KJSB

Korean Journal of Sport Biomechanics 2017; 27(2): 141-147
http://dx.doi.org/10.5103/KJSB.2017.27.2.141
http://e-kjsb.org eISSN 2093-9752

ORIGINAL

Countermovement Jump Strategy Changes with Arm Swing to Modulate Vertical Force Advantage

Seyoung Kim

Department of Robotics and Mechatronics, Korea Institute of Machinery and Materials, Daejeon, South Korea

Received : 07 February 2017
Revised : 23 May 2017
Accepted : 24 May 2017

Corresponding Author
Seyoung Kim
Department of Robotics and Mechatronics Korea Institute of Machinery and Materials 156 Gajeongbuk-Ro Yuseong-Gu Daejeon 34103, South Korea
Tel : +82-42-868-7614
Fax : +82-42-868-7611
Email : seyoungkim@kimm.re.kr

Objective: We obtained force-displacement curves for countermovement jumps of multiple heights and examined the effect of an arm swing on changes in vertical jumping strategy. Countermovement jumps with hands on hips (Condition 1) and with an arm swing (Condition 2) were evaluated to investigate the mechanical effect of the arm movement on standing vertical jumps. We hypothesized that the ground reaction force (GRF) and/or center of mass (CoM) motion resulting from the countermovement action would significantly change depending on the use of an arm swing.

Method: Eight healthy young subjects jumped straight up to five different levels ranging from approximately 10% (~25 cm) to 35% (~55 cm) of their body heights. Each subject performed five sets of jumps to five randomly ordered vertical elevations in each condition. For comparison of the two jumping strategies, the characteristics of the boundary point on the force-displacement curve, corresponding to the vertical GRF and the CoM displacement at the end of the countermovement action, were investigated to understand the role of arm movement.

Results: Based on the comparison between the two conditions (with and without an arm swing), the subjects were grouped into type A and type B depending on the change observed in the boundary point across the five different jump heights. For both types (type A and type B) of vertical jumps, the initial vertical force at the start of push-off significantly changed when the subjects employed arm movement.

Conclusion: The findings may imply that the jumping strategy does change with the inclusion of an arm swing, predominantly to modulate the vertical force advantage (i.e., the difference between the vertical force at the start of push-off and the body weight).

Keywords: Standing vertical jump, Arm movement, Force-displacement curve, Jumping strategy

INTRODUCTION

A standing vertical jump with a countermovement requires body muscles to contract quickly and explosively to cause the body's center of mass (CoM) to move against gravity to a higher position (Chiu, Bryanton, & Moolyk, 2014; Kim & Kim, 2009; Lees, Vanrenterghem, & Clercq, 2004a). The body muscles involved in altering joint angles (e.g., ankle, knee, hip, shoulder, and elbow) necessarily serve as important power sources for vertical jumping (Lee et al., 2015; Lee & Lee, 2010; Lees et al., 2004a). Among these body parts, arm-related joints such as the shoulder and the elbow can be selectively utilized because the arms are located above the CoM; these joints can also be merged into the upper extremity to be treated as one unit (Cheng, Wang, Chen, Wu, & Chiu, 2008; Feltner, Fraschetti, & Crisp, 1999; Shetty & Etnyre, 1989; Walsh, Bohm, Butterfield, & Santhosam, 2007).

To gain an understanding of this selective body part utilization, the effects of an arm swing motion on a vertical jump have been studied by numerous research groups attempting to determine the kinematic and kinetic differences between standing vertical jumps with and without arm movement. The energy and benefits of arm swings have been investigated in terms of the energy build-up and transfer mechanisms (Lees, Vanrenterghem, & Clercq, 2004b). The energy generated by an arm swing is transferred to the rest of the body, causing the take-off velocity to increase by 1) increasing the kinetic and potential energy of the arms; 2) helping the muscles and tendons around the ankle, knee, and hip joints to store and release energy; and 3) pulling on the body through an upward force acting on the trunk at the shoulder. The effects of an arm swing on the lower extremities have also been investigated to examine how an arm swing affects the lower extremities' torque, power and work in vertical jumping (Hara, Shibayama, Takeshita, & Fukashiro, 2006; Hara, Shibayama, Takeshita, Hay, & Fukashiro, 2008). The authors suggested that the increase in the lower extremities' work that is induced by an additional load on the lower extremities due to the arm swing is the cause of the increased vertical jump height. The contributions of the motions of the body segments to the vertical ground reaction force (GRF) and the joint torques have been determined to

Copyright © 2017 Korean Journal of Sport Biomechanics
This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0/) which permits unrestricted noncommercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

better understand the role of an arm swing during a vertical jump (Feltner, Bishop, & Perez, 2004). The authors suggested that arm motion causes the arms to make a larger maximal contribution to the GRF and decreases the extensor torques at the lower-extremity joints early in the propulsion phase but augments these same extensor torques later in the propulsion phase. The effects of an arm swing on the peak vertical GRF and the peak positive power have also been investigated (Harman, Rosenstein, Frykman, & Rosenstein, 1990), and the results suggest that an arm swing significantly improves jump height, with a higher peak vertical GRF and a higher peak positive power.

From the perspective of lumped body behavior, several studies have also been conducted in which a vertical jump has been described using CoM mechanics while considering the force and motion in the same coordinate system (Kim, Park, & Choi, 2014; Linthorne, 2001). A recent study has suggested that the boundary point on the force-displacement curve can be used to describe the strategy used in a countermovement jump; this boundary point represents the outcome of the countermovement action and corresponds to the GRF and the lowest CoM position at the end of the countermovement action. The GRF at this point can be used as the seed force for the positive CoM work during push-off (i.e., the propulsion phase), whereas the lowest CoM position can be used to determine the deviations of the joints from the initial upright posture (Kim et al., 2014). The seed force, which is the force resulting from the countermovement action, represents the difference between the initial push-off force and the subject's body weight, that is, the force advantage for the subsequent push-off. Empirical data have shown that the boundary point systematically changes with increasing vertical jump height, implying that subjects gradually change their countermovement strategy to accommodate feasible force constraints without exceeding the maximum allowable force (Kim et al., 2014).

In this study, countermovement jumps with hands on hips (Condition 1) and with a free arm swing motion (Condition 2) were studied to investigate the mechanical effect of arm movement on standing vertical jumps. We hypothesized that the position of the boundary point (i.e., the GRF and/or CoM displacement resulting from the countermovement action) would significantly change depending on the use of an arm swing. To test this hypothesis, we obtained force-displacement curves for countermovement jumps of multiple heights and observed the changes in the boundary point on the force-displacement curve, using a simplified framework based on CoM mechanics.

METHODS

1. Subjects

Eight healthy young subjects (8 males, mean age: 27 ± 2 yr, mean height: 177 ± 4 cm, mean body mass: 70 ± 5 kg), who reported no history of balance disorders or major leg injuries, participated in this study. All of the subjects signed an informed consent form approved by the Institutional Review Board of the Korea Advanced Institute of Science and Technology (KAIST) prior to the test.

2. Experimental procedures

Countermovement jumps with hands on hips (Condition 1, without arm swing) and with a free arm swing motion (Condition 2) were studied to observe the mechanical effects of an arm swing on a standing

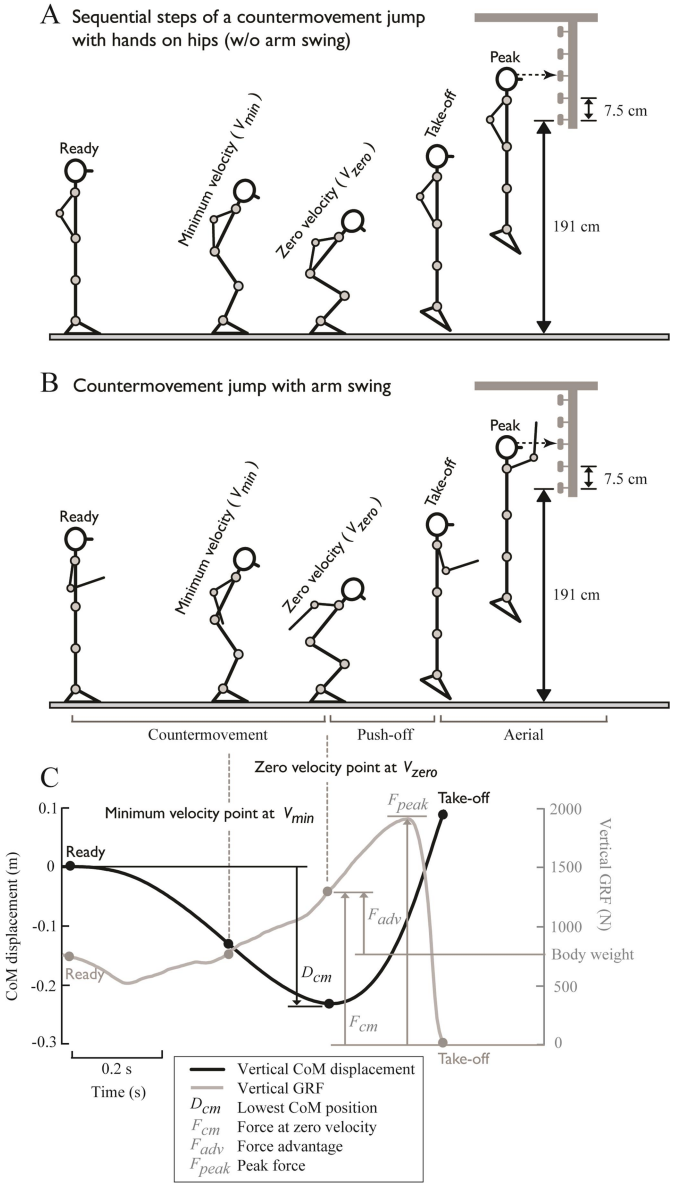

Figure 1. Simplified steps of countermovement jumps (A) without and (B) with an arm swing, pictured in the sagittal plane. A countermovement jump (CMJ) consists of four sequential stages, including the countermovement action, push-off, aerial, and landing (not shown in the figure). The downward momentum (at V_{min}) produced by lowering the center of mass (CoM) from the initial upright posture is quickly reduced to zero at the end of the countermovement (at V_{zero}), resulting in an upward CoM acceleration at the start of push-off. The impulse of the vertical GRF generated during push-off between the zero velocity point (at V_{zero}) and take-off determines the peak vertical jump height. The subjects were instructed to jump straight up to five different levels, ranging from approximately 10% to 35% of their body heights, guided by markers on a ceiling pole. (C) Representative time courses of the CoM displacement (thick black solid line) and the GRF (thick gray solid line) during a countermovement jump.

vertical jump. The subjects were instructed to stand upright and jump straight up to five different levels ranging from approximately 10% to 35% of their body heights (Figure 1). The lowest level was 191 cm above the ground, and the other levels were placed at equally spaced intervals of 7.5 cm. Black markers attached to a ceiling pole were used to guide the subjects to the corresponding heights. Each subject performed five sets of jumps to five randomly ordered vertical elevations with a 1-min rest between each set and a time interval of 30 min between Condition 1 and Condition 2. Prior to the tests for data collection, the subjects performed several practice trials to become accustomed to reaching the target elevations.

3. Measurements

A reflective marker was attached to the subject's sacrum (L5), and the three-dimensional coordinates of the marker were calculated using motion capture software (EVa Real-Time Software, EVaRTTM, US) and four motion capture cameras (Hawk®, Motion Analysis, US), whereas the GRFs were measured using a force plate (AccuGait®, AMTI, US). Both the kinematic and kinetic data were recorded at a sampling rate of 200 Hz, and the motion capture system and the force plate were synchronized with each other. The vertical GRFs were integrated over time to estimate the velocity and position of the CoM, and the synchronized data from the sacral marker were used to determine the integral constants (Kim & Park, 2011; Kim et al., 2014; Linthorne, 2001). The time integral of the impulsive force generated during the countermovement jump was then used to determine the peak vertical jump height (H_{peak}) based on the impulse-momentum method (Kim et al., 2014; Linthorne, 2001) as follows:

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

$$t_{peak} = \frac{V_{to}}{g} + t_{to} \quad (2)$$

$$H_{peak} = V_{to} \cdot (t_{peak} - t_{to}) - \frac{1}{2} \cdot g \cdot (t_{peak} - t_{to})^2 + CoM_{ver}(t_{to}) - CoM_{ver}(t_0) \quad (3)$$

where V_{to} represents the take-off velocity, M represents the body mass, F_{ver} represents the vertical GRF, g represents gravity, t_0 represents the initial time in the ready position (i.e., the upright position in which the subject stood still before beginning the countermovement action), t_{to} represents the time required for take-off from the ready position, t_{peak} represents the time required to reach the peak position from the ready position, and CoM_{ver} represents the vertical CoM displacement measured from the sacral marker (Figure 1). To ensure that the vertical jump heights were appropriately estimated, the motion capture data were also used to confirm the peak values as follows:

$$H_{peak} = CoM_{ver}(t_{peak}) - CoM_{ver}(t_0) \quad (4)$$

The optical marker positions and 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 force plate data.

4. Data analysis

The force-displacement curves for the countermovement jumps of multiple heights were obtained for all subjects and were then studied to determine whether any trend of change could be observed in the boundary point on the force-displacement curve between the sequential motion stages of countermovement and push-off (Figure 2), as characterized by the GRF and the CoM position.

All participants were grouped into type A and type B depending on the boundary point trend they exhibited. The major difference between type A and type B was the relative positions of the boundary points between the two conditions (with and without an arm swing; see Figure 3A and B). For type A, the boundary points corresponding to jumps with an arm swing lie below those corresponding to jumps without an arm swing for all jump heights (Figure 3A), whereas for type B, the boundary points corresponding to jumps with an arm swing lie above those corresponding to jumps without an arm swing for all jump heights (Figure 3B).

The steps of the initial data analysis were as follows: First, the force-displacement curves (i.e., vertical GRF vs. vertical CoM displacement) of the subjects corresponding to type A (Figures 2A and 3A) and type B (Figures 2B and 3B) were plotted to visualize the overall changes in countermovement strategy depending on the use of an arm swing. Second, the magnitudes of the vertical force (F_{cm} in Figures 1C, 3C, and 3D) and the lowest CoM position (D_{cm} in Figures 1C, 3E, and 3F) at the start of the push-off stage were plotted with linear and quadratic regression functions to quantitatively illustrate how the boundary point changes with an arm swing as the vertical jump height increases. Third, the percentages of subjects who showed significant differences in force advantage (i.e., the vertical force at the start of push-off minus the body weight; F_{adv} in Figure 1C), lowest CoM position (D_{cm} in Figure 1C), and peak vertical force (F_{peak} in Figure 1C) depending on the inclusion of an arm swing were plotted against the vertical jump height to determine which parameters are significantly affected by arm movement (Figure 4A and B).

To average the empirical data and perform a statistical comparison, we normalized the vertical jump height and CoM displacement data with respect to the subject's body height (m) and the force data with respect to the subject's body weight (N). Intra-subject data comparisons (e.g., differences in force advantage, lowest CoM position, and peak vertical force corresponding to jumps with and without an arm swing) were performed using the paired t-test with significance levels of $p < .05$ and $p < .1$, whereas within-subject differences (e.g., differences in peak vertical force) were performed using the two-sample t-test with a significance level of $p < .05$.

RESULTS

1. Force-displacement curves with and without an arm swing

The eight subjects were grouped into type A (N=6) and type B (N=2) depending on the trend due to arm movement observed in the vertical force and the CoM displacement at the boundary point at the end of the countermovement action (at V_{zero}) in the force-displacement curve (Figure 2). When the arms were allowed to swing (Condition 2), the boundary points for type A showed smaller force advantages but larger CoM displacements compared with those for jumps to the same vertical elevations with restricted arm movement (Condition 1), whereas the boundary points for type B showed larger force advantages but smaller CoM displacements (see the position of each boundary point and their relative changes in Figures 2 and 3).

Regardless of whether an arm swing was used, the boundary points gradually scaled with the vertical jump heights for all subjects of both types, whereas the maximum (peak) vertical force changed little with an increasing vertical jump height (Figures 2 and 3). Even for the highest vertical jump, the peak vertical force was not significantly different compared with that for the lowest jump (p = 0.29). The vertical force at the end of the countermovement action (F_{cm}), which can be regarded as the initial force for push-off, gradually increased with vertical jump height (Figure 3C and D), whereas the lowest CoM position (D_{cm}) just before push-off decreased with increasing vertical jump height (Figure 3E and F). The trends of change in the initial force and the lowest CoM position at the start of push-off were statistically significant for both types of subjects under both conditions (p < .05; Figure 3C, D, E, and F), with the exception of the increasing trend of the initial force observed for type B subjects in Condition 2 (Figure 3D).

The vertical forces observed between the initial upright posture ("Ready" in Figure 1) and the minimum velocity position (at V_{min}) were substantially smaller than the subjects' body weights; however, these forces drastically increased at the end of the countermovement action (at V_{zero}) (see the force-displacement curves in Figures 2 and 3). In fact, the forces resulting from the countermovement action were nearly twice as large as the body weights (see the position of each boundary point in Figures 2 and 3).

2. Significant differences between vertical jumps with and without an arm swing

The percentages of subjects who showed a significant difference in force advantage between countermovement jumps with and without an arm swing were approximately 44% for the low jump height and approximately 65% for the high jump height; these values increased to approximately 50% and approximately 73%, respectively, when the significance level (p) was doubled from 0.05 to 0.1. The corresponding percentages of subjects showing significant differences in the lowest CoM position and the peak vertical force during push-off were typically less than 40% for all vertical elevations, even with an increased significance level of p < .1 (Figure 4A and B).

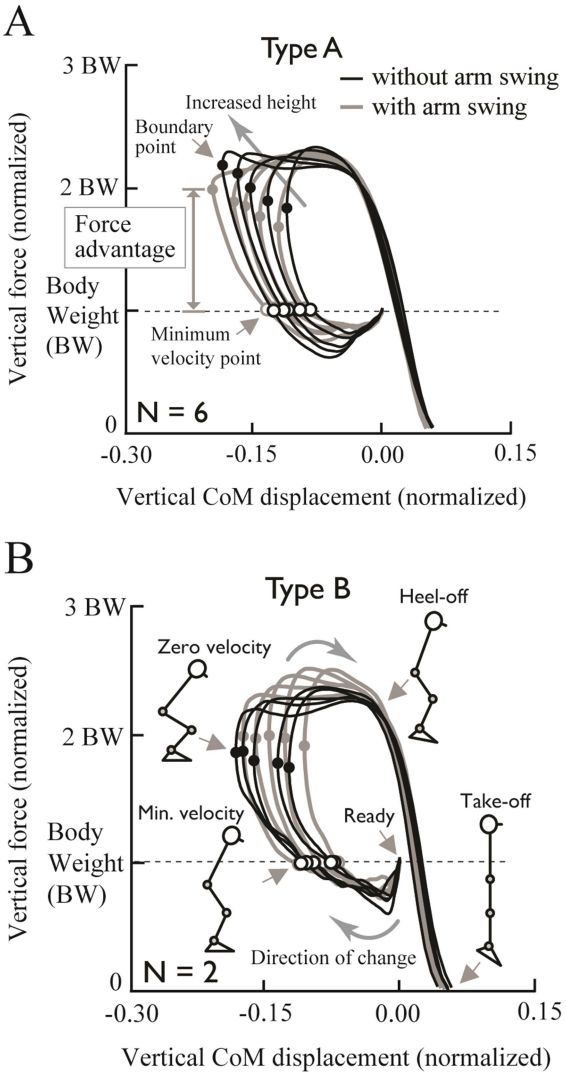

Figure 2. Average force-displacement curves corresponding to different vertical jump heights: (A) type A and (B) type B. Six subjects were assigned to type A, and two subjects were assigned to type B, according to how the boundary point changed with the use of an arm swing. The vertical CoM displacements were defined with respect to the subject's initial upright standing position ("Ready" in Figure 1), with a negative sign indicating a CoM lower than the initial one. The solid circles and hollow circles in (A) and (B) indicate the zero velocity position and the minimum velocity position, respectively, and the horizontal lines indicate the subjects' body weights. The large gray-colored arrow in (A) indicates the extension of the trajectories with increasing vertical jump height, whereas the arrows in (B) indicate the direction of change along the curve during a countermovement jump.

DISCUSSION

The countermovement action influences the boundary point, implying that the countermovement action determines the level of support for the push-off by providing an additional force and/or additional joint deviations depending on the vertical jump height. This additional force (i.e., the force advantage) is produced through a sequential process, from building downward momentum to generating resistive force, which means that the process is not one of simple direct control. Consequently,

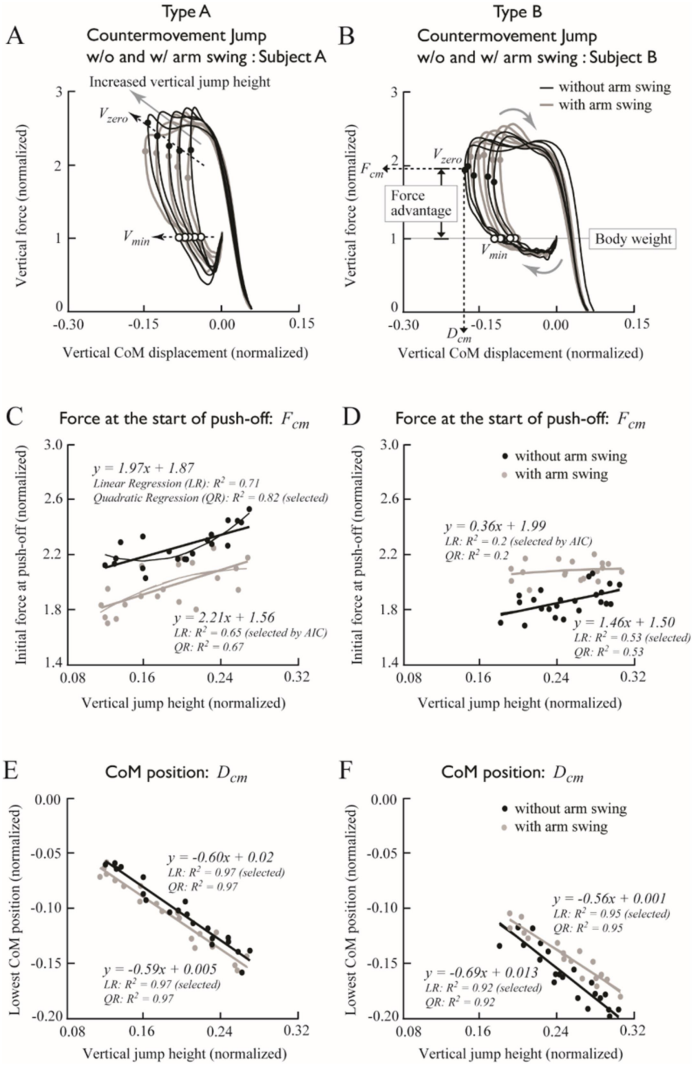

Figure 3. (A) and (B) Average force-displacement curves for subjects of type A (average over all trials for a representative subject of type A) and type B (average over all trials for a representative subject of type B). (C) and (D) Magnitude of the vertical force at the start of push-off as a function of the vertical jump height. (E) and (F) Lowest CoM position at the start of push-off as a function of the vertical jump height. The vertical CoM displacements were defined with respect to the subject's initial upright standing position, with a negative sign indicating a CoM lower than the initial one. The thick solid lines in (C), (D), (E), and (F) indicate the slopes of linear regressions of the empirical data for each subject as functions of the vertical jump height. The full equations for these curve fits are displayed in the form $y = ax + b$ along with goodness-of-fit data; in addition, quadratic regression (thin solid lines) was also used to fit the data. The most appropriate polynomial function for describing the trend of the data was selected based on the Akaike information criterion.

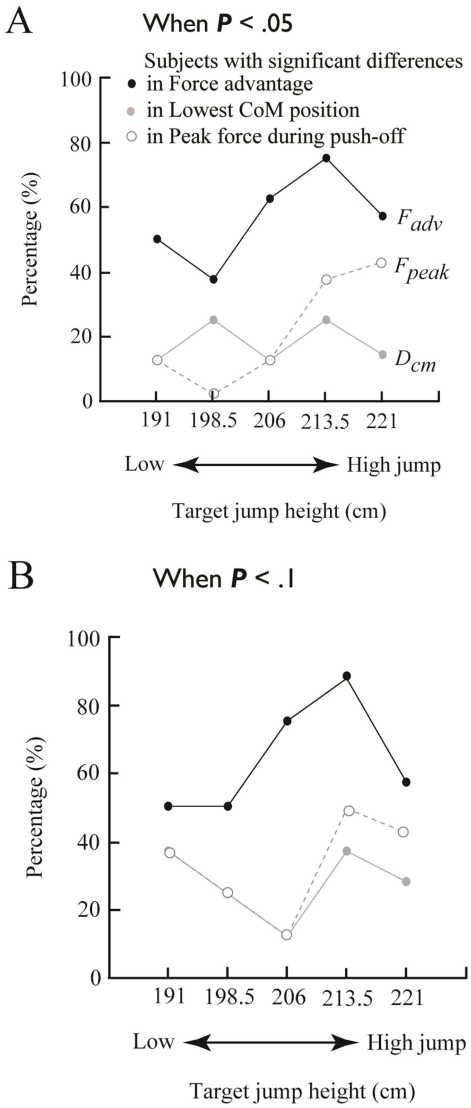

Figure 4. (A) and (B) Percentages of subjects who showed significant differences in force advantage (black circles), lowest CoM position (gray circles), and peak force during push-off (hollow circles) depending on the inclusion of an arm swing, for significance levels of (A) $p < .05$ and (B) $p < .1$. The X axis represents the target jump heights, whereas the Y axis represents the percentage of subjects showing a significant difference between the two arm swing conditions.

one might naturally expect the force advantage to be less manipulable than the CoM position, as evidenced by the finding that the initial force data (Figure 3C and D) are more scattered than the lowest CoM position data (Figure 3E and F) for all subjects. From a different perspective, the fact that the lowest CoM was more systematically modulated with the jump height than the force advantage was could suggest that humans place considerable priority on modulating energy absorption and recuperation in the form of potential energy in the muscle-tendon complex during a countermovement jump.

The countermovement strategy, as characterized by the position of the boundary point and its variation with jump height, significantly changes when a subject includes an arm swing, predominantly modulating the vertical force advantage. This finding indicates that our hypothesis holds true only for the force advantage. Although modifying the force advantage seems more challenging than altering the joint angles, the force advantages of the subjects during the countermovement action were significantly different when the arms were unconstrained, implying that the predominant change in the jumping strategy with an

arm swing is the modulation of the vertical force advantage rather than either of the other parameters, i.e., the lowest CoM position and the peak vertical force (Figure 4A and B). It is very interesting that humans are sufficiently aware of their body dynamics to manipulate their downward momentum to generate an upward acceleration to support propulsion. However, it remains unclear whether the trend observed in the vertical force advantage due to an arm swing is related to some sort of energy optimization or simply to the subjects' preferential use of different jump strategies.

Additionally, once the boundary points were determined for a specific vertical jump height, the push-off trajectories could be roughly estimated based on information describing how the positive work was performed (Figure 5A and B) because the maximum peak forces appeared to be nearly constant across the range of vertical jump heights (p > 0.2). This has similarly been shown in results addressing the apparent paradox that the GRFs are larger in sub-maximal jumps than in maximal jumps (Salles, Baltzopoulos, & Rittweger, 2011). Therefore, for example, regardless of the arm movement, if a boundary point is located at a higher vertical force but a smaller CoM displacement, the slope of the first half of the push-off trajectory must be steeper, as shown in Figure 5B. This may imply that the resulting force at the end of the countermovement action (i.e., the force advantage) and its variation with increasing vertical jump height could be the most representative quantitative characteristics of a particular countermovement jump strategy.

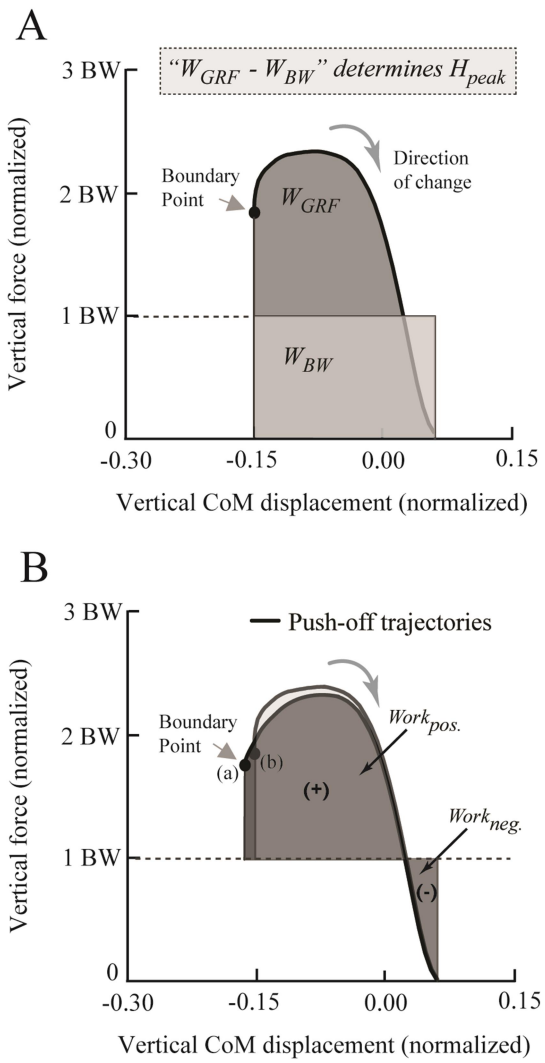

Figure 5. (A) and (B) Force-displacement curves during the push-off stage. The shaded areas in (A) represent the work done by the GRF (W_{GRF}) and the work done by the subject's body weight (W_{BW}), whereas the shaded areas in (B) represent the difference between W_{GRF} and W_{BW}. The total sum of the work performed (= W_{GRF} - W_{BW}) can be used to estimate the peak vertical jump height (H_{peak}) based on the simple work-energy method. The resultant areas (= W_{GRF} - W_{BW} = $W_{pos.}$ + $W_{neg.}$) under the two trajectories in (B) are assumed to be the same, indicating that the two cases produce the same vertical jump height. Boundary point (a) in (B) shows a smaller force advantage but a larger CoM displacement compared with boundary point (b). The large arrows indicate the direction of change along the curve over time.

CONCLUSION

We obtained force-displacement curves for countermovement jumps of multiple heights and examined the effect of an arm swing on the vertical jumping strategy. Countermovement jumps with hands on hips (Condition 1) and with a free arm swing motion (Condition 2) were evaluated to investigate the mechanical effect of arm movement on standing vertical jumps from the perspective of the relationship between force and motion. With increasing vertical jump height, the subjects' initial vertical forces at the end of the countermovement action signifi- cantly changed depending on the arm swing condition, perhaps implying that the jumping strategy changes with the inclusion of an arm swing predominantly to modulate the vertical force advantage, that is, the difference between the vertical force at the end of the countermovement action and the body weight.

ACKNOWLEDGEMENTS

This study has been supported by the R&D Program at the Korea Institute of Machinery & Materials (KIMM). The author thanks Sungwon Lee, Hyerim Lim, and Hyeob Choi for their contribution to the data collection.

REFERENCES

Cheng, K. B., Wang, C. H., Chen, H. C., Wu, C. D. & Chiu, H. T. (2008). The mechanisms that enable arm motion to enhance vertical jump performance-a simulation study. *Journal of Biomechanics*, *41*(9), 1847-1854. doi: 10.1016/j.jbiomech.2008.04.004

Chiu, L. Z., Bryanton, M. A. & Moolyk, A. N. (2014). Proximal-to-distal sequencing in vertical jumping with and without arm swing. *J Strength Cond Res*, *28*(5), 1195-1202. doi: 10.1519/jsc.0000000000000388

Feltner, M. E., Bishop, E. J. & Perez, C. M. (2004). Segmental and Kinetic Contributions in Vertical Jumps Performed with and without an Arm Swing. *Research Quarterly for Exercise and Sport*, *75*(3), 216-230. doi: 10.1080/02701367.2004.10609155

Feltner, M. E., Fraschetti, D. J. & Crisp, R. J. (1999). Upper extremity aug-

mentation of lower extremity kinetics during countermovement vertical jumps. *Journal of Sports Sciences*, *17*(6), 449-466. doi: 10.1080/026404199365768

Hara, M., Shibayama, A., Takeshita, D. & Fukashiro, S. (2006). The effect of arm swing on lower extremities in vertical jumping. *Journal of Biomechanics*, *39*(13), 2503-2511. doi: 10.1016/j.jbiomech.2005.07.030

Hara, M., Shibayama, A., Takeshita, D., Hay, D. C. & Fukashiro, S. (2008). A comparison of the mechanical effect of arm swing and countermovement on the lower extremities in vertical jumping. *Human Movement Science*, *27*(4), 636-648. doi: dx.doi.org/10.1016/j.humov.2008.04.001

Harman, E. A., Rosenstein, M. T., Frykman, P. N. & Rosenstein, R. M. (1990). The effects of arms and countermovement on vertical jumping. *Medicine & Science in Sports & Exercise*, *22*(6), 825-833. doi: 10.1249/00005768-199012000-00015

Kim, S. & Park, S. (2011). Leg stiffness increases with speed to modulate gait frequency and propulsion energy. *Journal of Biomechanics*, *44*(7), 1253-1258. doi: 10.1016/j.jbiomech.2011.02.072

Kim, S., Park, S. & Choi, S. (2014). Countermovement strategy changes with vertical jump height to accommodate feasible force constraints. *Journal of Biomechanics*, *47*(12), 3162-3168. doi: 10.1016/j.jbiomech.2014.06.013

Kim, Y.-W. & Kim, Y.-J. (2009). Biomechanical Comparison of Good and Bad Performances within Individual in Maximum Vertical Jump. *Korean Journal of Sport Biomechanics*, *19*(3), 489-497.

Lee, H.-D., Han, B.-R., Kim, J.-S., Oh, J.-H., Cho, H.-Y. & Yoon, S.-Y. (2015). Differences in the Length Change Pattern of the Medial Gastrocnemius Muscle-Tendon Complex and Fascicle during Gait and One-legged and Two-legged Vertical Jumping. *Korean Journal of Sport Biomechanics*, *25*(2), 175-182.

Lee, J.-H. & Lee, Y.-S. (2010). The Effect of Sports Taping on Lower Extremity Muscles in Vertical Jump. *Korean Journal of Sport Biomechanics*, *20*(4), 407-414.

Lees, A., Vanrenterghem, J. & Clercq, D. D. (2004a). The maximal and submaximal vertical jump: implications for strength and conditioning. *J Strength Cond Res*, *18*(4), 787-791. doi: 10.1519/14093.1

Lees, A., Vanrenterghem, J. & Clercq, D. D. (2004b). Understanding how an arm swing enhances performance in the vertical jump. *Journal of Biomechanics*, *37*(12), 1929-1940. doi: dx.doi.org/10.1016/j.jbiomech.2004.02.021

Linthorne, N. P. (2001). Analysis of standing vertical jumps using a force platform. *American Journal of Physics*, *69*(11), 1198-1204. doi: 10.1119/1.1397460

Salles, A. S., Baltzopoulos, V. & Rittweger, J. (2011). Differential effects of countermovement magnitude and volitional effort on vertical jumping. *European Journal of Applied Physiology*, *111*(3), 441-448. doi: 10.1007/s00421-010-1665-6

Shetty, A. B. & Etnyre, B. R. (1989). Contribution of arm movement to the force components of a maximum vertical jump. *J Orthop Sports Phys Ther*, *11*(5), 198-201. doi: 10.2519/jospt.1989.11.5.198

Walsh, M. S., Bohm, H., Butterfield, M. M. & Santhosam, J. (2007). Gender bias in the effects of arms and countermovement on jumping performance. *J Strength Cond Res*, *21*(2), 362-366. doi: 10.1519/r-19825.1