or impulse–momentum method. The opposite sign but more positive work performed by GRFs could lead to an increasing trend of total positive work as vertical jump height increased. This was also reflected in the linear regression analysis, which clearly showed opposite signs of slope and offset but larger magnitudes of the work performed by GRFs.

4. Discussion

4.1 Mechanical work-canceling modulates initial push-off force

The subjects took advantage of the countermovement action to produce initial push-off forces larger than their body weight in opposite to squat jump, wherein the initial push-off forces are always the same with their body weight [1]. The initial push-off forces more than the body weight were achieved by mechanical work-canceling strategy during the countermovement (Figs. 3 and 4). Positive work performed by gravity contributed to generating downward momentum in the early part of the countermovement, whereas negative work performed by GRFs mainly contributed to generating resistive force against the downward momentum in the latter half of the countermovement, resulting in the total work cancelled out (i.e., mechanical work-canceling). The work-canceling occurred regardless of the vertical jump height, but it produced a larger initial push-off force with increasing vertical jump height, implying that the work-canceling strategy modulate initial push-off force depending on the jump height. In other words, the subjects gradually changed their jumping strategy by modulating the intensity of their countermovement action based on the target height. This could also mean that humans may be aware of their body dynamics and select an appropriate movement strategy to meet the task goals.

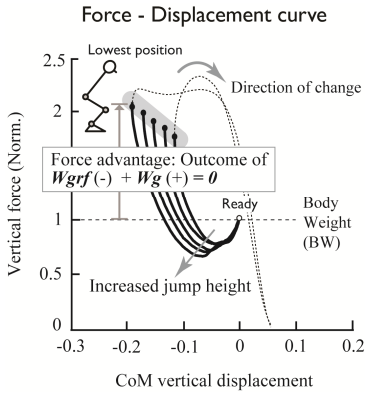

Fig. 4. Mean force–displacement curves of all subjects. The black solid and dotted lines represent the countermovement and push-off, respectively. The dotted lines are displayed only for the first and last trajectories. The solid circles marked at the end of the countermovement indicate the zero velocity position (V_{zero}; lowest CoM position), and the thick gray line overlapping those circles indicate the scaling trend. The gray arrows represent the extension of the trajectories with increasing vertical jump height and the direction of change during the countermovement jump.

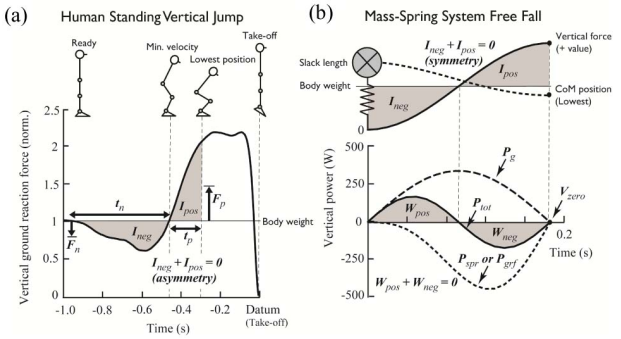

Fig. 5. (a) Vertical GRFs during the countermovement jump. The shaded areas, which are time integrals of the GRFs, show how the downward momentum (I_{neg}) is transformed to the positive impulse (I_{pos}), generating positive force advantage (F_{adv} = initial push-off – body weight) during the countermovement. The time duration is shortened ($t_n \rightarrow t_p$), whereas time-averaged GRFs is increased ($F_n \rightarrow F_p$) in the latter half of the countermovement, by asymmetrically reshaping the downward momentum; (b) vertical displacement, vertical force, and power trajectories of a free-falling object attached on top of the typical Mass-Spring system. P_{tot}, P_g, P_{spr}, P_{grf} and V_{zero} indicate the total power on CoM, power by gravity, power by spring, power by GRFs, and the lowest CoM position, respectively. The shaded areas indicate the time integrals of the corresponding trajectories: Impulse (upper; I_{neg} and I_{pos}) and work (bottom; W_{pos} and W_{neg}). The shapes of the impulse and the work in the first half of the cycle are exactly matched with those of the latter half of the cycle.

4.2 Asymmetric impulse shaping determines force advantages

Force advantage (F_{adv}), which means the difference between the outcome GRFs at the end of the countermovement and subject's body weight (i.e., F_{adv} = initial push-off – body weight) (Fig. 4), is determined by how the downward momentum produced in the early part of the countermovement is reshaped during the latter part of the countermovement (Fig. 5(a)), based on the law of momentum conservation. In the experiment, the duration time of the latter part of the countermovement was significantly shortened compared with the early part, whereas the time-averaged force was significantly increased to obtain benefits from having force advantages (Fig. 5(a)).

The non-zero acceleration (i.e., non-zero force advantage) at zero velocity (i.e., zero power) can also be found in the typical Mass-Spring system (Fig. 5(b)). In free fall or general oscillation of the passive compliant system with or without having initial velocities, trajectories of the total CoM power would show sinusoidal waveforms that cross the zero line, as shown in the countermovement jump, resulting in non-zero acceleration at the lowest position. However, the impulse shape of the first half of the cycle is exactly matched with that of the latter half of the cycle due to the passiveness of the system, as opposed to human jumping. This implies that the countermovement action may be difficult to be described only with a passive component but needs some additive ones for actively transforming the downward momentum, with a framework of the lumped mass (CoM) dynamics. This could also be explained with the concept of work-energy theorem. The work done by only conservative forces (e.g., gravitational force and spring force) is equal to the change in potential energy as shown in the typical Mass-Spring system (Fig. 5(b)), while the work done by the net force including both conservative force (e.g., gravitational force) and non-conservative force (e.g., applied force) is equal to the change in kinetic energy as shown in human vertical jumping (Figs. 4 and 5(a)). In short, the force advantage is not just an outcome of natural dynamics, meaning that the countermovement action or its momentum transformation mechanism cannot be described by a simple passive dynamic model having only conservative-force-components, unlike other human movements such as walking, running, and some other motions.

4.3 Countermovement strategies accommodating max. force production

Joint power and/or torque would be generally limited to produce a certain level due to physiological limitations [21-24], which was reflected in our study that showed the saturation of the total power on CoM with increasing vertical jump height (Figs. 2(d) and (f)). However, in contrast to our expectation, the amount of peak vertical forces was not significantly different across the vertical jump height ($P = 0.25$) (Fig. 2(c)), which was similarly shown in the results mentioning the apparent paradox of larger GRFs in sub-maximal jumps compared with maximal jumps [25]. Instead, the subjects recruited the different strategies that use either larger time-averaged force or longer time duration with increasing vertical jump height to increase total work performed during the push-off. In the physiological viewpoint, why the subjects recruited the same amount of peak vertical forces in different heights is

unclear; however, the amount of peak GRFs seems to be at work as a limiting factor (i.e., biomechanical constraints) for vertical jumping.

Acknowledgments

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