BIOMECHANICAL STUDIES ON TRIPLE JUMP TECHNIQUES: THEORETICAL CONSIDERATIONS AND APPLICATIONS

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The purpose of this paper is to summarise some most recent studies on the biomechanics of the triple jump. A linear relationship between the loss in the horizontal velocity and the gain in the vertical velocity during three support phases was found for individual athletes. Optimisation models were developed for determining optimum phase ratio and the actual distance with a given phase ratio for any given athlete. A biomechanical model of free limb motions was developed to determine the effects of free limb motions on the performance of the triple jump. The relationship between the loss in the horizontal velocity and the gain in the vertical velocity during support phases has a significant effect on the optimum phase ratio and the actual distance with optimised phase ratio. The free limb motions are associated with the gain in the vertical velocity and loss in the horizontal velocity. Optimum arm swing techniques for the triple jump were determined based on the functions of free limb motions.

KEY WORDS: sports biomechanics, jump, optimisation, modelling

INTRODUCTION: Triple jump is one of the three jumping events in track and field. A triple jump consists of an approach run followed by a hop, a step, and a jump. Compared to the long and high jumps which have only one touchdown and takeoff in each, the triple jump has three consecutive touchdowns and takeoffs at high speed and thus is more technically demanding than the long and high jumps. The techniques used by elite triple jumpers have received considerable attention from biomechanists in the last decade. Biomechanical studies have been conducted to identify those factors affecting the performance of the triple jump in an attempt to determine the optimum techniques for individual athletes. The purpose of this paper is to summarise some of my most recent studies on the triple jump techniques in terms of theoretical and practical considerations. I hope that this summary will assist in identifying some future research directions in this area.

OPTIMUM PHASE-RATIO: One of the most important considerations in triple jump techniques is the optimum phase ratio. In the triple jump, the distance measured from the toe of the athlete's takeoff foot on the board to the nearest mark the athlete made in the sandpit is referred to as actual distance. The distance from the toe of the athlete's takeoff foot at the takeoff to the toe of his or her landing foot at the landing during each phase is referred to as the phase distance. The percentage of a phase distance to the actual distance is referred to as phase percentage. The ratio of three phase percentages is referred to as phase ratio.
Phase ratio is an indirect measure of effort distribution in the triple jump. It should be the first consideration of triple jump techniques. Without a solution to the optimum phase ratio problem, studies on all other factors in triple jump techniques must be considered in ignorance of what is required (Hay, 1992). Although many studies have been conducted in an attempt to identify the optimum phase ratio, it is still not clear how to determine the optimum phase ratio, what factors affect the optimum phase ratio, whether there is an optimum phase ratio for all athletes, and how the phase ratio affects the actual distance.

Theoretical Considerations: The phase ratio affects the actual distance only if there is a pair or group of controversy effects on the phase distances and actual distance of the triple jump. To study the optimum phase ratio problem in the triple jump, it is essential to identify a critical pair or group controversy effects on the phase distances and actual distance of the triple jump.The actual distance is the sum of the three phase distances, and each phase distance is the sum of three partial distances: the takeoff distance, flight distance, and landing distance. The takeoff distance is defined as the horizontal distance between the centre of mass and toe of the takeoff foot at the takeoff. The flight distance is defined as the horizontal distance between the centre of mass at the landing and the centre of mass at the takeoff. The landing distance is defined as the horizontal distance between the toe of the landing foot and the centre of mass at the landing. The flight distance is the longest among the three partial distances and the major factor affecting the phase distance and thus the actual distance.

The flight distance in each phase is mainly affected by the horizontal velocity and vertical velocity of the centre of mass at each takeoff. In each support phase of a triple jump, the athlete inevitably loses horizontal velocity while gaining vertical velocity for takeoff. Gaining vertical velocity tends to increase the phase distance but losing horizontal velocity tends to decrease the phase distance. These two factors could form a pair of controversy effects and thus the basis for optimum phase ratio if they are correlated. Therefore, it was hypothesised that the loss in horizontal velocity ($\Delta v_{x,i}$) and the gain in vertical velocity ($\Delta v_{z,i}$) during each support phase are correlated for a given athlete (Yu and Hay, 1996).

To test the above-formulated hypothesis, ten elite triple jumpers including six males and four females served as the subjects. A videographic technique with panning cameras (Yu et al., 1993) was used to obtain three-dimensional coordinates of 21 body landmarks of these subjects under the competition conditions. Each subject had at least four trials that were videotaped and can be analysed. The horizontal and vertical velocities at the touchdown and takeoff of each support phase in each trial were determined for each subject. The loss in the horizontal velocity and the gain in the vertical velocity during a support phase were estimated as the differences in the corresponding velocity between the takeoff and the touchdown. A regression analysis with dummy variables was conducted to determine the relationship between the loss in the horizontal velocity and the gain in the vertical velocity in different phases for each subject (Yu and Hay, 1996).

The results of regression analyses suggest that the loss in the horizontal velocity and the gain in the vertical velocity during each support phase be significantly correlated. The best regression equation for the relationship between the loss in the horizontal velocity and the gain in the vertical velocity are exclusively in a form:

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

(i = 1 for the hop, 2 for the step, and 3 for the jump; $P_{l,i} = 0$ for $i = 1$; $P_{l,i} = 1$ for i = 2 or 3)
The regression coefficients A_0 , B_0 , and A_1 are different for different subjects. The intersections of the regression line A_0 and B_0 can be estimated from A_1 .

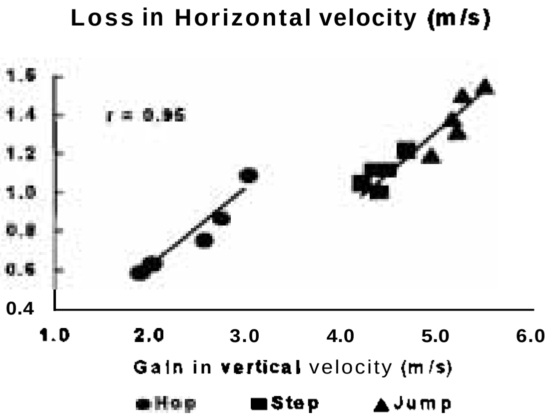

Figure 1. The relationship between the loss in horizontal velocity and the gain in the vertical velocity during triple Jump.

The relationship between the loss in the horizontal velocity and the gain in the vertical velocity during three support phases suggests that the greater the gain in the vertical velocity during each phase, the greater the loss in horizontal velocity during the same phase (Figure **1).** This relationship is a result of the horizontal-to-vertical kinetic energy conversion during the support phase. The kinetic energy due to the vertical velocity possessed by an athlete at the takeoff 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 (Wilters et al., **1992).** The kinetic energy due to the 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 is the gain in the vertical velocity due to the gain in the kinetic energy in the vertical direction, the greater is the loss in the kinetic energy in the horizontal direction, and thus, the greater is the loss in the horizontal velocity. Based on these considerations, the regression coefficient A_1 is referred **to as** the horizontal-to-vertical velocity coefficient.

The relationship between $\Delta v_{x,i}$ and $\Delta v_{z,i}$ is affected by the magnitude of A_1 (Figures *2* and 3). For a small gain in the vertical velocity, the greater the magnitude of A_1 was, the less the loss in the horizontal velocity was. For a large gain in the vertical velocity, the lower the magnitude of **A,** was, the less the loss in the horizontal velocity was. The sensitivity of the loss in the horizontal velocity to the gain in the vertical velocity increases as the magnitude of **A,** increases.

These results support the hypothesis that $\Delta v_{x,i}$ and $\Delta v_{z,i}$ are correlated for a given athlete. The relationship between $\Delta v_{x,i}$ and $\Delta v_{z,i}$ indicates that an optimum phase ratio may exist for a given athlete and that different athletes may have different optimum phase ratios because of the difference in A_1 .

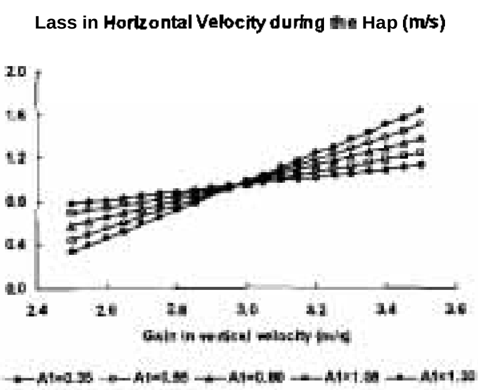

Figure 2 - Horizontal-to-vertical velocity conversion during the hop.

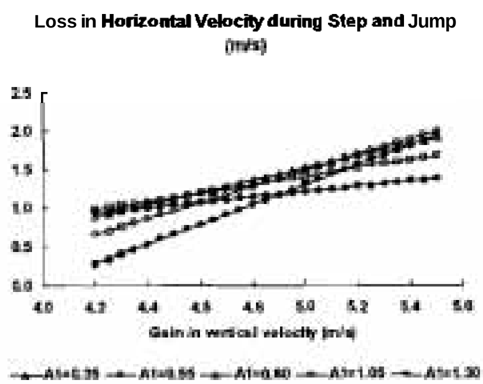

Figure 3 - Horizontal-to-vertical velocity conversion during the **steo** and iurno.

Applications: Based on the results of the study on the relationship between $\Delta v_{x,i}$ and $\Delta v_{z,i}$, a optimisation model was developed to determine the optimum phase ratio for individual athletes (Yu and Hay, 1996). In this model, the actual distance is expressed as the sum of three phase distances. Each phase distance is expressed as the sum of the takeoff, flight, and landing distances. The flight distance of each phase was expressed as a function of the horizontal and vertical velocities at the takeoff, and takeoff and landing heights. The takeoff height was defined as the vertical distance between the centre of mass and the ground at the takeoff. The landing height was defined as the vertical distance between the centre of mass and the ground at the landing. The horizontal velocity at a takeoff was defined as the sum of the horizontal velocity at the touchdown of the support phase and the loss in the horizontal velocity during the support phase. The vertical velocity at a takeoff was defined in a similar way. The loss in the horizontal velocity during each support phase was estimated from the gain in the vertical velocity during that phase using the regression equation for the relationship between $\Delta v_{x,i}$ and $\Delta v_{z,i}$ the given athlete. The takeoff and landing distances and heights were considered as constants for the given subject and estimated from the corresponding means of the subjects in all his or her analysed trials. Therefore, the actual distance is eventually expressed as a function of the gains in the vertical velocity during the support phases of the hop, step, and jump. The optimum gains in the vertical velocity during the three support phases were obtained by maximising the actual distance subject to the constraints of the gains in the vertical velocity during the three phases. The phase ratio corresponding to the optimum gains in the vertical velocity during the three support phases was considered as the optimum phase ratio for the given athlete.

The optimisation results show that the optimum phase ratio is different for different athletes. The results of a sensitivity analysis show that the optimum phase ratio is mainly affected by the horizontal-to-vertical velocity conversion coefficient A_1 (Figure 4). The difference between optimum jump and hop percentages was generally less than 2 % when magnitude of A_1 was less than or equal to 0.5. This means that the athletes with the magnitudes of A_1 less than 0.5 should use a hop-dominated technique (Hay, 1992). Further, the optimum jump percentage was at least 1% greater than the optimum hop percentage when A_1 was between 0.5 and 0.9. This means that the athletes with the magnitudes of A_1 between 0.5 and 0.9 should use either a balanced or jump-dominated technique (Hay, 1992). Furthermore, the optimum jump percentage was at least 2% greater than the optimum hop percentage when A_1 was greater than or equal to 0.9. This means that the athletes with magnitudes of A_1 greater than 0.9 should use a jump-dominated technique (Hay, 1992). In addition, the results of the sensitivity analysis suggest that takeoff and landing distances and heights have little effects on the optimum phase ratio.

The Difference between Jump and Hop Percentages (%)

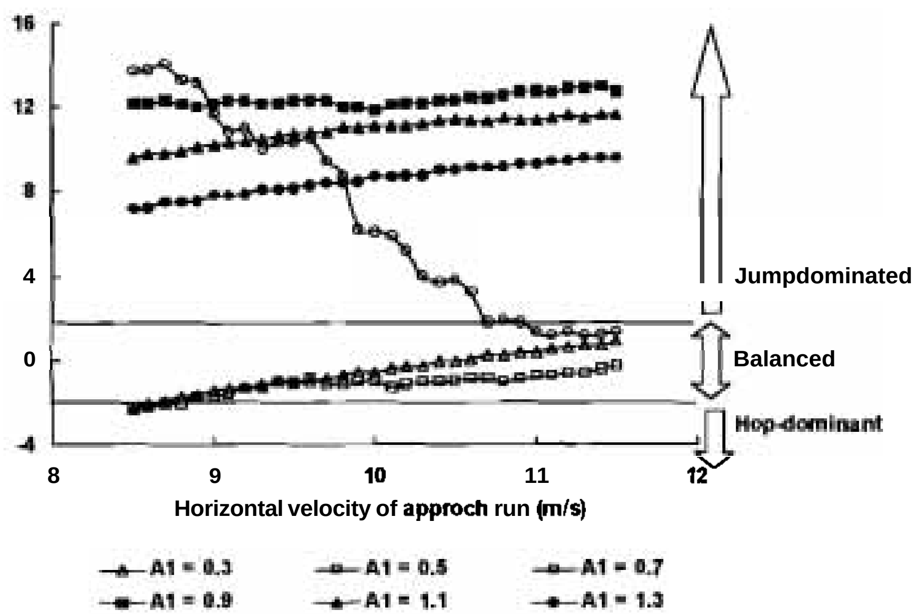

Figure 4 - The effect of the horizontal-to-vertical velocity conversion coefficient and the velocity of approach run on the optimum techniques of the triple jump measured by the optimum phase ratio.

ACTUAL DISTANCE **WITH OPTIMISED** PHASE RATIO: The results of the study on the optimum phase ratio raised new questions that require further research. The most important questions are: how phase ratio affect the actual distance and what are the effect of the horizontal-to-vertical velocity conversion coefficient and other factors on the actual distance with optimised phase ratio? The answer to this question will provide additional essential information regarding the development of triple jump techniques.

Theoretical Considerations: As the results of the previous study showed, the **horizontal**-to-vertical velocity conversion coefficient is a key factor in determining the optimum phase ratio for a given athlete. The effect of the horizontal-to-vertical velocity conversion coefficient on the actual distance combined with its effect on the optimum phase ratio will indicate which technique has the greatest potential for the longest actual distance. It will also provide important information for the identification of potential elite triple jumpers and general direction of physical training of the triple jump. It is likely that the horizontal-to-vertical velocity conversion coefficient of a given athlete is related to physical characteristics of his or her musculoskeletal system (Yu and Hay, 1996). Therefore, the horizontal-to-verticalvelocity conversion coefficient could be an indication of the potential of a given athlete in the triple jump and a target for improvement in his or her physical and technical training.

In addition, the optimisation model developed in the previous study allows a more effective investigation of the influences of the other factors such as the horizontal velocity of approach run, the takeoff and touchdown heights, and takeoff and landing distances on the performance of the triple jump with optimised phase ratio. The results of such a study will provide more complete information for the development of the detailed techniques of the triple jump.

To investigate how the phase ratio affects the actual distance, an optimisation model was developed to estimate the actual distance for a given athlete with a given phase ratio. In this optimisation model, the actual distance is expressed as a function of the gains in the vertical velocity during the three support phases as described in the previous study. The gains in the vertical velocity during three support phases were optimised to minimise the difference between the given phase ratio and the estimated phase ratio. The actual distance corresponding to the optimum gains in the vertical velocity during the three support phases was considered as the actual distance of the given athlete with the given phase ratio. The actual distance with each given phase ratio were compared to the actual distance with optimum phase ratio.

As indicated by a deterministic model of the triple jump (Hay, 1993), besides horizontal and vertical velocity at the takeoff, takeoff and landing distances and heights also affect the phase distance and thus actual distance. To minimise possible interaction effects of standing height and actual distance on the effect of techniques, the actual distance and takeoff and landing distances and heights of a given subject were normalised to the subject's standing height. Each of the normalised takeoff and landing distances and heights was systematically alternated within its observed range of variation in the optimisation model for optimum phase ratio.

The phase ratio had significant effect on the actual distance. The optimisation results show that the loss in the actual distance was up to nearly one meter when an athlete whose optimum technique was jump-dominated used a hop-dominated technique. The loss in the actual distance was up to nearly 0.5 meters when an athlete whose optimum technique was a hop-dominated technique used a jump-dominated technique.

The horizontal-to-vertical velocity conversion coefficient A_1 has significant effect on the actual distance with optimised phase ratio (Figure 5). The nature of the effect of this coefficient on the actual distance with optimised phase ratio depends on its absolute value. If A_1 is greater than 0.7, the greater the A_1, the longer the actual distance with optimised phase ratio. An increase of 0.1 in A_1 results in an increase about 0.5 times standing height of the athlete in the actual distance with optimised phase ratio. If A_1 is less than 0.5, the lower the A_1, the longer the actual distance with optimised phase ratio. A decrease of 0.1 in A_1 result in an increase about 0.3 times standing height of the athlete in the actual distance with optimised distance. The horizontal-to-vertical velocity coefficient A_1 has little effect on the actual distance with optimised phase ratio if it is between 0.5 and 0.7.

The horizontal velocity of approach run also has significant effect on the actual distance with optimised phase ratio (Figure 6). The relationship between the actual distance and the horizontal velocity of approach run is essentially linear. An increase of 1 m/s in the horizontal velocity of approach run result in an increase about 0.8 times standing height of the athlete in actual distance.

The takeoff distances, landing distances, takeoff heights, and landing heights had little effects on the optimum phase ratio and actual distance with optimised phase ratio. The individual variation in takeoff and landing distances was generally less than 5% of the standing height, and less than 3% in takeoff and landing heights. The sensitivity analysis showed that within these observed ranges of the variations, the effects of each of these parameters on the optimum phase percentages were less than 0.2%. The sensitivity analysis also showed that, although increasing the magnitudes of these parameters proportionally increase the actual distance with optimised phase ratio, the effects of the variation in each parameter on the actual distance were generally less than 1% of the actual distance. These effects were even less when the negative correlation between takeoff distance and height was considered.

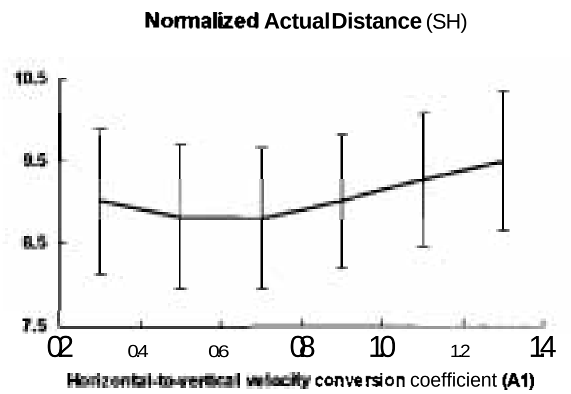

Figure 5 - The effect of the horizontal to-vertical velocity conversion coefficient on the actual distance with optimised phase ratio.

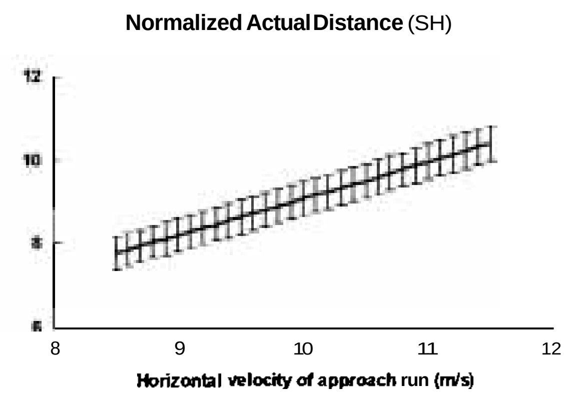

Figure 6 - The effect of the velocity of approach run on the actual distance with optimised phase ratio.

Applications: The results of this study suggest that the effort distribution measured by the phase ratio and the velocity of approach run are two variables that have the dominant effects on the performance of the triple jump. Within the observed variations in these two variables of individual athletes, the effect of the effort distribution measured by phase ratio on the actual distance is greater than that of the velocity of approach run. This indicates that phase ratio may be the most important consideration in triple jump techniques.

Although how the horizontal-to-vertical velocity conversion coefficient vary and what physical characteristics this variable actually represents are not clear yet, the results of this study suggest that the horizontal-to-vertical velocity conversion coefficient is an important variable affecting the optimum phase ratio and actual distance of a given athlete.

The horizontal-to-vertical velocity conversion coefficient A_1 may be a parameter for differentiation of elite triple jumpers from elite long jumpers. During the takeoff of a long jump, the athlete needs to gain as much vertical velocity as possible with as little loss in the horizontal velocity as possible. The results of this study suggest that an athlete with low magnitude of A_1 lose less horizontal velocity for a large gain in the vertical velocity than does an athlete with high magnitude of A_1. Therefore, the athletes with low magnitudes of A_1 may be potential elite long jumpers. This notion supported by the previous study (Witters et al., 1992) that shows that the greater the magnitude of the kinetic energy recovery efficiency, the longer the actual distance of a long jump.

The optimisation results suggest that in comparison to the athletes with low magnitudes of A_1, the athletes with high magnitudes of A_1 tend to have relative longer actual distances with optimised phase ratios. These results suggest that the athletes with high magnitudes of A_1 may be potential elite triple jumpers.

The horizontal-to-vertical velocity conversion coefficient A_1 may also be used as a guideline for physical and technical training in the triple and long jumps. The physical and technical training for elite triple jumpers should be designed to increase the magnitude of A_1. In contrast, the physical and technical training of elite long jumpers should be designed to decrease the magnitude of A_1. The magnitude of A_1 for a given athlete may be a function of the maximum contraction speed of his or her muscles or the maximum force the athlete's muscles are capable of generating. The maximum muscle contraction speed and force may affect the force-velocity relationship of the muscle and thus the efficiency of the conversion of the strain energy to kinetic energy (Anderson and Pandy, 1993; Pandy et al., 1990). The magnitude of A_1 may also a function of the leg stiffness, which is the ratio of the force generated by the leg and the compression distance of the leg. Farley and Gonzalez (1996) reported that the leg stiffness for the maximum compression of the leg during the stance phase of running had a significant effect on efficiency of the kinetic-to-elastic and elastic-to-kinetic energy conversion.

Lees et al. (1993) pointed out that it is important to place the takeoff foot well in front of G at the touchdown and keep the takeoff leg as stiff as possible during the support phase to minimise the loss in the horizontal velocity during the long jump takeoff. The results of the present study combined with those in previous studies indicate that, if the magnitude of A_1 is related to the some technical characteristics, a low magnitude of A_1 is likely associated with a long touchdown distance and small knee flexion during the takeoff. In contrast, a great magnitude of A_1 is likely associated with a short touchdown distance and relative large knee flexion during the takeoff. This indicates 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. In a certain degree, this notion is supported by the study of Koh and Hay (1990) on the landing leg motion in the triple jump. Although the results of that study did not show significant correlation between landing leg motion and performance in the triple jump, they did show that there was a trend that the touchdown distance of the hop was shorter than that of the takeoff in the long jump. In addition, and the results of that study showed that there was a trend that the active landing leg motion had a greater first-order correlation coefficient with the performance in the triple jump than in the long jump.

FUNCTIONS OF ARM SWING MOTIONS: The support (or takeoff) leg is obviously an important contributor to the changes in the velocity and angular momentum during each support phase of the triple jump but it is not the only contributor. In each support phase, three of the jumper's four limbs are in a swinging state. As these free limbs move relative to the trunk during the support phase, they exert forces on the trunk. These forces affect the force that is transmitted through the support leg to the ground and thus lead to a modification of the reaction force exerted by the ground on the athlete's body. The ground reaction force and its moment serve to modify the translation and rotation of the athlete's body during the support phase.

Arm swing motions in the triple jump received many attentions in coaching literature. However, what has been written about the motions of the free limbs in the support phases of the triple jump is essentially intuitive and qualitative in nature. A recent extensive review of the relevant literature did not reveal any scientific evidence to support these qualitative notions (Hay, 1992).

Theoretical Considerations: To study the functional of arm swing motions and their effects on the performance of the triple jump, a biomechanical model is needed to determine the contributions of arm swing motions to the whole body movements in the triple jump. Several biomechanical models were used to study segment contributions to whole body movements. However, these models failed to provide critical information relevant to techniques or basic form of human body motion because of the failure to express the whole body movement as a function of joint angular motions.

To express the whole body movement as a function of joint angular motions of the arms, the changes in the velocity vector and angular momentum vector of each arm segment were partitioned in terms of angular motions of shoulder and elbow joints and the general motions of the trunk. The measures of angular motions of the shoulders and elbows included the changes in the joint angular velocities and positions of these joints. The sum of all the terms of the change in the velocity vector of the whole body associated with any of the changes in the shoulder and elbow angular velocities and positions was considered as the contribution of the joint to the whole body linear motion. Similarly, the sum of all the terms of the changes in the angular momentum vector of the whole body associated with any of the changes in the shoulder and elbow angular velocities and positions was considered as the contribution of the joint motion to the whole body angular motion (Yu and Andrews, 1998).

Thirteen elite male triple jumpers served as subjects. A Direct Linear Transformation technique with panning cameras (Yu, Koh, & Hay, 1993) was used to obtain three-dimensional coordinates of 21 body landmarks the subjects during the last two steps of the approach run and the subsequent triple jump under competition conditions. Joint angles and angular velocity vectors of the free limbs and whole body velocity and angular momentum vectors at the touchdown and takeoff of each support phase were estimated and changes in these variables during the support phase were determined.

The arm swing motions were associated with the loss in the horizontal velocity. The relative contributions of the arm swing motions to the changes in the forward horizontal velocity of G during the three support phases were 9%, 16%, and 19%, respectively. The contribution of the arm swing motions and the total change in the forward horizontal velocity of the whole body were significantly correlated (Yu and Andrews, 1998).

The arm swing motions were also associated with the gain in the vertical velocity. The relative contributions of the arm swing motions to the changes in the vertical velocity of G during the three support phases were 8%, 9% and 9%, respectively. The contribution of the arm swing motions and the total change in the vertical velocity of the whole body were significantly correlated (Yu and Andrews, 1998).

Further, the arm swing motions had significant contribution to the changes in the side-somersaulting angular momentum toward the free leg side during the support phase of the step, and the backward somersaulting angular momentum during the support phases of the hop and jump. However, none of these contributions is significantly correlated with the total change in the corresponding whole body angular momentum (Yu and Andrews, 1998)

Applications: There are three commonly used arm swing techniques in the triple jump: alternate-arm swing, double-arm swing, and arm-and-half swing. The arm swing model was applied to compare the effects of these three arm swing techniques on the whole body linear movements in an attempt to determine the optimum arm swing techniques for the triple jump (Figure 7).

The alternate-arm swing technique had the least loss in the horizontal velocity. The double-arm swing technique had the highest capacity to great the vertical velocity. The alternate-arm swing technique had the lowest ratio of the loss in the horizontal velocity to the gain in the vertical velocity, and the double-arm swing had the highest. The arm-and-half swing technique is between the alternate- and double-arm swing techniques in all these measures.
One of the objectives of the hop and step of the triple jump was to minimize the loss in the horizontal velocity (Miller and Hay, 1986). This is an important objective for these two phases regardless the techniques to be used in t e n s of phase ratio according to the study on optimum phase ratio. The results of this study suggest that the alternate-arm swing technique had the lowest ratio of the loss in the horizontal velocity to the gain in the vertical velocity. This means that the loss in horizontal velocity for creating same magnitude of the vertical velocity is less when the alternate-arm swing technique is used than when the double-arm or arm-and-half swing technique is used. Therefore, the alternate-arm swing technique appears to be optimum for the hop and step of the triple jump.

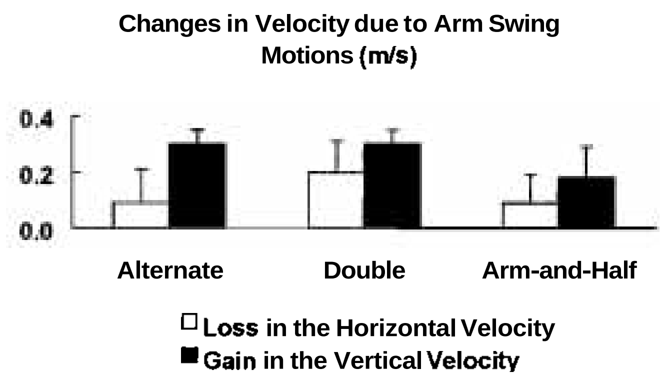

Figure 7 - A comparison of changes in velocity due to arm swing motions with three arm swing techniques.

According to the study on the optimum phase ratio, triple jumpers should jump with their maximum vertical jumping effort during the jump phase of the triple jump regardless the techniques in terms of phase ratio. The results of this study suggest that the double-arm swing technique had the highest production of vertical velocity. Therefore, the double-an swing technique appears to be optimum for the jump phase of the triple jump.

SUGGESTED FUTURE STUDIES: The results of previous studies summarised in this paper suggest that future studies may be conducted to investigate the effects of selected physical characteristics on the horizontal-to-vertical velocity conversion coefficient. Future studies may also be conducted to determine the effects of selected technical parameters on the horizontal-to-vertical velocity conversion coefficient. More sophisticated biomechanical model of the triple jump may need to be developed to express the changes of the velocity of the whole body as functions of different technical variables. In addition, future studies may be conducted to examine the horizontal-to-vertical velocity conversion coefficient in long jump.

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