

Biomechanical Analysis of the Techniques and Phase Ratios of Domestic Elite Triple Jumpers

Joo-Ho Song^a, & Jae-Kyun Ryu^{b*}

Korea Institute of Sport Science^a, & Kyung Hee University^b, Korea

Abstract

The purpose of this study was to analyze and improve the techniques of the KDH triple jumper. Both successful and failed trials of the subject who won the triple jump championship in the 63th National Athletics Championship in 2009 were included in this study. The analyzed data (final stride, hop distance, step distance, jump distance, phase ratio, location of center of gravity, velocity, and the takeoff angle) during each event were studied after filming the actual competition of the KDH jumper. Six video cameras (PD170, Sony) were used to record the performance of the jumper and they were installed as to not interrupt o the performance. The film speed was set at 30frames/sec and the shutter speed was 1/250 sec. The data were smoothed using a Butter worth second order low pass filter with a cut off frequency of 10 Hz.

The following conclusions were reached by analyzing the subject's trials.

The subject used both the hop-dominated technique and the balanced technique simultaneously, and the best national record was established by using the balanced technique. To improve his record, the KDH jumper needs to reduce the loss of horizontal velocity by creating the longer takeoff distance and the shorter landing distance throughout the hop, the step, and the jump. The technique used for the stamping motion during the step phase requires further development because the KDH jumper lost 20% of his horizontal velocity during this phase. Also, the KDH jumper should decrease his takeoff angle by $\sim 1^\circ$ in the step phase and increase it by $\sim 1^\circ$ in the jump phase.

Key Words: *Hop-dominated technique, Balanced technique, Takeoff distance, Landing distance, Takeoff angle*

· This paper is translated from the outstanding paper published in "Korea Journal of Sport Science (2010, Vol. 21, No. 2, 1105-1114)"

* Correspondence : Jae-Kyun Ryu (ryu69kor@khu.ac.kr)

Introduction

The triple jump is one of the more complicated and challenging athletic events in track and field competition. The triple jump consists of 3 phases: the hop, the step, and the jump after the approach run, and 3 jumps are performed instead of only 1 jump, despite the fact that there is an approach run similar to that used in other jumping events. The hop starts with the athlete jumping from a takeoff mark on 1 leg, using the speed gained from the approach run, and ends by landing on the runway with the same leg. In the step, the athlete immediately jumps with the takeoff leg and lands on the runway with the opposite leg. This is followed by the jump, where the athlete jumps from that same non-takeoff leg and brings the opposite leg to land in a sand-filled pit. The 3 jumping movements (the hop, the step and jump) require a high level of physical coordination and balance (Brimberg et al., 2006). Among jumping events, the long jump and the triple jump are judged by the horizontal distance covered by the jumping, and the most crucial kinematic factor in these 2 events is the speed of the take off (Hay et al., 1986; Hay, 1995; Larkins & Ramey, 1994; Nixdorf & Bruggemann, 1990; Lees et al., 1994). In long jumping, horizontal velocity is the most important factor influencing the level of performance, and maximum distance is achieved by using only 1 jump. However, in the triple jump, both the phase distance and the distribution have to be considered because the phase distance should be optimally distributed while simultaneously reducing the speed loss as little as possible. Therefore, the successful triple jump should be performed to optimally distribute each phase with the speed, rather than to land at the maximum speed, and the athletes who minimize the horizontal momentum throughout the 3 phases become the elite triple jumpers (Larkins & Ramey, 1994). The optimal triple jump strategy is to aid the jumpers to show their best ability by distributing their kinetic energies evenly from the takeoff mark to the sand filled pit.

Triple jump techniques are classified into 3 different types, the hop-dominated technique, the jump-dominated technique, and the balanced technique depending on the distribution of the phase distance and the phase ratio. This classification was defined by Hay (1990), who claimed that in the hop-dominated technique and the jump-dominated technique respectively, the hop distance and jump distance should be at least 2% of the actual distance greater than the distance of the next longest phase, and the distance of the longest phase should be < 2% of the actual distance greater than the distance of the next longest (Hay, 1995). On the other hand,

Brimberg et al. (2006) claimed that in the jump-dominated technique, the jump distance should be at least 4% of the actual distance greater than the distance of the next longest phase.

Hay (1999) analyzed 8 elite triple jumpers and their techniques in the Atlanta Olympics in 1996 and 4 of them used the hop-dominated technique, 3 of them used the balanced technique, 1 of them used the jump-dominated technique, and 4 of them used the balanced and jump-dominated technique.

Their average official records were 17.23 m, 17.41 m, 17.40 m and 17.41 m respectively, but the actual average distances were 17.34 m (jump-dominated), 17.47 m (balanced and jump-dominated), 17.56 m (balanced), and 17.49 m (hop-dominated). The hop-dominant technique is used the most in competitions, but the jump-dominated technique is the best in terms of the level of performance. In the past, Jonathan Edward, Willie Banks, Kenny Harrison, and Mile Conley changed their techniques from the hop-dominated to the jump-dominated technique and broke the world record. For these reasons, the jump-dominated technique is currently considered to be the optimal technique for improving the level of performance.

The analysis of triple jump techniques started the refutation of claims that the kinetic and kinematic variants such as speeds, angle, angular momentum, and shock loading in the triple jump were less than the similar variants in the long jump. For example, the speed of the approach run in the long jump used to be reported to be much faster than in the triple jump, and this claim has been generalized, but the speed of the approach run in the triple jump is currently as fast as the speed in the long jump, because triple jump techniques have changed.

Studies conducted abroad on the triple jump have investigated the kinematic variants that elite jumpers possessed at the beginning and compared each other after classifying the accumulated resources according to the records (Hackett, 1995; Hay & Miller, 1985; Hay, 1994, 1997; Ae et al., 1994). Since then, the optimal phase ratio has been tailored to each jumper and simulated to develop the optimal technique for individual jumpers also, studies have focused on the development of techniques (Brimberg et al., 2006; Hay, 1995, 1999; Yu & Hay, 1996). However, there is a total lack of accumulated resources for analysis of techniques, including the phase ratio distributions and the speed changes of domestic elite jumpers, although some researchers (Ryu, 2005; Ryu et al., 2000; Ryu & Yun, 2001; Ryu & Yeo, 2008, 2009) have conducted such studies at home.

Therefore, this study analyzed the techniques of domestic elite jumpers (KDH

jumpers) and searched for any improvements that could be made. We then aimed to provide quantitative resources and suggest training strategies to enable KDH jumpers to advance to the finals in the upcoming international tournaments and Dae-Gu World Championships in Athletics.

Methods

Subjects

The subject was the KDH jumper who won the National Athletics Championship in 2009, and both successful and failed trials of the subject were examined. <Table 1> shows the physical characteristics and records of the subject.

Table 1. The physical characteristics and records of the subject.

Subject	Height (cm)	Weight (Kg)	Age (yr)	Trial	Official records (m) (film measured records)
KDH	180	70	25	First	(16.96)
				Second	16.94
				Third	(16.87)
				fourth	17.10

*First and third were foul and fifth and sixth were not attended.

Analysis and experiment process

The final single stride, the distance of hops, steps and jumps, the phase ratio, changes in the athlete's center of gravity in each event, velocity, and changes in the hop angle were analyzed by viewing KDH jumpers filmed in the national athletic championships in 2009. Six camera recorders (PD170, Sony) were used for filming and they were installed so as to not interrupt the competition. Picture 1 shows the arrangement. Trials 1-4 out of a total of 6 were analyzed the shutter speed was 1/250 and the film speed was 30 frames/sec.

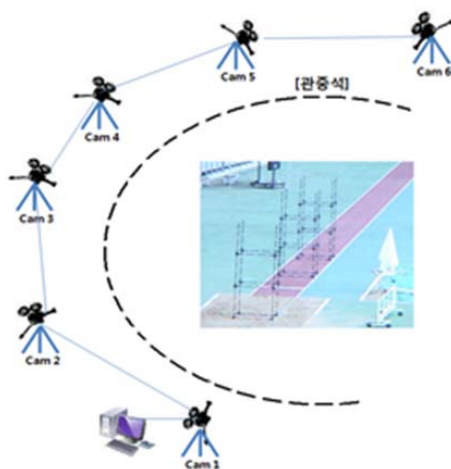


Figure 1. Arrangement of Experimental Device.

Events and Angle Definitions

<Figure 2> shows the phases and the events that were selected for analysis. The terms used for analysis were defined as follows (Ryu, 2008).

The takeoff distance of hop (H1), step (S1), and jump (J1): the horizontal distance between the athlete's center of gravity and the toe of the takeoff foot before the takeoff foot is removed from the support phase of the hop, the step, and the jump.

The flying distance of the hop (H2), the step (S2), and the jump (J2): the horizontal distance that the athlete's center of gravity traveled during the hop, the step, and the jump.

The landing distance of the hop (H3) and the step (S3): the horizontal distance between the toe of the landing foot and the athlete's center of gravity after the flying phase of the hop and the step.

The landing distance of the jump (J3): the horizontal distance between the heel of the landing foot and the athlete's center of gravity during the jump phase.

Touchdown (TD): the moment when the foot touches the ground.

Takeoff (TO): the moment when the foot comes off the ground during the approach run phase, the hop phase, and the jump phase.

Takeoff angle: the angle between the ground and the velocity of center of gravity.

Measured distance (MD): the horizontal distance between the end of the takeoff foot and the nearest point in the sand filled pit.

Phase ratio: the hop, the step, and the jump distance / the measured distance.

Landing (LD): the moment when both heels touch the sand filled pit

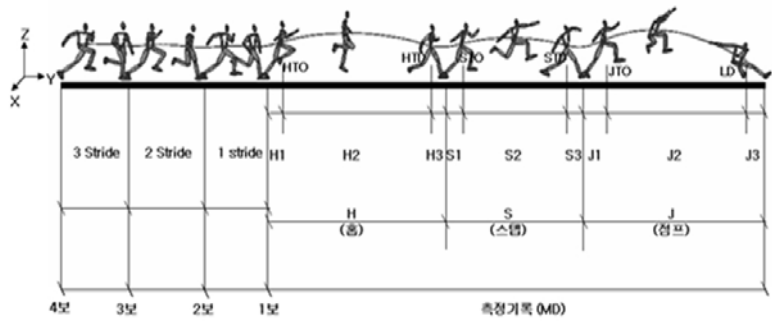


Figure 2. Phases and events.

Analysis methods

The filmed images were analyzed by producing 3-dimensional coordination views after calculating the real-space coordination of the control point using the Kwon3D 3.1 program and the 2-dimensional coordination views from each camera recorder using the cubic spline function and direct linear transformation (DLT) formula. The errors caused by the noise created by digitizing were smoothed by the second order low-pass filter of a Butter worth filter. When this was done, the cut-off frequency was set at 10 Hz.

Results

The final stride, the distances of the hop, the step, and the jump, and the phase ratio

<Table 2>, <Figure 3, and Figure 4> show the final stride, the distances of the hop, the step and the jump, the phase ratio, and the techniques classified according to the phase ratio.

The average step measurement of the final stride of the KDH jumper in this study was 2.19 m

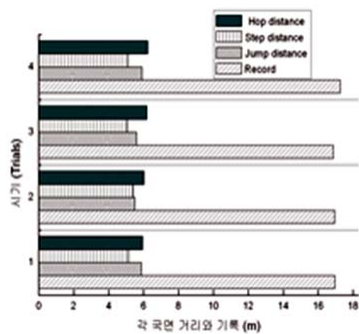


Figure 3. The distance of the hop, the step and the jump and the records.

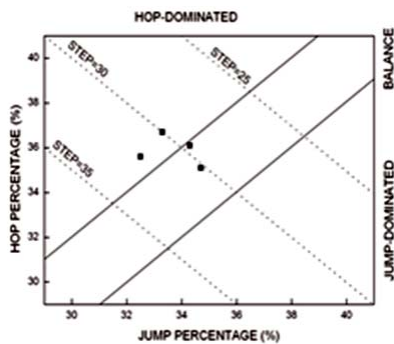


Figure 4. The hop percentage versus the jump percentage and the techniques used.

Table 2. Each phases ratio and distances.

term	Last stride	Hop	Step	Jump	Actual record/ official record
The first (foul)	2.15	5.95 (35.1%)	5.13 (30.2%)	5.88 (34.7%)	16.96/ ·
The second (success)	2.19	6.03 (35.6%)	5.41 (31.9%)	5.51 (32.5%)	16.95/16.94
The third (foul)	2.23	6.19 (36.7%)	5.07 (30.1%)	5.61 (33.3%)	16.87/ ·
The fourth (success)	2.20	6.24 (36.1%)	5.12 (29.6%)	5.92 (34.3%)	17.28/17.10
Mean	2.19	6.10 (35.8%)	5.18 (30.4%)	5.73 (33.6%)	17.02/17.02
± SD	0.03	0.14	0.15	0.20	0.18/0.11

Ryu & Yeo (2009) reported that the average step measurement of the final strides of 5 finalist triple jumpers in the Dae-Gu Universiade in 2003 was 2.43 m, and Hay & Miller (1985) reported an average of 2.28 m. This shows that the step measurement in this study was slightly shorter than the one in the previous study. This is thought to be due to the difference between the heights of the subjects used in each study (the height of subject in the study of Ryu & Yeo (2009) was 180 cm and the average height of subjects in the study of Hay & Miller (1985) was 185 cm) and generally speaking, when the final stride is shorter, the height of the center of gravity become higher, and this enables the athlete to perform the hop at lower and faster level.

Looking at the phase ratio of the KDH jumper as indicated in <Table 2>, the hop percentage (35.8%) was higher than the jump percentage (33.6%). When the techniques were classified according to the phase ratio, the hop-dominated technique (the second term and the third term) and the balanced technique (the first and the fourth term) were used simultaneously and the records were improved when the balanced technique was used.

Susanka et al. (1987) reported that the ratios of 36% : 30.5% : 33.5% (6.5 m + 5.5 m + 6.0 m) and 34.5% : 31% : 34.5% (6.2 m + 5.6 m + 6.2 m) were optimal to complete 18 m, and Hay (1995, 1997) reported that the phase ratio was 37.7% : 27.5% : 34.8% when the American triple jumper, Harrison, reduced the hop distance by 0.22 m and established the record of 18.01 m. The phase ratios of the dominant jumpers Conley and Edwards were each 32% : 30% : 39% and 31.7% : 32.0% :

36.3% and they established the records of 18.05 m and 18.29 m respectively. As previously shown, the hop-dominated technique decided the level of performance in the past, but use of the jump-dominated technique is rising and currently provides the best performance.

The KDH jumper needs to change his technique to the jump-dominated technique by increasing the jump distance to > 6.40 m while maintaining the current hop distance and step distance in order to further improve his level of performance.

Event distance and height of center of gravity

<Table 3>, <Figure 5, and Figure 6> show the distance of the hop, the step, and the jump used in triple jumping and the height changes in the center of gravity.

Table 3. Each event distance and height of COG.

variants	Hop			Step			Jump		
	TO	Flight	TD	TO	Flight	TD	TO	Flight	TD
Each event distance									
The first (foul)	0.40	4.98	0.57	0.48	4.15	0.50	0.52	4.89	0.47
The second (success)	0.37	5.05	0.61	0.57	4.31	0.53	0.54	4.54	0.43
The third (foul)	0.36	5.22	0.61	0.51	4.06	0.50	0.53	4.52	0.44
The fourth (success)	0.49	5.37	0.38	0.47	4.09	0.56	0.48	4.96	0.48
Mean	0.41	5.16	0.54	0.51	4.15	0.52	0.52	4.73	0.46
± SD	0.06	0.18	0.11	0.05	0.11	0.03	0.03	0.23	0.02
Center of gravity									
The first (foul)	1.11	1.42	1.02	1.09	1.36	1.03	1.18	1.50	0.63
The second (success)	1.10	1.41	1.01	1.15	1.44	1.06	1.18	1.44	0.62
The third (foul)	1.14	1.47	1.05	1.12	1.31	1.04	1.19	1.40	0.61
The fourth (success)	1.15	1.46	1.02	1.11	1.36	1.03	1.16	1.49	0.58
Mean	1.13	1.44	1.03	1.12	1.37	1.04	1.18	1.46	0.61
± SD	0.02	0.03	0.02	0.02	0.05	0.01	0.01	0.05	0.02

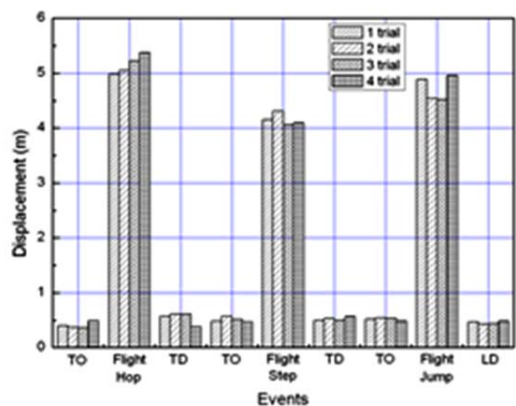


Figure 5. Distance in each event.

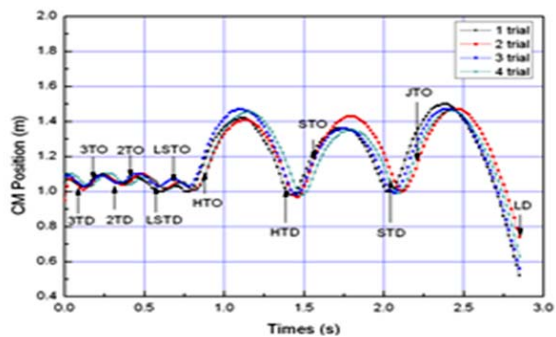


Figure 6. The height changes for the center of gravity in each trial.

After observing the takeoff distance and the landing distance in each phase, the takeoff distance (0.49 m) and landing distance (0.38 m) of the hop phase were longer and shorter, respectively, compared to the other phases. On the other hand, the takeoff and landing distances of the step phase were shorter, with distances of 0.47 m and 0.56 m, respectively. The takeoff distance of the jump was the shortest (0.48 m).

The takeoff distance and the landing distance in each phase had an impact on

the flying distance, and especially, the takeoff distance and the landing distance in the hop phase influenced the takeoff distance and the landing distance in the following phases (Hay, 1992).

Koh & Hay (1990) reported that the average takeoff distance and landing distance in the step phase were 0.53 m and 0.60 m, respectively. Bruggemann (1990) reported that the average takeoff distance and the landing distance in the hop phase were 0.55 m and 0.41 m, respectively, the average takeoff distance and the landing distance in the step phase were 0.61 m and 0.41 m respectively, and the takeoff distance of the jump was 0.49 m (Rye, 2005).

The takeoff distance of the jump phase in this study was similar to that in the previous studies. On the other hand the values of the step phase were contrary to the results of Bruggemann (1990), and tended to be similar to the results of Koh & Hay (1990). The takeoff distance of the KDH jumper during the step phase was shorter than in other phases, and this was because the takeoff leg was not sufficiently stretched due to imbalance of the takeoff in the step phase, which was induced by the rapid hop landing. Also, the landing distance of the step phase was long and the takeoff foot was damped when it touched the ground. This prevented the takeoff motion from being perfect and resulted in the short takeoff distance during the jump phase. An improvement of this motion is required because this process enables the body to fly higher but not further.

The height of the center of gravity during the second term gradually increased to 1.10 m, 1.15 m, and 1.18 m at the moment of takeoff in each phase, then decreased to 1.15 m, 1.11 m, and 1.16 m at the step, and were similar at the hop and the jump phases during the fourth term.

The greatest changes in the height of center of gravity were shown at the moment of the hop and the landing during the fourth term with values of 1.01 m and 1.06 m, respectively.

Ryu & Yeo (2008) reported that the average heights of center of gravity at the moment of the takeoff during each phase were 1.20 m, 1.19 m and 1.24 m, and those at the moment of the hop and the landing during each phase averaged 1.08 m and 1.08 m, respectively.. They also reported that the optimal height pattern for center of gravity at the takeoff and the landing during each phase was the medium-medium-high pattern. If there were the small differences between the height of each phase created by the similar levels at each phase, there would be more competitive advantages although they can be different according to the subjects' level

of performance, in other word, the technique the subjects used. Hay & Miller (1985) reported that the average heights of center of gravity at the moment of takeoff during each phase were 1.20 m, 0.95 m and 1.03 m, and those at the moment of the hop and the step were 1.03 m and 0.82 m, respectively.

These results were similar to those of Ryu & Yeo (2008), but were different from those of Hay & Miller (1985). Especially, the changes in the height of center of gravity of the KDH jumper during the fourth term were identical to the results of Ryu & Yeo (2008) nevertheless, the technique developments requires to enable the stamping create the heights of center of gravity at the takeoff moment during the step to the same level of other phases. The reason for differences between the results of this study and the study of Hay & Miller (1985) is thought to be that the hop-dominated technique most frequently used by the subjects at that time.

The horizontal velocities and vertical velocities of the hop, the step, the jump, and the take off angle

<Table 4> shows the horizontal velocities and the vertical velocities of the center of gravity at the final stride during the approach run, at the hop, at the step, at the jump takeoff, and at the landing and takeoff angle. Picture 7 shows the changes in the horizontal velocities and the vertical velocities of the center of gravity at each phase.

The mean horizontal velocity of takeoff moments at the final stride was 9.55 m/s and the mean horizontal velocity of takeoff moments at the hop, the step, and the jump of each phase were 9.64 m/s, 8.03 m/s and 7.03 m/s, respectively. The decreased horizontal velocities during the stamping at each support phase were 20% and 14% each, excluding the hop. The horizontal velocity during the stamping at the hop increased 0.9%.

Bruggemann (1990) reported that the mean horizontal velocities of the takeoff moments at the hops, the steps, and the jumps were 9.26 m/s, 8.29 m/s and 6.84 m/s, respectively, and Hay (1992) reported that the decreased horizontal velocities during the hop support phase, the step support phase, and the jump support phase were 5~9%, 7~15%, and 13~20%. Furthermore, Miller & Hay (1986) reported that the mean horizontal velocities at the takeoff moments of each phase of the jumper who established the record of 17.97 m were 9.5 m/s, 8.7 m/s, and 7.3 m/s (Ryu, 2008).

Table 4. Each event horizontal velocity, vertical velocity, angle of takeoff.

Variants		Horizontal velocity (m/s)		Vertical velocity (m/s)		Angle of takeoff (deg.)
		TO	TD	TO	TD	TO
Last stride	The first	9.41	9.72	0.50	-0.55	
Last stride	The second	9.61	9.48	0.54	-0.38	
Last stride	The third	9.73	9.32	0.59	-0.23	
Last stride	The fourth	9.45	9.21	0.59	-0.51	
Last stride	Mean	9.55	9.43	0.56	-0.42	
Last stride	± SD	0.15	0.22	0.04	0.14	
Hop	The first	9.36	8.64	2.44	-1.97	14.6
Hop	The second	9.49	9.16	2.35	-1.92	13.9
Hop	The third	9.86	9.31	2.63	-2.31	14.9
Hop	The fourth	9.85	9.36	2.63	-1.91	14.9
Hop	Mean	9.64	9.12	2.51	-2.03	14.58
Hop	± SD	0.25	0.33	0.14	0.19	0.47
Step	The first	8.05	7.17	2.31	-1.62	16.0
Step	The second	8.10	7.62	2.46	-2.16	16.9
Step	The third	7.96	8.16	2.34	-1.79	16.4
Step	The fourth	8.02	7.96	2.36	-1.86	16.4
Step	Mean	8.03	7.73	2.37	-1.86	16.43
Step	± SD	0.06	0.43	0.07	0.23	0.37
Jump	The first	7.02		2.58		20.2
Jump	The second	6.84		2.59		20.7
Jump	The third	6.93		2.47		19.6
Jump	The fourth	7.33		2.60		19.5
Jump	Mean	7.03		2.56		20.00
Jump	± SD	0.21		0.06		0.56

These results were similar to the result of Miller & Hay (1986), but showed a difference in the step, and these results were different from those of Bruggemann (1990).

In this study, the horizontal velocity at the hop takeoff of the KDH jumper was greater than his horizontal velocity at the final stride of takeoff, which indicated that the acceleration by his stamping was superior. This movement is highly difficult to perform, but is a required technique for triple jumpers. However, 20% deceleration was shown in the step, and this was judged to be due to problems with the approach posture of the stamping and the upper body posture in this phase. Therefore, techniques must be developed to improve this phase.

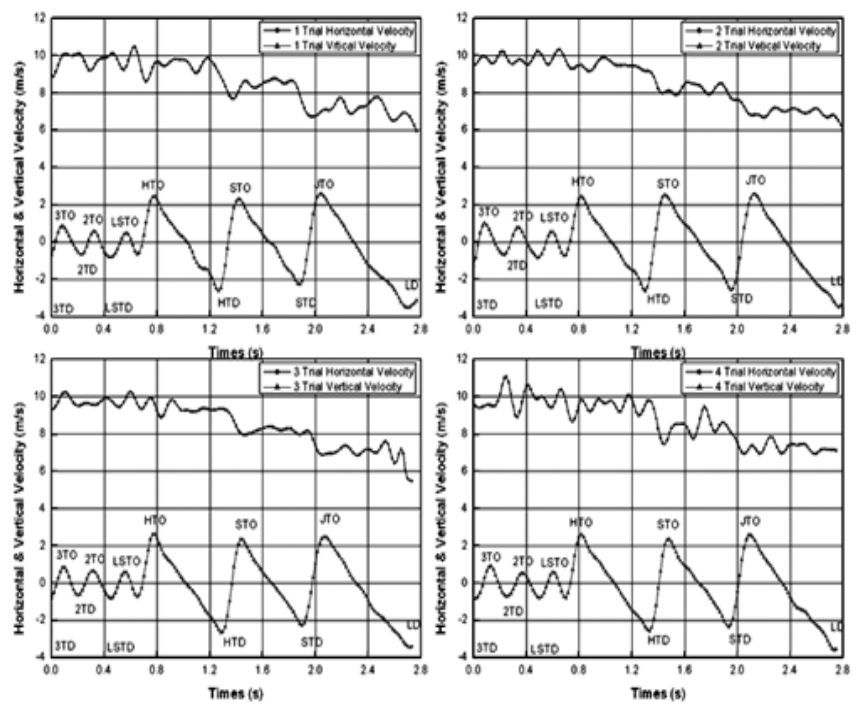


Figure 7. The horizontal velocities and the vertical velocities at the takeoff moments of the final stride during the approach run those of the hop, step, the jump, and the landing.

The mean vertical velocities of the takeoff moments at the hop, the step, and the jump were 2.51 m/s, 2.37 m/s and 2.56 m/s, respectively. The vertical velocity of the hop during the third and the fourth terms (2.63 m/s) was the highest, and that of the step during the fourth term (2.60 m/s) was the highest. Observing the patterns of vertical velocities at the takeoff moments in each phase, they all either gradually decreased, or they decreased during the step and increased during the jump, excluding the second term.

Bruggemann (1990) reported that these values were 2.39 m/s, 2.06 m/s, and 2.68 m/s respectively, and Hay & Miller (1985) reported that they were 2.09 m/s, 1.82 m/s and 2.37 m/s. Miller & Hay (1986) also reported that the vertical velocities at the takeoff moments of the jumper who established the record of 17.97 m were 2.2 m/s, 1.7 m/s, and 2.8 m/s (Ryu, 2008).

These results differed from the results of previous studies, and especially, the vertical velocity during the step was higher than that of previous studies. This was induced by the great reduction in the horizontal velocity of the KDH jumper. The level of performance can be expected to improve further if he can jump with the horizontal velocity of the fourth term by gradually increasing the vertical velocity and keeping the same track of center of gravity throughout the hop, the step, and the jump, similar to the second term (see Figure 6).

The average takeoff angles at the takeoff moments of the hop, the step, and the jump phase were 14.58°, 16.43°, and 20.00°, respectively. The takeoff angles showed the same pattern which gradually increased. It would be better for the effective phase distance distribution if the KDH reduces his step takeoff angle by ~ 1° and increases his jump takeoff angle by ~ 1°.

Conclusion

The following conclusions were reached after examining and analyzing the techniques (both the successful trials and the failed trials) of the domestic elite triple jumper (KDH jumpers) who won the national athletic championships in 2009, and searching for any improvements that could be made.

1. The KDH jumper was found to be using both the hop-dominated technique and the balanced technique simultaneously, and the best Korean record was

made by using the balanced technique. After observing the top global jumpers who established world records by using the jump-dominated technique, it may be necessary to switch the technique to the jump-dominated technique in the future.

2. The height of center of gravity should be kept as high as possible by making the final stride be a short step at the takeoff mark, and the movement should be carried out to make the height of center of gravity at the takeoff moments of the hop, the step and the jump gradually become higher.

The posture that maintains the velocity of the approach run to the landing by intending the movement track height of center of gravity in the hop and the step to the same level and making the jump higher or intending the movement track height of center of gravity to the same level throughout the three phases.

3. The horizontal velocity of the step was reduced an average of 20%, as required for development of the stamping technique in this phase. Also, the acceleration should be increased by making the horizontal velocity of the takeoff moment in the hop phase faster than the velocity of the previous takeoff moment (similar to the third term and the fourth term), and the velocity of the approach run should be maintained. The vertical velocity should also be gradually increased. The takeoff angle should be 1° lower in the step and 1° higher in the jump.

References

- Ryu, J. K. (2005). The image analysis of biomechanical characteristics of male triple jumpers. *The Korean journal of physics*, **44**(1), 353-364.
- Ryu, J. K., Kim, C. H., & Kim, Y. H. (2000). The biomechanical analysis of the hop phase in triple jumps. *The Korean journal of biomechanics*, **9**(2), 67-80.
- Ryu, J. K., & Yeo, H. C. (2008). The shock loading and biomechanical analysis of male triple jumpers in universities. *The Korean journal of biomechanics*, **18**(4), 209-216.
- Ryu, J. K., & Yeo, H. C. (2009). The approach run techniques of elite triple jumpers in the takeoff preparation phase. *The Korean journals of social physics*, **35**, 1073-1081.
- Ryu, J. K., & Yun, H. J. (2001). The comparison study of kinematic characteristics between the best records of triple jumpings. *The Korean journal of physics*, **40**(2), 833-841.

- Abdel-Aziz, Y. I., & Karara, H. M. (1971). Direct linear transformation: From comparator coordinates into object coordinates in close-range photogrammetry. Proceeding of ASPUI symposium on Cross-Range Photogrammetry, Urbana, Illinois (1-19). Falls Church, VA: *American Society of Photogrammetry*.
- Ae, M., Fukushima, S., Yamamoto, E., Ito, N., & Saito, N. (1994). Biomechanical analysis of the takeoff techniques of men's triple jump. In H. Sasaki, K. Kobayashi, & M. Ae (eds.), *Techniques of the World's Best Track and Field Athletes*[Japanese], Baseball Magazine Co. Ltd, Tokyo, 152-166.
- Brimberg, J., Hurley, B., & Ladany, S. P. (2006). An operations research approach to the triple jump. *Int. J. Sport Management and Marketing*, **1**(3), 208-214.
- Bruggeman, G-P. (1990). Biomechanical analysis of the triple jump-An approach towards a biomechanical profile of the world's best triple jumpers. *New Studies in Athletics* (Scientific Research Project at the Games of the XXIVth Olympiad-Seoul 1988), 303-362.
- Hackett, B. (1995). Triple jump basics. *Track Technique*, winter. 4138-4141.
- Hay, J. G. (1973). *The biomechanics of sports techniques*. Englewood Cliffs, NJ : Prentice-Hall.
- Hay, J. G. (1990). The biomechanics of triple jump techniques. In *Techniques in Athletics Congress Proceedings* (ed. by G-P Bruggemann and J. K. Ruhl), Cologne, Federal Republic of Germany: Deutsche Sporthochschule Koln, **1**, 296-308.
- Hay, J. G. (1992). The biomechanics of the triple jump: A review. *Journal of Sports Science*, **10**, 343-378.
- Hay, J. G. (1994). Effort distribution in the triple jump. *Track Technique*, spring. 4042-4048.
- Hay, J. G. (1995). The case for a jump-dominated technique in the triple jump. *Track Coach*, summer. 4214-4219.
- Hay, J. G. (1997). Phase distances, percentages, and techniques in the men's triple jump at the 1996 U.S. Olympic trials. *Track Coach*, spring. 4435-4442.
- Hay, J. G. (1999). Effort distribution and performance of Olympic triple jumpers. *Journal of Applied Biomechanics*, **15**, 36-51.
- Hay, J. G., & Miller, J. A. (1985). Techniques used in the triple jump. *International Journal of Sports Biomechanics*, **1**, 185-196.
- Hay, J. G., Miller, J. A., & Canterna, R. W. (1986). The techniques of elite male long jumpers. *Journal of Biomechanics*, **19**, 855-866.
- Koh T. J., & Hay, J. G. (1990). Landing leg motion and performance in the horizontal jumps, II: The triple jump. *International Journal of Sports Biomechanics*, **6**, 361-373.
- Larkins, C., & Ramey, M. R. (1994). Can triple jumpers really use an equal phase ratios strategy?, *Track Technique*, summer. 4081-4086.
- Lee, A., Graham-Smith, P., & Fowler, N. (1994). A biomechanical analysis of the last stride, ouchdown, and takeoff characteristics of the man's long jump. *Journal of Applied Biomechanics*, **10**, 61-78.
- Miller, J. A., & Hay, J. G. (1986). Kinematics of a world record and other world-class

- performances in the triple jump. *International Journal of Sports Biomechanics*, **2**, 272-288.
- Nixdorf, E., & Bruggemann, G-P. (1990). Biomechanical analysis of the long jump-An approach towards a biomechanical profile of the world's best long jumpers. *New Studies in Athletics*(Scientific Research Project at the Games of the XXIVth Olympiad-Seoul 1988), 263-301.
- Plagenhoef, S. (1983). Anatomical data for analyzing human motion. *Research Quarterly for Exercise and Sports*, **54**(2), 169-178.