

# Horizontal-to-vertical velocity conversion in the triple jump

BING YU

*Division of Physical Therapy, The University of North Carolina at Chapel Hill, CB #7135 Medical School Wing E, Chapel Hill, NC 27599-7135, USA*

Accepted 26 March 1998

The aim of this study was to determine the effects of selected factors on horizontal-to-vertical velocity conversion in the triple jump. An understanding of this conversion is important not only for studies on the techniques of the triple jump, but also for other jumping events. Ten elite jumpers were studied. Three-dimensional kinematic data were collected for at least four complete trials in the same competition for each athlete. The loss in horizontal velocity and the gain in vertical velocity during each support phase were calculated for each trial. The loss in horizontal velocity was found to be a linear function of the gain in vertical velocity. The slope of this linear function,  $A_1$ , is referred to as the horizontal-to-vertical velocity conversion coefficient. The loss in horizontal velocity increased as the gain in vertical velocity increased. The sensitivity of the loss in horizontal velocity to the gain in vertical velocity increased as the magnitude of  $A_1$  increased. Further studies are required on the optimum techniques of the triple jump.

*Keywords:* kinetic energy, optimization, sport biomechanics, triple jump, velocity.

## Introduction

A triple jump consists of an approach run followed by a hop (a take-off from one foot and a landing on the same foot), a step (a take-off from one foot and a landing on the other foot) and a jump (a take-off from one foot and a landing on both feet in the sand pit). Because the triple jump has three consecutive take-offs and landings at high speed, the event is technically and physically more demanding than the long and high jumps and the pole vault, each of which has one take-off and landing.

During each support phase of the triple jump, athletes gain vertical velocity for the take-off following the support phase. Simultaneously, they inevitably lose horizontal velocity. To attain the longest possible jump, the loss in horizontal velocity during each support phase has to be minimized while gaining vertical velocity (Hay and Miller, 1985), because losing horizontal velocity tends to shorten the overall distance jumped. A recent study on triple jump techniques (Yu and Hay, 1996) found that the loss in horizontal velocity can be expressed as a linear function of the gain in vertical velocity during each support phase of the triple jump for each individual athlete. The slope of this linear function,  $A_1$ , is referred to as the horizontal-to-vertical velocity

conversion coefficient. The relationship between the loss in horizontal velocity and the gain in vertical velocity appears to be crucial in determining the optimum phase ratio in the triple jump for a given athlete (Yu and Hay, 1996). The phase ratio, defined as the ratio of the three phase distances (Hay, 1992), plays a key role in determining the distance jumped by a given athlete (Yu and Hay, 1996).

Hay and Miller (1985) suggested that maintaining horizontal velocity while gaining vertical velocity is an important task in the triple jump (Hay and Miller, 1985). The relationship between the loss in horizontal velocity and the gain in vertical velocity, found by Yu and Hay (1996), suggested that the gain in vertical velocity occurs at the expense of horizontal velocity during each support phase of the triple jump. The results of their study indicated that there is a conversion of horizontal velocity to vertical velocity during each support phase of the triple jump. Furthermore, this relationship suggests that, in terms of the loss in horizontal velocity, the efficiency of the gain in vertical velocity may be affected by the gain in vertical velocity and the horizontal-to-vertical velocity conversion coefficient. An understanding of these effects is essential for an enhanced understanding of the effects of the

phase ratio on the overall distance jumped, and provides the basis for further biomechanical studies on the optimum phase ratio and other factors in triple jump techniques and training.

The aim of this study was to examine the effects of the gain in vertical velocity and the horizontal-to-vertical velocity conversion coefficient on horizontal-to-vertical velocity conversion during each support phase of the triple jump.

## Methods

### Data collection

Ten elite triple jumpers (six males and four females) were studied, including four of the finalists of the men's triple jump competition in the 1992 US Olympic Trials, two of the finalists of the men's triple jump competition in the 1995 US Track and Field Championships, two of the finalists of the women's triple jump competition in the 1990 TAC Championships, and two of the finalists of the women's triple jump competition in the 1995 US Track and Field Championships. Each jumper had at least four legal or foul trials in which they completed the full sequence of the jump (that is, the jump was not aborted partway through); these were videotaped in their entirety.

A direct linear transformation procedure with panning cameras (Yu *et al.*, 1993) was used to collect three-dimensional coordinates of 21 body landmarks. Two S-VHS video cameras were used to record the control object and the performances of the jumpers at a frame rate of 60 Hz. Each camera was panned by rotating about a fixed axis. A tape with black and white stripes was placed on each side of the triple jump runway and used to determine the panning position for each camera. During the calibration procedure, a control object with 68 control points was placed in different locations on the triple jump runway to establish a control volume that covered the space in which the last two steps of the approach run, the hop, the step and the jump occurred. A global reference frame was defined so that the x-axis was parallel to the runway pointing in the jumping direction; the y-axis was perpendicular to the x-axis pointing to the left of the runway; and the z-axis was perpendicular to the surface of the runway and pointing upwards. Details of this data collection procedure are given elsewhere (Yu *et al.*, 1993; Yu and Hay, 1995, 1996).

### Data reduction

The videotape records of the control object and each of the selected trials were digitized with the aid of a S-VHS

videocassette recorder, a 14-inch colour monitor, a microcomputer and Peak2D computer software (Peak Performance Technologies, Denver, CO). The record of each selected trial from each camera was digitized at a sampling frequency of 60 Hz from two fields before the touchdown of the second last stride to two fields after the landing in the sand pit. Touchdown or landing was defined as the first field showing the jumper on the ground following a flight phase. Take-off was defined as the last field showing the jumper on the ground during a support phase. In each digitized field, 21 body landmarks defining a 14-segment model of the human body (Clauser *et al.*, 1969) were digitized. Control volume calibrations, mathematical time-synchronization of the digitized two-dimensional data from the two cameras, and the transformation from digitized two-dimensional coordinates to real-life three-dimensional coordinates were all conducted on a microcomputer using specially written computer software.

The real-life three-dimensional coordinates of the 21 body landmarks were filtered using a fourth-order Butterworth digital filter (Winter *et al.*, 1974). The optimum cut-off frequency was estimated from the sampling frequency (Yu and Hay, 1995). The estimated optimum cut-off frequency for the three-dimensional coordinates in this study was 7.4 Hz (Yu and Hay, 1995). The three-dimensional coordinates of the centre of mass of the whole body were calculated using the basic segmental procedure described by Hay (1993) and the segment inertial data of Clauser *et al.* (1996).

The horizontal velocity of the whole-body centre of mass at take-off in the support phase  $i$  ( $v_{x(\text{to}), i}$ ) was calculated using the equation:

$$v_{x(\text{to}), i} = \frac{x_{(\text{td}), i+1} - x_{(\text{to}), i}}{\Delta t}$$

where  $x_{(\text{td}), i+1}$  is the  $x$ -coordinate of the whole-body centre of mass at touchdown in the support phase  $i+1$ ;  $x_{(\text{to}), i}$  is the  $x$ -coordinate of the whole-body centre of mass at take-off in the support phase  $i$ ; and  $\Delta t$  is the duration of the flight phase after the support phase  $i$ . The horizontal velocity of the whole-body centre of mass at touchdown in the support phase  $i+1$ ,  $v_{x(\text{td}), i+1}$ , was equated with  $v_{x(\text{to}), i}$  by neglecting air resistance.

The vertical velocities of the whole-body centre of mass at take-off in the support phase  $i$  and touchdown in the support phase  $i+1$ ,  $v_{z(\text{to}), i}$  and  $v_{z(\text{td}), i+1}$ , were calculated using the equations:

$$v_{z(\text{to}), i} = \frac{z_{(\text{td}), i+1} - z_{(\text{to}), i} + 0.5 g \Delta t^2}{\Delta t}$$

$$v_{z(\text{td}), i+1} = v_{z(\text{to}), i} - g \Delta t$$

where  $z_{(to),i}$  and  $z_{(td),i+1}$  are the  $z$ -coordinates of the whole-body centre of mass at take-off in the support phase  $i$  and the touchdown in the support phase  $i+1$ ; and  $g$  is acceleration owing to gravity.

The loss in horizontal velocity and the gain in vertical velocity of the whole-body centre of mass during a given support phase were calculated using the equations:

$$\Delta v_{x,i} = v_{x(td),i} - v_{x(to),i}$$

$$\Delta v_{z,i} = v_{z(to),i} - v_{z(td),i}$$

where  $\Delta v_{x,i}$  and  $\Delta v_{z,i}$  are the loss in horizontal velocity and the gain in vertical velocity of the whole-body centre of mass, respectively, during support phase  $i$ .

### Data analysis

A multiple-regression analysis with dummy variables (Kleinbaum *et al.*, 1987) was conducted to determine the relationship between  $\Delta v_x$  and  $\Delta v_z$  during the three support phases for each jumper. A multiple-regression analysis with dummy variables is a statistical procedure used to develop and compare different regression equations using a single multiple-regression model. The dummy variables in this kind of regression analysis are used to distinguish different regression equations. The regression model suggested by the results of a previous study (Yu and Hay, 1996) was used here in full:

$$\Delta v_{x,i} = A_0 + B_0 P_i + A_1 \Delta v_{z,i} + B_1 P_1 \Delta v_{z,i} \quad (1)$$

where  $A_0$ ,  $B_0$ ,  $A_1$  and  $B_1$  are regression coefficients, and  $P_i$  is a dummy variable denoting different support phases.  $P_i$  was assigned a value of zero for the support phase of the hop ( $i=1$ ) and a value of 1 for the support phases of the step ( $i=2$ ) and jump ( $i=3$ ). The assignment of these values yielded:

$$\Delta v_{x,1} = A_0 + A_1 \Delta v_{z,1}$$

for the support phase of the hop and:

$$\Delta v_{x,i} = (A_0 + B_0) + (A_1 + B_1) \Delta v_{z,i} \quad (i=2,3)$$

for the support phases of the step and the jump.

A forward elimination procedure was used to determine the optimum regression equation and the magnitudes of  $A_0$ ,  $B_0$ ,  $A_1$  and  $B_1$  for each jumper. The 0.05 level of confidence was chosen to indicate the statistical significance of each regression coefficient and the overall regression.

The regression coefficient  $A_1$  was referred to as the horizontal-to-vertical velocity conversion coefficient (Yu and Hay, 1996). Yu and Hay (1996) reported that the regression coefficients  $A_0$  and  $B_0$  were functions of

$A_1$ . In this study, a second-order polynomial regression model was used to determine the relationships between  $A_1$  and the other regression coefficients that contributed significantly to the prediction of  $\Delta v_{x,i}$ . A forward elimination procedure was used to determine the best regression equations for the relationships between  $A_1$  and the other regression coefficients. The 0.05 level of confidence was used to determine the best regression equations.

To examine the effects of  $A_1$  on the relationship between  $\Delta v_{x,i}$  and  $\Delta v_{z,i}$ ,  $\Delta v_{x,i}$  was estimated from  $\Delta v_{z,i}$  with selected magnitudes of  $A_1$ . The magnitudes of  $\Delta v_{z,i}$  and  $A_1$  were in their observed ranges. The magnitudes of  $A_0$ ,  $B_0$  and  $B_1$  were estimated from  $A_1$  using the best regression equations for these coefficients as functions of  $A_1$ .

To examine the effects of  $A_1$  on the optimum phase ratio and overall distance jumped, the phase ratio for each jumper was optimized for the longest overall distance jumped. The gains in vertical velocity during the three support phases were used as the independent variables. The horizontal and vertical velocities at the touchdown of the hop, touchdown and take-off height and distance of each support phase, and landing distance of a given jumper were treated as the constant and represented by the corresponding means of the jumper. The magnitude of  $\Delta v_{x,i}$  was estimated from  $\Delta v_{z,i}$  using the relationship between  $\Delta v_{x,i}$  and  $\Delta v_{z,i}$  for a given subject. The details of the optimization model can be found in Yu and Hay (1996).

## Results

A linear relationship between  $\Delta v_{x,i}$  and  $\Delta v_{z,i}$  was obtained for each subject (Fig. 1 and Table 1). The best regression equation for this relationship for each subject was exclusively in the form:

$$\Delta v_{x,i} = A_0 + B_0 P_i + A_1 \Delta v_{z,i} \quad (2)$$

This equation, using values of  $P_i$  for different support phases, yielded:

$$\Delta v_{x,1} = A_0 + A_1 \Delta v_{z,1}$$

for the support phase of the hop and:

$$\Delta v_{x,i} = (A_0 + B_0) + A_1 \Delta v_{z,i} \quad (i=2,3)$$

for the support phases of the step and jump. The correlation coefficients for overall regressions ranged from 0.71 to 0.95, with  $P$ -values less than 0.013 (Table 1).

The regression coefficients  $A_0$  and  $B_0$  were functions of  $A_1$  (Fig. 2). The relationships can be expressed as follows:

$$A_0 = 0.946 - 2.976 A_1 \quad (3)$$

$$B_0 = -0.296 - 1.167 A_1^2 \quad (4)$$

There was no evidence to suggest that these relationships were significantly different between male and female athletes (Fig. 2).

The magnitude of  $A_1$  had a significant effect on the relationship between  $\Delta v_{x,i}$  and  $\Delta v_{z,i}$  (Fig. 3). For a small gain in vertical velocity, the greater the magnitude of  $A_1$  and the smaller the loss in horizontal velocity. For a large gain in vertical velocity, the lower the magnitude of  $A_1$  and the smaller the loss in horizontal velocity. The sensitivity of the loss in horizontal velocity to the gain in vertical velocity increased as the magnitude of  $A_1$  increased.

The optimization results (Table 2) show a trend that jump-dominated techniques (Hay, 1992) are optimum for athletes with high values of  $A_1$  ( $A_1 > 0.6$ ), and that hop-dominated or balanced (Hay, 1992) techniques are

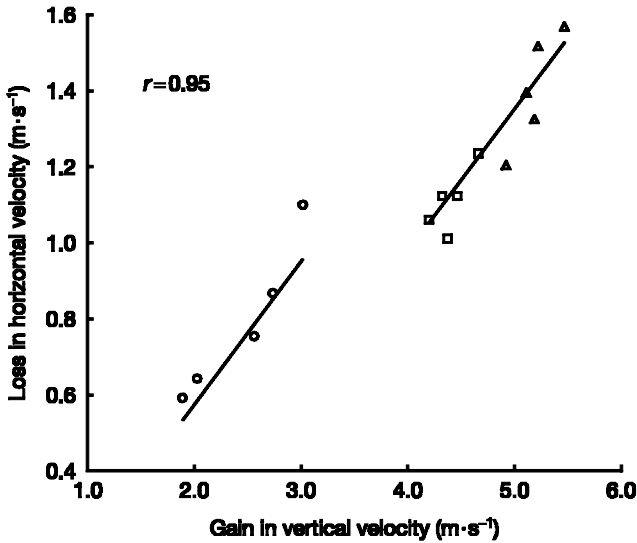
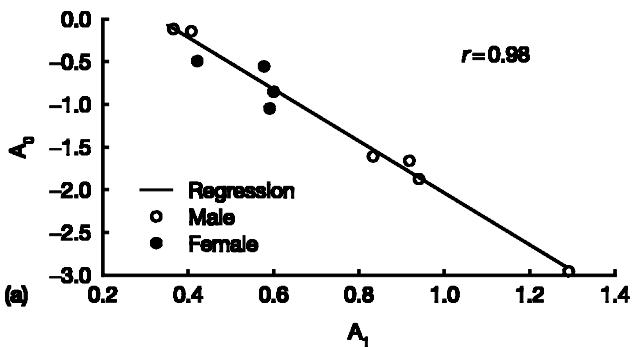


Figure 1 The relationships between the loss in horizontal velocity and the gain in vertical velocity during the three support phases for one jumper.



generally optimum for athletes with low values of  $A_1$  ( $A_1 < 0.6$ ). The optimization results also show a trend for the distance jumped to be longer for jumpers with high values of  $A_1$  than for jumpers with low values of  $A_1$  (Table 2).

### Discussion

The relationship between  $\Delta v_{x,i}$  and  $\Delta v_{z,i}$  for each jumper in this study (equation 2) was consistent with that reported previously (Yu and Hay, 1996). This relationship suggests that the loss in horizontal velocity during each support phase was a linear function of the gain in vertical velocity during the same support phase. Furthermore, this relationship suggests that the effect of the gain in vertical velocity on the loss in horizontal velocity was the same for all three support phases for a given athlete. This relationship also suggests that, for

Table 1 Regression coefficients ( $A_1$ ,  $A_0$  and  $B_0$ ) for the linear relationships between the loss in horizontal velocity and the gain in vertical velocity, correlation coefficients ( $r$ ) for overall regressions, and  $P$ -values of the overall regression

Jumpers	$A_1$	$A_0$	$B_0$	$r$	$P$
<b>Males</b>					
<i>(n = 6)</i>					
A	1.299	-2.959	-2.263	0.815	0.001
B	0.946	-1.876	-1.180	0.885	0.000
C	0.924	-1.666	-1.453	0.896	0.000
D	0.837	-1.619	-1.053	0.941	0.000
E	0.408	-0.180	-0.614	0.710	0.008
F	0.366	-0.157	-0.348	0.952	0.000
<b>Females</b>					
<i>(n = 4)</i>					
G	0.602	-0.875	-0.811	0.740	0.003
H	0.592	-1.068	-0.618	0.763	0.013
I	0.579	-0.585	-0.894	0.723	0.012
J	0.422	-0.525	-0.410	0.827	0.000

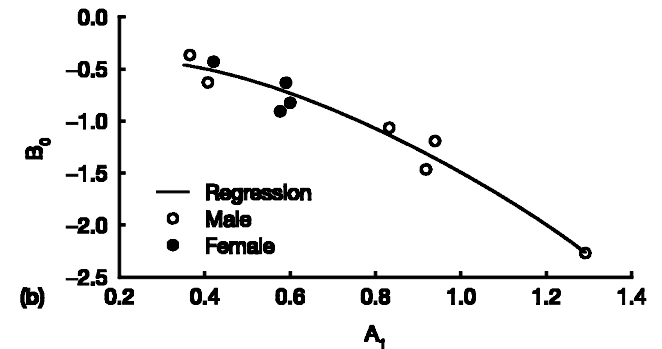
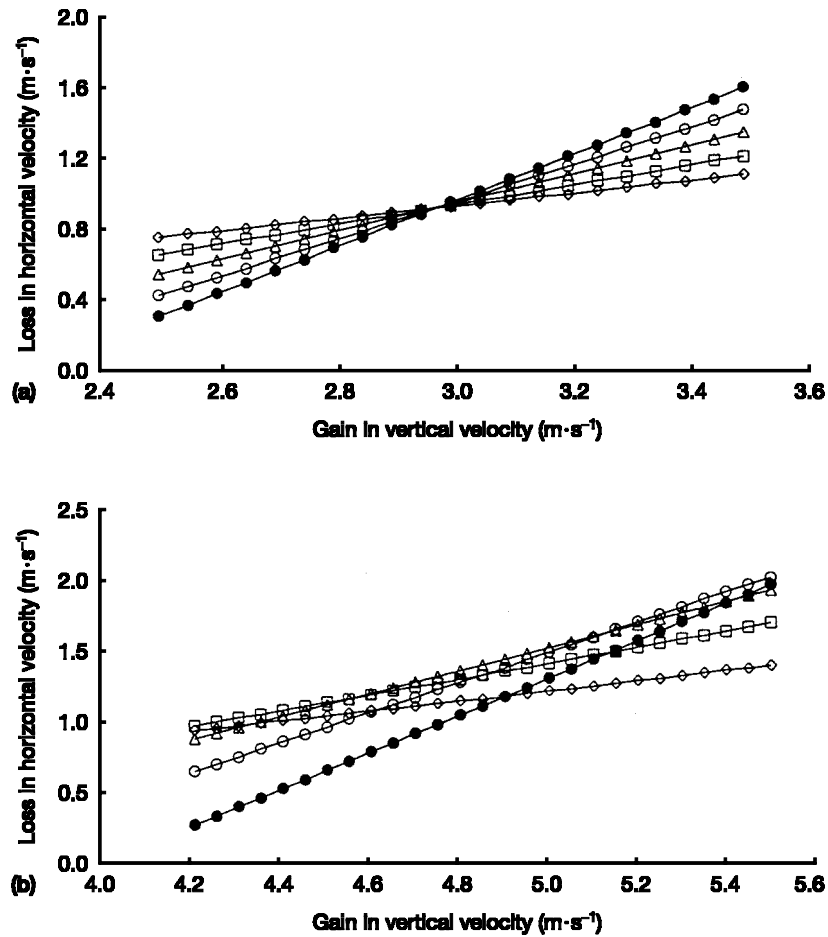


Figure 2 The relationships between regression coefficients: (a)  $A_0$  vs  $A_1$ ; (b)  $B_0$  vs  $A_1$ .



**Figure 3** The effects of the horizontal-to-vertical velocity conversion coefficient  $A_1$  on the relationship between the loss in horizontal velocity and the gain in vertical velocity during the three support phases. Horizontal-to-vertical velocity conversion during (a) the hop and (b) the step and jump.  $\diamond$ ,  $A_1 = 0.35$ ;  $\square$ ,  $A_1 = 0.55$ ;  $\triangle$ ,  $A_1 = 0.80$ ;  $\circ$ ,  $A_1 = 1.05$ ;  $\bullet$ ,  $A_1 = 1.30$ .

**Table 2** Optimized phase distances, phase ratios and corresponding overall distances jumped

Jumpers	$A_1$	Phase distance (m)			Phase ratio	Overall distance (m)
		Hop	Step	Jump		
<b>Males</b>						
<i>(n = 6)</i>						
A	1.299	5.48	5.48	7.31	30:30:40	18.27
B	0.946	4.91	5.26	7.36	28:30:42	17.52
C	0.924	5.13	5.68	7.52	28:31:41	18.33
D	0.837	4.92	4.47	6.96	30:27:43	16.36
E	0.408	6.28	5.26	5.43	37:31:32	16.97
F	0.366	5.79	4.75	6.39	34:28:38	16.93
<b>Females</b>						
<i>(n = 4)</i>						
G	0.602	4.95	3.79	5.52	35:27:39	14.27
H	0.592	4.99	4.06	4.44	37:30:33	13.49
I	0.579	5.07	3.90	4.83	37:28:35	13.80
J	0.422	5.14	4.33	5.08	35:30:35	14.55

the same gain in vertical velocity, the loss in horizontal velocity during the support phase of the hop was  $B_0 \text{ m} \cdot \text{s}^{-1}$  more than that in the support phase of the step or jump.

The relationships between regression coefficients obtained in this study were qualitatively consistent with those obtained previously (Yu and Hay, 1996), when only four male athletes were studied. The quantitative discrepancies in these relationships between the two studies are probably a result of sampling error; they had no significant effect on the relationship between the optimum phase ratio and the magnitude of  $A_1$  (Yu and Hay, 1996).

The relationship between the loss in horizontal velocity and the gain in vertical velocity during each support phase is a result of horizontal-to-vertical kinetic energy conversion during the support phase. The kinetic energy due to the vertical velocity possessed by an athlete at the take-off of a support phase derives from two sources: the mechanical energy possessed by the athlete at the touchdown of a support phase and the chemical energy released through muscle contractions during the support phase (Witters *et al.*, 1992). The kinetic energy due to horizontal velocity constitutes a major part of the total mechanical energy possessed by the athlete at the touchdown of the support phase. Part of this kinetic energy is stored in the muscles and tendons in the form of strain energy through the eccentric contractions of the muscles of the support leg during the first part of the support phase, and then released in the vertical direction through concentric contractions of the same muscles during the second part of the support phase. The greater the gain in vertical velocity due to the gain in kinetic energy in the vertical direction, the greater the loss in kinetic energy in the horizontal direction, and thus the greater the loss in horizontal velocity.

The 'horizontal' kinetic energy can also be converted to 'vertical' kinetic energy by swinging motions of the arms and free leg. Consider the mechanical energy conversion in the motion of a simple pendulum. When the centre of mass of the pendulum is in its lowest position, the kinetic energy possessed by the pendulum is entirely due to the velocity in the horizontal direction. This kinetic energy is converted to gravitational potential energy and kinetic energy in the vertical direction while the pendulum is moving up. When the pendulum is in the horizontal position, the kinetic energy is entirely due to the velocity in the vertical direction. The swinging motions of the arms and free leg during each support phase are similar to the motion of a simple pendulum. The results of a recent study on the techniques of elite triple jumpers (Yu, 1993) showed that the velocity of the centre of mass of each arm or free leg owing to its swinging motions was basically in the horizontal direc-

tion at the touchdown of each support phase, and in the vertical direction at take-off. As an athlete swings his or her arms and free leg more vigorously at the touchdown of a support phase, the kinetic energy in the horizontal direction possessed by the arms and free leg at this time increases, and thus more kinetic energy is converted to the vertical direction during the support phase. The results of Yu (1993) suggest that the swinging motions of the arms and free leg are responsible for up to 19% of the loss in horizontal velocity and up to 12% of the gain in vertical velocity of the centre of mass during the three support phases of the triple jump. The results of that study further suggest that the loss in horizontal velocity and the gain in vertical velocity owing to the swinging motions of the arms and free leg are correlated with each other. These results support the belief that the 'horizontal' kinetic energy is converted to 'vertical' kinetic energy by the swinging motions of the arms and the free leg.

The magnitude of  $A_1$  is related to the efficiency of horizontal-to-vertical kinetic energy conversion. Witters *et al.* (1992) described the take-off of the long jump using a mechanical energy model. In their model, the efficiency of recovery of horizontal kinetic energy,  $\alpha$ , was used to express the gain in vertical kinetic energy as the loss in horizontal kinetic energy and mechanical energy from other sources:

$$\Delta v_z^2 = \alpha [v_{x(\text{td})}^2 - (v_x - \Delta v_x)^2] + v_a^2 \quad (5)$$

where  $v_a^2$  represents all contributions to  $\Delta v_z^2$  that are independent of the loss in horizontal kinetic energy. Equation (5) can be reorganized as follows:

$$\alpha \Delta v_x^2 - 2\alpha v_{x(\text{td})} \Delta v_x - v_a^2 + \Delta v_z^2 = 0 \quad (6)$$

Solving equation (6) for  $\Delta v_x$ :

$$\Delta v_x = v_{x(\text{td})} + \sqrt{v_{x(\text{td})}^2 + \frac{v_a^2}{\alpha} - \frac{v_z^2}{\alpha}} \quad (7)$$

Comparing equations (2) and (7), the magnitude of  $A_1$  is probably related to the magnitude of  $1/\alpha^{1/2}$ . This means that the lower the magnitude of  $A_1$ , the more efficient the horizontal-to-vertical kinetic energy conversion during the take-off.

The magnitude of  $A_1$  may be a reflection of some physical or technical characteristics of the athlete. One possibility is that the magnitude of  $A_1$  for a given athlete is a function of the maximum contraction speed of his or her muscles or the maximum force that his or her muscles are capable of generating, because the maximum muscle contraction speed and force may affect the force-velocity relationship of the muscle and the efficiency of the conversion of the strain energy to

kinetic energy (Pandy *et al.*, 1990; Anderson and Pandy, 1993). Another possibility is that the magnitude of  $A_1$  is a function of leg stiffness, which is the ratio of force generated by the leg and the compression distance of the leg. Farley and González (1996) reported that leg stiffness for maximum compression of the leg during the stance phase of running had a significant effect on the efficiency of kinetic-to-elastic and elastic-to-kinetic energy conversion.

Lees *et al.* (1993) pointed out that it is important to place the take-off foot well in front of the whole-body centre of mass at touchdown and keep the take-off leg as stiff as possible during the support phase to minimize the loss in horizontal velocity during the long jump take-off. The results of the present study, combined with those of previous studies, indicate that, if the magnitude of  $A_1$  is related to some technical characteristics, a low magnitude of  $A_1$  is probably associated with a long touchdown distance and relatively little knee flexion during the take-off. In contrast, a large magnitude of  $A_1$  is probably associated with a short touchdown distance and relatively large knee flexion during the take-off. This suggests that the support phases of the triple jump, especially the hop and step, should be similar to that of running, and that an active landing technique (Koh and Hay, 1990) may be more important for the triple jump than for the long jump. To a certain extent, this notion is supported by the results of the study of Koh and Hay (1990) on landing leg motion in the triple jump. Although the results of that study did not show a significant correlation between landing leg motion and performance in the triple jump, they did show that there was a trend for the touchdown distance of the hop in the triple jump to be shorter than that of the last stride in the long jump, and that there was a trend for the active landing leg motion to have a greater first-order correlation coefficient with performance in the triple jump than in the long jump.

The magnitude of the loss in horizontal velocity was sensitive to the magnitude of the gain in vertical velocity, especially for large  $A_1$  (Fig. 3). The results suggest that, for a given magnitude of  $A_1$ , the greater the magnitude of the gain in vertical velocity, the greater the magnitude of the loss in horizontal velocity. The magnitude of the two were virtually independent for a low magnitude of  $A_1$ .

The magnitude of the loss of horizontal velocity was sensitive to the magnitude of  $A_1$  as well (Fig. 3). The results suggest that the greater  $A_1$ , the smaller the magnitude of the loss of horizontal velocity for a small magnitude of the gain in vertical velocity, but the greater the magnitude of the former for a large magnitude of the latter. These results indicate that an athlete with a large  $A_1$  was efficient in maintaining horizontal velocity while achieving a small gain in vertical velocity. Also,

an athlete with a small  $A_1$  was efficient in maintaining horizontal velocity while achieving a large gain in vertical velocity.

The effect of  $A_1$  on the relationship between the loss in horizontal velocity and the gain in vertical velocity provides an explanation of the effect of  $A_1$  on the optimum phase ratio (Yu and Hay, 1996). Irrespective of the ability of an athlete to obtain vertical velocity during the other support phases, he or she must always jump with full effort in the vertical direction during the support phase of the jump if he or she is to achieve the longest possible distance. Whether the athlete should jump with full effort in the vertical direction during the support phases of the hop and step depends on the relationship between the loss in horizontal velocity and the gain in vertical velocity during each of the support phases. If the magnitude of the loss in horizontal velocity is not very sensitive to the magnitude of the gain in vertical velocity and is relatively low for a large magnitude of that variable, then jumping with full effort in the vertical direction during the support phase with high horizontal velocity at touchdown would result in the longest overall distance jumped. This assumes that the other conditions remain constant, such as take-off heights and distances, touchdown heights and distances, the ability to gain vertical velocity during each support phase, the magnitude of  $A_1$ , and horizontal and vertical velocities at the touchdown of the hop. The high horizontal velocity at the touchdown maximizes the positive effect of the gain in vertical velocity on the phase distance, whereas the independence of the loss in horizontal velocity on the gain in vertical velocity minimizes the negative effect of the loss in horizontal velocity on the subsequent phase distances.

With small  $A_1$ , the loss in horizontal velocity of the whole-body centre of mass is not very sensitive to the gain in vertical velocity during the support phase of the hop (Fig. 3). In addition, the horizontal velocity at touchdown of the hop is greater than that at the touchdown of the step and jump. Jumping with full effort during a support phase with the greatest horizontal velocity at the touchdown and a loss in horizontal velocity not very sensitive to the gain in vertical velocity is efficient for overall distance jumped, and certainly makes the hop distance longer than that of the other phases. Therefore, for an athlete with a small  $A_1$ , a long hop distance benefits the overall distance jumped, and a hop-dominated technique is optimum (Table 2).

With large  $A_1$ , the loss in horizontal velocity during each support phase is sensitive to the gain in vertical velocity (Fig. 3). The loss in horizontal velocity is sharply increased as the gain in vertical velocity increases during each support phase. For an athlete with a large  $A_1$ , an increase in the hop distance owing to an increased vertical jumping effort is always accompanied

by a large increase in the loss in horizontal velocity. In contrast, minimizing the gain in vertical velocity during the support phase of the hop may result in a decreased hop distance but maintain horizontal velocity for the support phases of the step and jump, and thus improve the overall distance jumped for the athlete with a large  $A_1$ . Therefore, a jump-dominated technique is optimum for an athlete with a large  $A_1$  (Table 2).

Four female athletes were recruited to this study. There was no evidence that the relationships between regression coefficients were different between male and female athletes. This indicates that the relationship discussed above between the optimum phase ratio and  $A_1$  can be applied to female athletes as well as to male athletes (Table 2).

The effect of  $A_1$  on the relationship between the loss in horizontal velocity and the gain in vertical velocity also indicates that the size of  $A_1$  may help to differentiate between elite triple jumpers and elite long jumpers. During the take-off of a long jump, the athlete needs to gain as much vertical velocity as possible with as little a loss in horizontal velocity as possible. An elite long jumper should have a small loss in horizontal velocity for a large gain in vertical velocity. The results of this study suggest that an athlete with a small  $A_1$  will experience a smaller loss in horizontal velocity for a large gain in vertical velocity than an athlete with a large  $A_1$ . Therefore, athletes with small  $A_1$  may be potential elite long jumpers. This notion is supported by the results of a previous study (Witters *et al.*, 1992), which showed that the greater the magnitude of the recovery in efficiency of kinetic energy,  $\alpha$ , the longer the distance jumped in the long jump.

The optimization results (Table 2) suggest that, in comparison to athletes with small  $A_1$ , athletes with large  $A_1$  tend to jump relative longer overall distances with optimized phase ratios. Although these results do not show the systematic effect of  $A_1$  on the overall distance jumped in the triple jump, they indicate that athletes with large  $A_1$  may be potential elite triple jumpers.

In the present study, the magnitude of  $A_1$  was estimated for each athlete using a three-dimensional video analysis technique for panning cameras. If the results of future studies reveal that the magnitude of  $A_1$  for a given athlete is related to his or her physical characteristics, as discussed here, the magnitude of  $A_1$  for that athlete may be predicted from the relevant characteristics. In the meantime, image analysis remains the only means of estimating  $A_1$ . However, the data collection procedure can be simplified by using a two-dimensional image analysis technique with multiple stationary cameras (Hay and Miller, 1985).

The relationship between the loss in horizontal velocity and the gain in vertical velocity for each athlete

was estimated using a minimum of four trials and a maximum of six trials. Two independent variables were used in the regression analysis, while each trial provided three data points. This resulted in a minimum of six and a maximum of nine for the ratio of the number of data points to the number of independent variables in the regression analyses. Even the maximum of this ratio in this study was lower than 10, which is commonly recommended for regression analysis. This relatively low ratio might affect the reliability of the estimated regression parameters. A minimum of seven trials is needed for a ratio greater than 10. However, it is not possible to have more than six trials during a competition. In addition, each athlete tends to adopt a given technique during competition and thus there is a small variation in the changes in velocity during each support phase. The small number of trials and variation in observations may also have affected the reliability of the estimated regression parameters in this study. A minimum of seven trials using different techniques in an experiment under competition conditions with the athlete at, or close to, his or her peak form, might improve the reliability of the estimated regression parameters, so long as fatigue does not occur.

## Conclusions

The results appear to warrant the following conclusions:

- The loss in horizontal velocity and the gain in vertical velocity are linearly correlated during each support phase of the triple jump.
- The loss in horizontal velocity per unit gain in vertical velocity during each support phase of the triple jump increases as the gain in vertical velocity increases.
- The sensitivity of the loss in horizontal velocity per unit gain in vertical velocity during each support phase of the triple jump increases as the absolute value of the horizontal-to-vertical velocity conversion coefficient increases.

Further studies are required for a systematic investigation of the factors that affect the magnitude of the horizontal-to-vertical velocity conversion coefficient for a given athlete and the effects of this coefficient and other factors on the overall distance jumped in the triple jump.

## References

- Anderson, F.C. and Pandy, M.G. (1993). Storage and utilization of elastic strain energy during jumping. *Journal of Biomechanics*, 26, 1413–1427.



- Clauser, C.E., McConville, J.T. and Young, J.W. (1969). Weight, volume and center of mass of segments of the human body. *AMRL Technical Report 69-70*, pp. 46–55, 59. Dayton, OH: Wright-Patterson Air Force Base.
- Farley, C.T. and González, O. (1996). Leg stiffness and stride frequency in human running. *Journal of Biomechanics*, **29**, 181–186.
- Hay, J.G. (1992). The biomechanics of the triple jump: A review. *Journal of Sports Sciences*, **10**, 343–378.
- Hay, J.G. (1993). *The Biomechanics of Sports Techniques*, 3rd edn. Englewood Cliffs, NJ: Prentice-Hall.
- Hay, J.G. and Miller, J.A. (1985). Techniques used in triple jump. *International Journal of Sport Biomechanics*, **1**, 185–196.
- Kleinbaum, D.G., Kupper, L.L. and Muller, K.E. (1987). *Applied Regression Analysis and Other Multivariable Methods*, 2nd edn. Boston, MA: PWS-KENT.
- Koh, T.J. and Hay, J.G. (1990). Landing leg motion and performance in the horizontal jumps II: The triple jump. *International Journal of Sport Biomechanics*, **6**, 361–373.
- Lees, A., Fowler, N. and Derby, D. (1993). A biomechanical analysis of the last stride, touchdown and take-off characteristics of the women's long jump. *Journal of Sports Sciences*, **11**, 303–314.
- Pandy, M.G., Zajac, F.E., Sim, E. and Levine, W.S. (1990). An optimal control model for maximum-height human jumping. *Journal of Biomechanics*, **23**, 1185–1198.
- Winter, D.A., Sidwall, H.G. and Hobson, D.A. (1974). Measurement and reduction of noise in kinematics of locomotion. *Journal of Biomechanics*, **7**, 157–159.
- Witters, J., Bohets, W. and Van Coppenolle, H. (1992). A model of the elastic take-off energy in the long jump. *Journal of Sports Sciences*, **10**, 533–540.
- Yu, B. (1993). The functions of free limbs and their relationships with the performance in the triple jump. Unpublished doctoral dissertation, The University of Iowa, Iowa City, IA.
- Yu, B. and Hay, J.G. (1995). Angular momentum and performance in the triple jump: A cross-sectional analysis. *Journal of Applied Biomechanics*, **11**, 81–102.
- Yu, B. and Hay, J.G. (1996). Optimum phase ratio in the triple jump. *Journal of Biomechanics*, **29**, 1283–1289.
- Yu, B., Koh, T.J. and Hay, J.G. (1993). A panning DLT procedure for three-dimensional videography. *Journal of Biomechanics*, **26**, 741–751.