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Original article

# Effect of approach run velocity on the optimal performance of the triple jump

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**Abstract**

*Purpose*: The purpose of this study was to determine the effect of horizontal and vertical velocities at the landing of the last step of approach run on the performance and optimal phase ratio of the triple jump.

*Methods*: Three-dimensional kinematic data of 13 elite male triple jumpers were obtained during a competition. Computer simulations were performed using a biomechanical model of the triple jump to determine the longest actual distance using the optimal phase ratio with altered horizontal and vertical velocities at the landing of the last step of approach run.

*Results*: The actual distance obtained using the optimal phase ratio significantly increased as the horizontal velocity at the landing of the last step of approach run increased ($p = 0.001$) and the corresponding downward vertical velocity decreased ($p = 0.001$). Increasing horizontal velocity at the landing of the last step of approach run decreased optimal hop percentage and increased optimal jump percentage ($p = 0.001$), while decreasing corresponding downward vertical velocity increased optimal hop percentage and decreased optimal jump percentage ($p = 0.001$).

*Conclusion*: The effects of the velocities at the landing of the last step of approach run on the optimal phase ratio were generally small and did not qualitatively alter optimal techniques.



*Keywords:* Biomechanics; Computer simulation; Optimization; Sports; Techniques

## 1. Introduction

Triple jump is a technically and physically demanding jump event in track and field because of requirement of the three consecutive takeoffs and landings at high speeds. The three phases (jumps) of the triple jump are named as hop, step, and jump. The performance of a triple jump is determined by the official distance that is the actual distance minus distance lost at the hop takeoff.[1] The distance lost at the hop takeoff is the distance from the toe of the takeoff foot to the front edge of the takeoff board, while the actual distance is the sum of the three phase distances. Each of the hop and step distances is measured from the toe of the takeoff foot at the corresponding takeoff to the toe of landing foot at the corresponding landing. The jump distance is measured from the toe of the takeoff foot at the jump takeoff to the nearest mark the jumper made in the sand pit. All these distances are measured parallel to the runway.

The percentage of each phase distance with respect to the actual distance is referred to as phase percentage. The ratio of the three phase percentages is referred to as phase ratio.[1] Phase ratio is a measure of effort distribution in the triple jump and has been identified as a critical factor that affects the performance of the triple jump.[1] In terms of phase ratio, triple jump techniques were categorized as (1) hop dominant, (2) jump dominant, and (3) balanced.[1] Previous studies have demonstrated that an optimum phase ratio exists for a given triple jumper that yields the longest actual distance.[2,3] The optimum phase ratio for a given triple jump is mainly determined by a parameter named as velocity conversion coefficient that is the slope of the linear relationship between the loss in the horizontal velocity and the gain in the vertical velocity for the given athlete.[2,3] A recent study demonstrates that phase ratio significantly affects the actual distance of the triple jump.[4]

Biomechanically, approach run velocity is another factor that affects the performance of the triple jump. Understanding how approach run velocity and velocity conversion coefficient interactively affect the optimal phase ratio would provide

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further information for athletes and coaches to understand triple jump techniques and select optimal phase ratio to maximize performance. As a continuation of the previous study, the purpose of this study was to determine the effects of approach run velocity and velocity conversion coefficient on the optimal phase ratio and actual distance of the triple jump. We hypothesized that the horizontal and vertical velocities of approach run would affect the longest actual distance a triple jumper could achieve with optimal phase ratio. We also hypothesized that the horizontal and vertical velocities of approach run would affect the optimal phase ratio of a triple jumper with a given velocity conversion coefficient.

## 2. Methods

The subjects of this study were 13 finalists of the men's triple jump competition at the 1992 US Track and Field Olympic Team Trials (Table 1). The use of human subjects was approved by USA Track & Field. Each subject had at least one legal trial in which the subject completed the full sequence of the triple jump and was entirely videotaped for quantitative data reduction.

Two S-VHS video camcorders were used to collect three-dimensional (3D) coordinates of 21 body landmarks[5] at a frame rate of 60 frames per second with a setup for a direct linear transformation (DLT) procedure with two panning cameras.[6] A control frame with 68 control points was placed at 10 consecutive positions along the runway to form a calibration volume 24 m long, 2 m wide, and 2.5 m high in which the last two steps of the approach run, hop, step, and jump occurred.[2,6]

The real life 3D coordinates of the 21 body landmarks were obtained using the DLT procedure with panning cameras.[2,6] The raw 3D coordinates were filtered through a second-order recursive Butterworth digital filter[7] with an estimated optimum cutoff frequency of 7.14 Hz.[8,9] The 3D coordinates of the whole center of mass (COM) of each subject in each video frame were estimated using the segmental procedure.[5,10] The horizontal and vertical velocities of the COM at the takeoff and landing of the last stride of the approach run, hop, step, and jump, and the losses in horizontal velocity of the COM and gains in vertical velocity of the COM during the stances of the hop, step, and jump were estimated for each trial.[2,3,11] The takeoff and landing heights and distances of the hop, step, and jump were also estimated for each trial. The takeoff and landing distances of each phase were defined as the horizontal distances between the COM and the toe in the last frame in which the toe was on the ground before the flight and in the first frame in which the toe was on the ground after the flight, respectively.[4] Takeoff and landing heights of each phase were defined as the vertical coordinates of the COM relative to the ground in the last frame in which the takeoff foot was on the ground before the flight and in the first frame in which the landing foot was on the ground after the flight, respectively.[4]

Table 1
Subjects and performances ($n = 13$).

| | Height (m) | Mass (kg) | Actual distance of analyzed trial (m) |
|---|---|---|---|
| Mean | 1.86 | 74.4 | 16.94 |
| SD | 0.04 | 5.3 | 0.70 |
| Maximum | 1.93 | 84.1 | 18.05 |
| Minimum | 1.78 | 62.7 | 15.45 |

Computer simulations were performed using a simulation model of the triple jump developed and validated in previous studies[2–4] to determine the effects of horizontal and vertical velocities of approach run on the optimal phase ratio and longest actual distance with a given velocity conversion coefficient that is defined as the slope of the linear relationship between the loss in horizontal velocity and gain in vertical velocity during each stance.[2] Each phase distance was expressed as the sum of the takeoff, flight, and landing distances in the model. The flight distance was expressed as a function of takeoff velocities and height, and landing height using equations for projectile movements. The horizontal takeoff velocity of a given phase was expressed as the sum of the horizontal landing velocity of the previous phase and the loss in the horizontal velocity during the given stance. The vertical takeoff velocity of a given phase was expressed as the sum of the vertical landing velocity of the previous phase and the gain in the vertical velocity during the given stance. The loss in the horizontal velocity during each stance ($\Delta v_{x,i}$) was expressed as a function of the gain in the vertical velocity ($\Delta v_{z,i}$):[2,3]

$$\Delta v_{x,i} = A_0 + P_i B_0 + A_1 \Delta v_{z,i}$$

($i = 1$ for the hop, $i = 2$ for the step, $i = 3$ for the jump; $P_1 = 0$, $P_2 = P_3 = 1$)

$A_1$ is the velocity conversion coefficient. The relationships of $A_0$ and $B_0$ with $A_1$[3] were expressed as

$$A_0 = 0.946 - 2.976 A_1$$

$$B_0 = -0.296 - 1.167 A_1$$

The horizontal and vertical velocities of the COM at the landing of the last stride of approach run before hop takeoff were referred to as the horizontal and vertical velocities of approach run (Fig. 1).

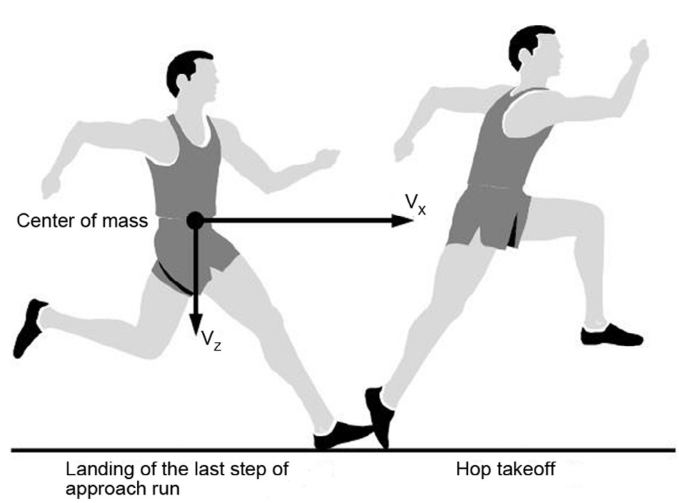


Fig. 1. Horizontal and vertical velocities of approach run in the triple jump.

A computer simulation was performed for each subject. In each computer simulation, the horizontal and vertical velocities of approach run were varied from 8 to 11 m/s with an increment of 1 m/s, and from −0.5 to −1.1 m/s with an increment of 0.2 m/s, respectively. These ranges of variations in horizontal and vertical velocities of approach run were obtained from the database of the Biomechanical Service Program for Horizontal Jumps at University of Iowa supported by USA Track & Field from 1988 to 1996. The velocity conversion coefficient was also varied from 0.3 to 1.3 with an increment of 0.2 to determine possible interaction effects of velocity conversion coefficient and approach run velocity on performance and optimal phase ratio. An optimization was performed for the longest actual distance with optimized phase ratio at each combination of the horizontal and vertical velocities of approach run and velocity conversion coefficient. A total of 96 optimizations were performed for each subject, which yielded 96 simulated sets of data for each subject.

In each optimization, gains in the vertical velocity during the stances of the hop, step, and jump were optimized for the longest actual distance a given subject could achieve as described by Yu and Hay.[2] The phase ratio corresponding to the longest actual distance was considered as the optimal phase ratio for the given combination of horizontal and vertical velocities of approach run and velocity conversion coefficient. The gains of the vertical velocity during the support phases of the hop, step, and jump were constrained to the lower and upper bounds of the gain in the vertical velocity. To ensure the technical and physical feasibility of the optimization results, the lower bound of the gain in the vertical velocity during each stance was set as the minimum gain in the vertical velocity resulting in a loss in the horizontal velocity during the given stance,[2,3] while the upper bound of the gain in vertical velocity was set as the observed maximum gain in the vertical velocity for three stances of the given subject. The increment of the gain in vertical velocity in each support phase was 0.2 m/s. The vertical velocity at the takeoff of each phase was also constrained with a lower bound of 0.2 m/s and an upper bound of the maximum vertical velocity at the takeoff of all three phases observed for the given subject. The takeoff and landing heights and distances of the hop, step, and jump phases were considered as constants for each subject and represented by the observed means of the corresponding parameters of the subject.

Three regression analyses were performed to determine the effects of horizontal and vertical velocities of approach run on the optimal performance of the triple jump using 1248 simulated data points (96 optimizations/subject × 13 subjects). The dependent variables were longest actual distance ($D_o$), optimal hop percentage ($P_h$), and optimal jump percentage ($P_j$). The independent variables were velocity conversion coefficient ($A_1$), and horizontal and vertical velocities of approach run ($v_x$ and $v_z$). The full regression model for each analysis was

$$y = a_0 + a_1 A_1 + a_2 A_1^2 + (b_1 + b_2 A_1) v_x + (c_1 + c_2 A_1) v_z + d_1 v_x v_z$$

where $a_i$, $b_i$, $c_i$, and $d_i$ were regression coefficients. The main interests of each analysis was in all the terms including $v_x$ or/and $v_z$. The inclusion of $A_1$ and $A_1^2$ in the regression analyses was based on the results of the previous study[4] that demonstrated a non-linear relationship between $A_1$ and $D_o$ with a given set of $v_x$ and $v_y$. A backward selection procedure was employed to determine the best regression equation for each analysis. The best regression equation is the regression equation in which (1) the overall regression was significant, (2) the contribution ($\Delta r^2$) of the term alone or with other terms as a group to the overall regression was no less than 0.01; and (3) the contribution was significant. The regression determinant ($r^2$) was also determined as a measure of the quality of the best regression equation. A Type I error rate less than 0.05 was chosen as the indication of statistical significance. All statistical analyses were performed using version 5.03 of the SYSTAT statistical computer program package (SYSTAT Software, Inc., Chicago, IL, USA). Tables of optimal phase ratios and performances of the triple jump were developed based on the regression results.

## 3. Results

The best regression equation for the longest actual distance obtained using optimal phase ratio was

$$D_o = 1.12 - 3.72 A_1 + 3.20 A_1^2 + 1.62 v_x + 1.05 A_1 v_z$$

with a regression determinant of 0.99. The combined contribution of $A_1$ and $A_1^2$ to the regression determinant was 0.04 ($p = 0.001$), while the contributions of $v_x$ and $A_1 v_z$ to the regression determinant were 0.94 ($p = 0.001$) and 0.01 ($p = 0.001$), respectively (Fig. 2). The best regression equation showed that the greater the horizontal velocity of approach run was, the longer the actual distance would be, and that the less the downward vertical velocity of approach run was, the longer the actual distance would be. The effect of the downward vertical velocity of approach run on the longest actual distance increased as the velocity conversion coefficient increased. The effect of horizontal velocity of approach run on the longest actual distance within the corresponding range of variation in this study was 4.5 m regardless the magnitude of velocity conversion coefficient (Fig. 2). The effect of vertical velocity of approach run on the longest distance within the corresponding range of variation in this study was 0.25 m with a velocity conversion coefficient of 0.25, and 0.85 m with a velocity conversion coefficient of 1.30 (Fig. 2).

The best regression equation for the optimal hop percentage was

$$P_h = 58.51 - 47.04 A_1 + 21.87 A_1^2 + 0.31 v_x + 5.12 A_1 v_z$$

with a regression determinant of 0.80 ($p = 0.001$). The combined contribution of $A_1$ and $A_1^2$ to the regression determinant was 0.73 ($p = 0.001$), while the contributions of $v_x$ and $A_1 v_z$ to the regression determinant were 0.02 ($p = 0.006$) and 0.05 ($p = 0.001$), respectively (Fig. 3). The best regression equation showed that the greater the horizontal velocity of approach run was, the greater the optimal hop percentage would be, and that the less the downward vertical velocity of approach run was, the greater the optimal hop percentage would be. The effect of the downward vertical velocity of approach run on the

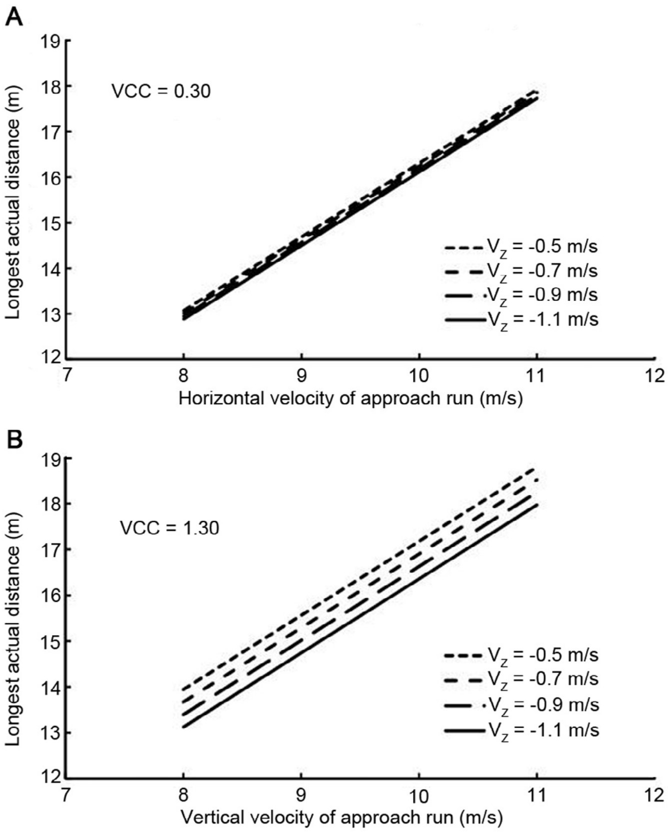


Fig. 2. Effects of horizontal (A) and vertical (B) velocities of approach run and velocity conversion coefficient (VCC) on performance of the triple jump. $v_z$ = vertical velocity of approach run.

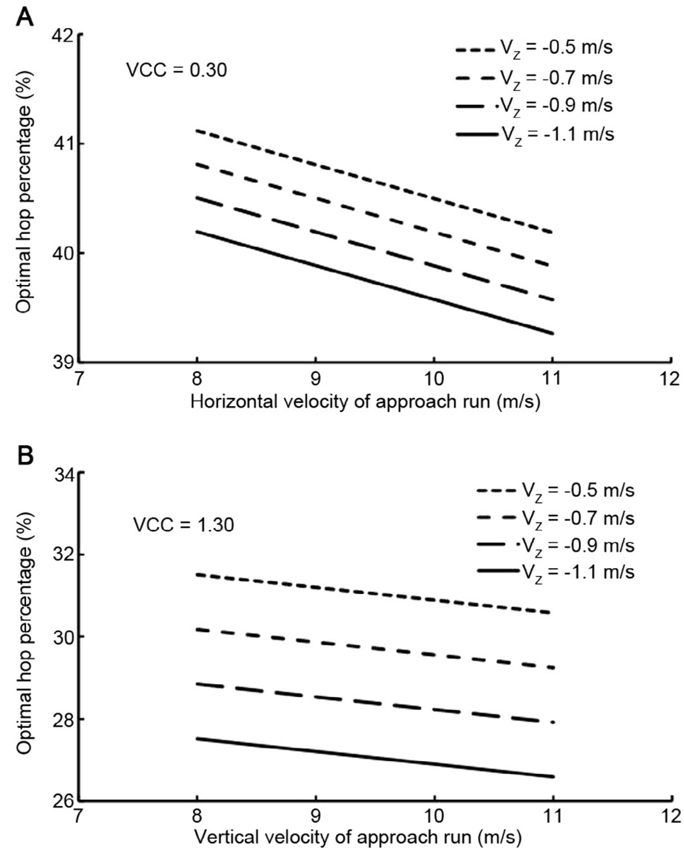


Fig. 3. Effects of horizontal (A) and vertical (B) velocities of approach run and velocity conversion coefficient (VCC) on optimal hop percentage of the triple jump. $v_z$ = vertical velocity of approach run.

optimal hop percentage increased as the velocity conversion coefficient increased. The effect of horizontal velocity on the optimal hop percentage within the corresponding range of variation was no greater than 1% regardless of the magnitude of velocity conversion coefficient (Fig. 3). The effect of vertical velocity on the optimal hop percentage was less than 1% with a velocity conversion coefficient of 0.30, and 4% with a velocity conversion coefficient of 1.30 (Fig. 3).

The best regression equation for the optimal jump percentage was

$$P_j = 21.39 - 38.07A_1 - 21.50A_1^2 + 0.25v_x - 0.51A_1v_z$$

with a regression determinant of 0.76. The combined contribution of $A_1$ and $A_1^2$ to the regression determinant was 0.73, while the contributions of $v_x$ and $v_z$ to the regression determinant were 0.01 ($p = 0.009$) and 0.02 ($p = 0.006$), respectively (Fig. 4). The best regression equation showed that the greater the horizontal velocity of approach run was, the greater the optimal jump percentage would be, and that the greater the downward vertical velocity of approach run was, the greater the optimal jump percentage would be. The effect of the downward vertical velocity of approach run on the optimal jump percentage increased as the velocity conversion coefficient increased. The effects of horizontal and vertical velocities on the optimal jump percentage were less than 1% within corresponding ranges of variations in this study regardless of the magnitude of velocity conversion coefficient (Fig. 4).

## 4. Discussion

The results of this study support our first hypothesis that the horizontal and vertical velocities of approach run significantly affected the longest actual distance a triple jump could achieve. The results of this study demonstrated that within the ranges of the variation of the horizontal velocity of approach run and the coefficient of velocity conversion, the horizontal velocity of approach run explained 94% of the variance of the longest actual distance. The results of this study also demonstrated that the effect of horizontal velocity of approach run on the performance of the triple jump with optimal phase ratio was substantial. These results are consistent with the observations by Zissu.[12]

The results of this study also demonstrated that within the ranges of the variations of the vertical and horizontal velocities of approach run and the coefficient of velocity conversion, the vertical velocity of approach run and the coefficient of velocity conversion explained 1% of the variance of the longest actual distance. Although the vertical velocity of approach run apparently was not a primary determinant of the performance of triple jump with optimal phase ratio, a decrease in the downward vertical velocity of approach run from 1.1 to 0.5 m/s, however, could result in average increases in the longest actual distance from 0.25 to 0.85 m when velocity conversion coefficients were 0.3 and 1.3, respectively, which should be considered as substantial improvements in performance. Hay[1] defined

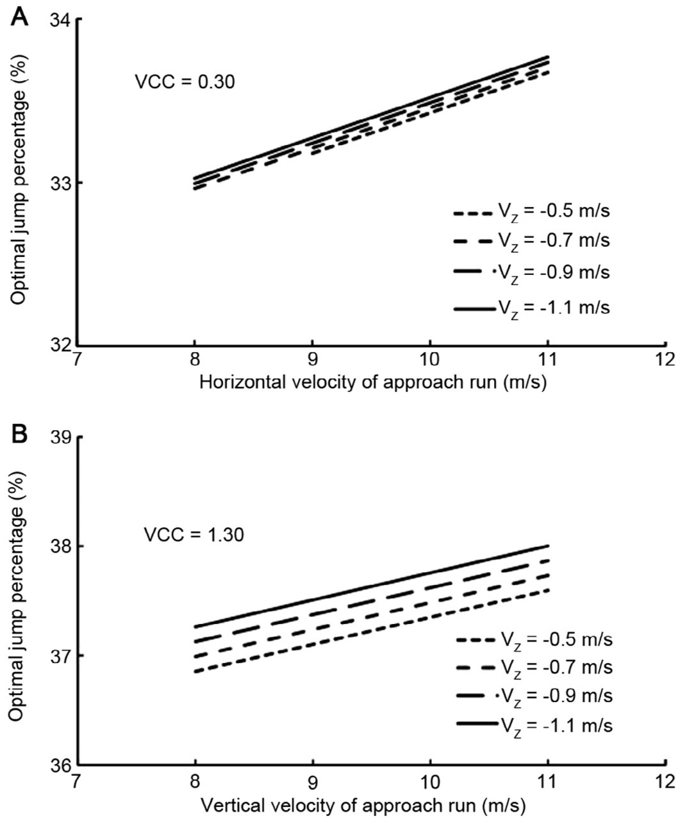


Fig. 4. Effects of horizontal (A) and vertical (B) velocities of approach run and velocity conversion coefficient (VCC) on optimal jump percentage of the triple jump. $v_z$ = vertical velocity of approach run.

three triple jump techniques in terms of phase ratio: (a) hop-dominated—the hop percentage is at least 2% greater than the next largest phase percentage; (b) jump-dominated—jump percentage is at least 2% greater than the next largest phase percentage; and (c) balanced—the largest phase percentage is less than 2% greater than the next largest phase percentage. A previous study[4] found that the hop-dominated technique is optimal when the coefficient of velocity conversion is less than or equal to 0.55, that the jump-dominated technique is optimal when the coefficient of velocity conversion is greater than or equal to 0.80, and that either hop-dominated or jump-dominated technique could be optimal when the coefficient of velocity conversion is between 0.60 and 0.75. The previous study demonstrated that the balanced technique is not an optimal technique for longest actual distance. Combined with the results of the previous study, the results of the current study suggest that the vertical velocity of approach run affected the performance of the triple jumpers whose optimal techniques were jump-dominated more than those whose optimal techniques were hop-dominated. Although some previous studies presented the vertical velocity of approach run,[13,14] no studies on the correlation between the vertical velocity of approach run and the actual distance of the triple jump were found.

The vertical velocity of approach run affected the performance of the triple jump through different mechanisms for different optimal phase ratios. The vertical velocity of approach run affected the performance of the triple jump with hop dominated techniques as optimal techniques because of the constraint to the maximum gain in the vertical velocity during hop takeoff. The maximum gain in the vertical velocity during each takeoff in the biomechanical model of the triple jump used in this study was constrained to the observed maximum gain in the vertical velocity a triple jumper had to ensure that the simulation results were realistic.[2,3] The constraint to the maximum gain in the vertical velocity during the hop takeoff was active in hop dominated techniques. As the gain in the vertical velocity reached its maximum, the greater the downward vertical velocity of approach run, the less the vertical velocity at the hop takeoff, and consequently the shorter the hop distance. The vertical velocity of approach run affected the performance of the triple jump with jump dominated techniques as optimal techniques because the vertical velocity of approach run affects the loss in horizontal velocity during the hop takeoff. Although the vertical velocity at the hop takeoff was the minimum for the jumper to complete the hop when a jump dominated technique is used, the gain in vertical velocity during hop takeoff, however, has to be increased when the downward vertical velocity of approach run is increased, which would increase the loss in the horizontal velocity during the hop takeoff.[2,3] The increased loss in the horizontal velocity during the hop takeoff would affect not only the hop distance but also the step and jump distances as well, which is consistent with the observations by Fukashiro et al.[15] and Zissu.[12]

The results of this study do not support our second hypothesis that the horizontal and vertical velocities of approach run significantly affect the optimal phase ratio. The results demonstrated that increasing the horizontal velocity of approach run would make the optimal phase ratio more jump dominated, while reducing the vertical velocity of approach run would make the optimal phase ratio more hop dominated. The results also demonstrated that the regression coefficients for the vertical velocity of approach run in the regressions for hop and jump percentages were greater than those for the horizontal velocity, and that the contributions of the vertical velocity of approach run to the regression determinants of the regression for the hop and jump percentages were greater than those of the horizontal velocity. These results suggest that the vertical velocity of approach run had greater effect on the optimal phase ratio than did the horizontal velocity of approach run. The results also suggest that the vertical velocity of approach run had greater effect on the optimal phase ratio for the triple jumpers whose optimal techniques were jump-dominated in comparison to the triple jumps whose optimal techniques were hop-dominated. Although the effect of horizontal velocity of approach run on the optimal phase ratio was statistically significant, the regression coefficient showed that the effect was small. Changing horizontal velocity of approach run did not qualitatively alter the optimal techniques in terms of phase ratio within the ranges of the variations of the horizontal velocity in this study.

Only male triple jumpers were included in this study. Female triple jumpers may have different physical and technical characteristics that may alter the relationship between the approach run velocity and the performance of the triple jump. Female triple jumpers may need to be included in future studies. Also, vertical jumping ability is another variable that may significantly affect the optimal phase ratio and longest distance in the triple jump. The vertical jumping ability is represented by the constraint to the maximum gain in the vertical velocity in the biomechanical model of the triple jump in this study. Future studies are needed to determine how this constraint affects the optimal phase ratio and performance of the triple jump. With known effects of these factors on the optimal phase ratio, a table of optimal phase ratio will be developed for athletes to find the optimal phase ratios for themselves. In addition, the takeoff and landing heights and distances were considered as constants in the optimization in this study. Previous studies, however, demonstrated that this limitation did not result in substantial errors in the optimization results.[2]

## 5. Conclusion

The horizontal and vertical velocities of approach run at the landing of the last step of approach run before the hop takeoff substantially affect the longest distance with optimal phase ratio. Triple jumpers should maintain a great horizontal velocity and minimize the downward vertical velocity at the landing of the last step of approach run before the hop takeoff, which would significantly improve their performances. The horizontal and vertical velocities of approach run do not substantially affect the optimal phase ratio in the triple jump.

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