Mid-phase sprinting movements of Tyson Gay and Asafa Powell in the 100-m race during the 2007 IAAF World Championships in Athletics

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Abstract

In the present study, the running movements of Tyson Gay (9.85 seconds) and Asafa Powell (9.96 seconds) who finished first and third, respectively, in the 2007 IAAF World Championships in Athletics were analyzed. Their data were compared to past data (Ito et al., 1998) in order to determine the characteristics of both sprinters.

Maximal sprint running velocity was 11.85 m/s for Gay and 11.88 m/s for Powell. For Gay and Powell, step frequency was 4.90 and 4.96 steps/s, respectively, and step length was 2.42 and 2.40 m, respectively. According to Ito et al. (1998), sprint running velocity is not related to maximum thigh angle “high knee”, but the faster the sprint running velocity, the greater the minimum knee angle. The maximum thigh angle for Gay and Powell was comparable at 65° and 70°, and the minimum knee angle for Gay and Powell was 41° and 38°, respectively, and these numbers were similar to the data obtained by Ito et al. (1998). The horizontal distance from the toe at the point of landing to the center of gravity for the two sprinters was 0.31 m, and this number is comparable to that for sprinters who run 100 meters in 11 seconds (Fukuda and Ito, 2004). Therefore, it is not necessarily good to land immediately underneath the center of gravity when landing. In support leg movements, an interesting finding was seen with maximum knee extension velocity for Gay and Powell. During landing, the knee joint of both sprinters always remained bent, and when acceleration force was expressed during the later half of the support phase, the extension velocity had a negative value: -50 degrees/s for Gay and -68 degrees/s for Powell.

Training guidance that attempts to increase sprint running velocity by reducing the deceleration associated with landing must be reexamined because the landing distance for Gay and Powell is comparable to that of sprinters who run 100 m in 11 seconds. What is important here is that Gay and Powell continue to bend the knee of the support leg during the support phase, and training guidance that instructs sprinters to actively extend the knee and ankle joints of the support leg must be reevaluated.

1. Introduction

While the 100-m sprint is a simple sport, it requires athletes to compete by running at top speed, and the winner of the 100-m sprint receives the greatest accolades in track and field. In order to run the 100-m sprint with good results, fast reaction time after the start signal and acceleration after the start are important, but the most important element is maximum sprint running velocity. World-class sprinters reach their maximum sprint running velocity in about 70-80 m (Ae and Ito, 1992), and the maximum sprint running velocity of sprinters who run 100 m in less than 10 seconds is ≥11.8 m/s (Ito et al., 1998). Fast sprint running requires a strong body and efficient running movements.

In the present study, the running movements of Tyson Gay (9.85 seconds) and Asafa Powell (9.96 seconds) who finished first and third, respectively, in the 2007 IAAF World Championships in Athletics were analyzed while they were running at top speed in the final race. Their data were compared to past data (Ito et al., 1998) in order to determine the characteristics of both sprinters.

2. Methods

During the final race for the men's 100-m sprint event during the 2007 IAAF World Championships in Athletics, two high-speed video cameras (Phantom v4, Vision Research Inc, USA)were placed at the highest row of the spectator stands on the start line and on the finish line in order to capture Tyson Gay and Asafa Powell at the 60-m mark. The two cameras were synchronized and captured images at 100 Hz. Using motion analysis software (DKH, Tokyo, Japan), the two-dimensional coordinates of 24 body points were scanned at 100 fps, and the direct linear transformation method (DLT) was used to calculate three-dimensional coordinates where the x-axis was the direction of sprinting, the y-axis the vertical direction perpendicular to the ground, and the z-axis was the horizontal line parallel to the starting line. The error between calculated three-dimensional coordinates and the actual values of the calibration points in the x, y and z-axis directions was 0.005 m, 0.005 m and 0.005 m, respectively. The three-dimensional coordinates were subjected to smoothing at 7 Hz using the Butterworth method.

For comparison, data accumulated from men's 100-m sprint events in international competitions and official Japanese track and field meets were used. Of our previous data, the best sprint record was the 9.86 seconds that Carl Lewis ran at the 1991 IAAF World Championships in Athletics in Tokyo.

3. Results and Discussion

Step frequency and step length

Sprint running velocity was determined based on the distance covered by the center of gravity over two steps, and sprint running velocity at the measurement point was 11.85 m/s for Gay and 11.88 m/s for Powell. Figure 1 shows the relationships among sprint running velocity, step frequency and step length. According to past data (Ito et al., 1998), the faster the sprint running velocity, the greater the step frequency and the larger the step length. For Gay and Powell, step frequency was 4.90 and 4.96 steps/s, respectively, and step length was 2.42 and 2.40 m, respectively, and these numbers mostly agreed with past data. Gay is 1.83 m tall and Powell is 1.90 m tall, and the step length to height ratio for Gay and Powell is 1.32 and 1.26, respectively. Hence, while Gay is a step-length type sprinter, Powell is a step-frequency type sprinter. When Carl Lewis set the world record of 9.86 seconds in 1991, step frequency was 4.67 steps/s, step length 2.53 m and step length-to-height ratio 1.35 (Ito et al., 1994).

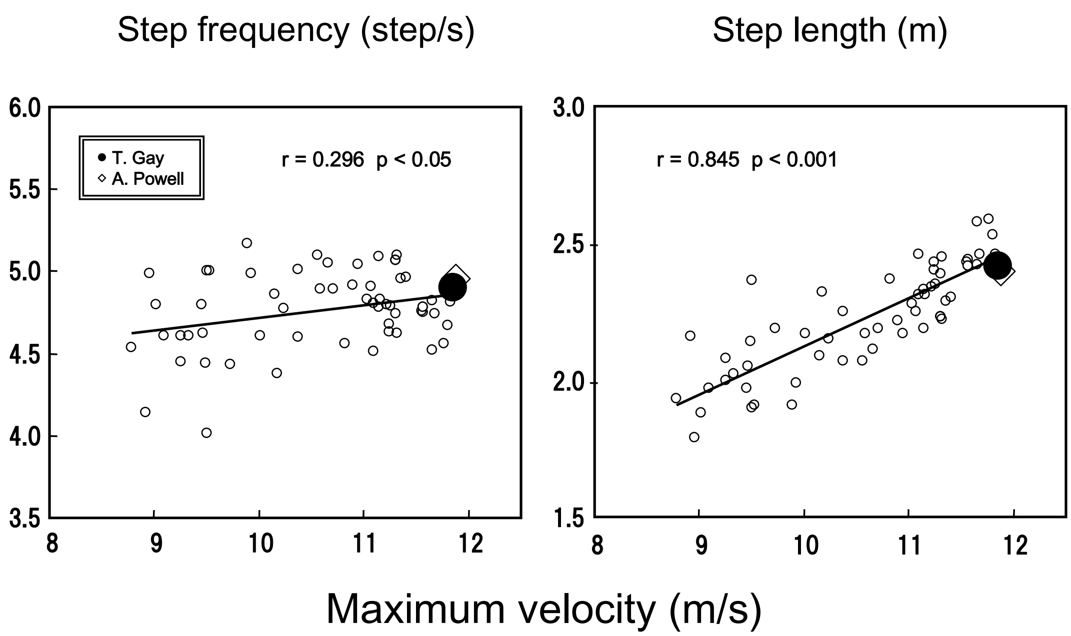

Figure 1. Relationships among sprint running velocity, step frequency and step length.

Recovery leg movements

Leg movements during the recovery phase when the support leg leaves the ground and then the leg is moved forward were analyzed in terms of maximum thigh angle (maximum angle formed by the thigh and the vertical line), minimum knee angle, and maximum leg angle (maximum angle formed by the vertical line and the line connecting the hip joint and the lateral malleolus) (Figure 2). According to Ito et al. (1998), sprint running velocity is not related to maximum thigh angle and maximum leg angle, but the faster the sprint running velocity, the greater the minimum knee angle. The maximum thigh angle for Gay and Powell was comparable at 65° and 70°, and these numbers were similar to the data obtained by Ito et al. (1998). The minimum knee angle for Gay and Powell was 41° and 38°, respectively, and these numbers were comparable to past data.

The maximum leg angle for both sprinters was 34°, and this number was similar to the data obtained by Ito et al. (1998).

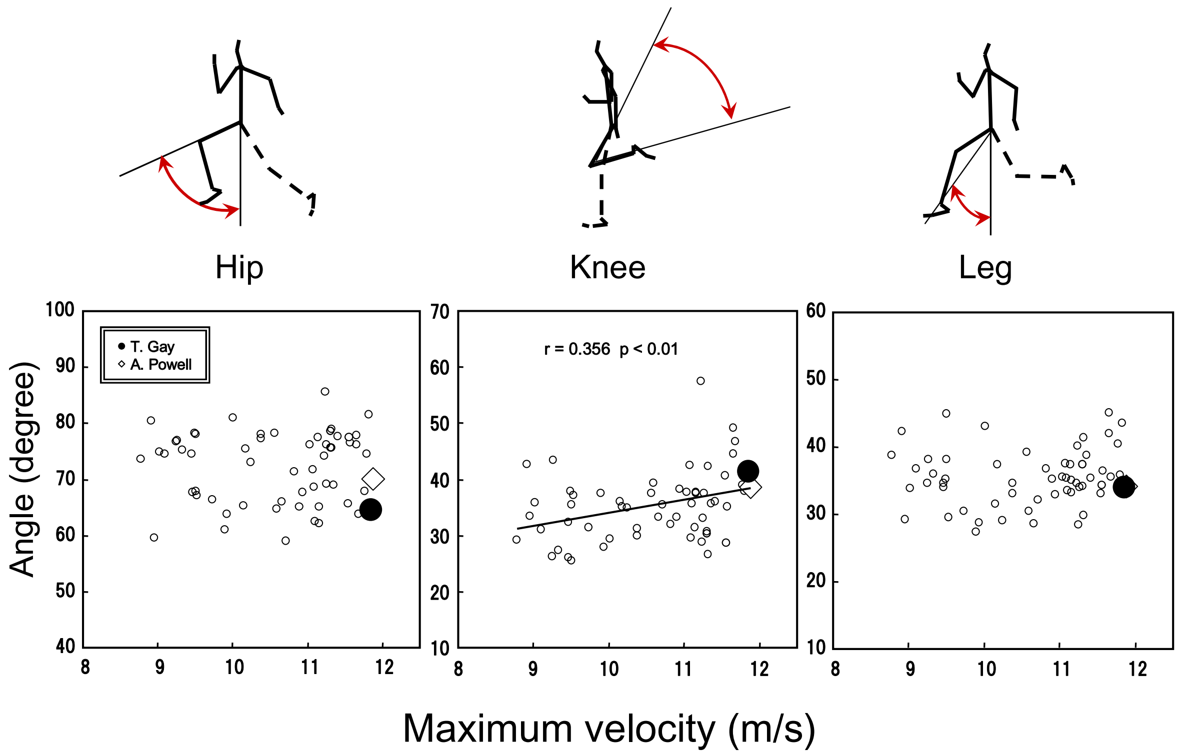

Figure 2 Relationships among sprint running velocity and recovery leg movements

Although the technique of the two sprinters appeared different to the naked eye, there were no marked differences in the parameters measured in the present study. In other words, both sprinters moved their legs forward without excessively raising the thigh, thus resulting in relatively low knee height. The horizontal distance from the toe at the point of landing to the center of gravity (this relates to the maximum leg angle) for the two sprinters was 0.31 m, and this number is comparable to that for sprinters who run 100 meters in 11 seconds (Fukuda and Ito, 2004). Therefore, it is not necessarily good to land immediately underneath the center of gravity when landing.

Support leg movements

In the present study, the driving movements of the support leg were analyzed in terms of the maximum extension velocity of the hip, knee and ankle joints of the support leg during landing (Figure 3). Ito et al. (1998) reported that while fast sprinters exhibited fast hip extension and slow knee extension, the maximum ankle extension velocity did not correlate to sprint running velocity.

However, an interesting finding was seen with maximum knee extension velocity for Gay and Powell. During landing, the knee joint of both sprinters always remained bent, and when acceleration force was expressed during the later half of the support phase, the extension velocity had a negative value: -50 degrees/s for Gay and -68 degrees/s for Powell. According to our unpublished data, Maurice Greene, the previous world record holder, exhibited the similar movement. The knee extension velocity for Lewis was almost zero (Ito et al., 1998), and the results of the present study suggest that sprint running technology has entered a new era.

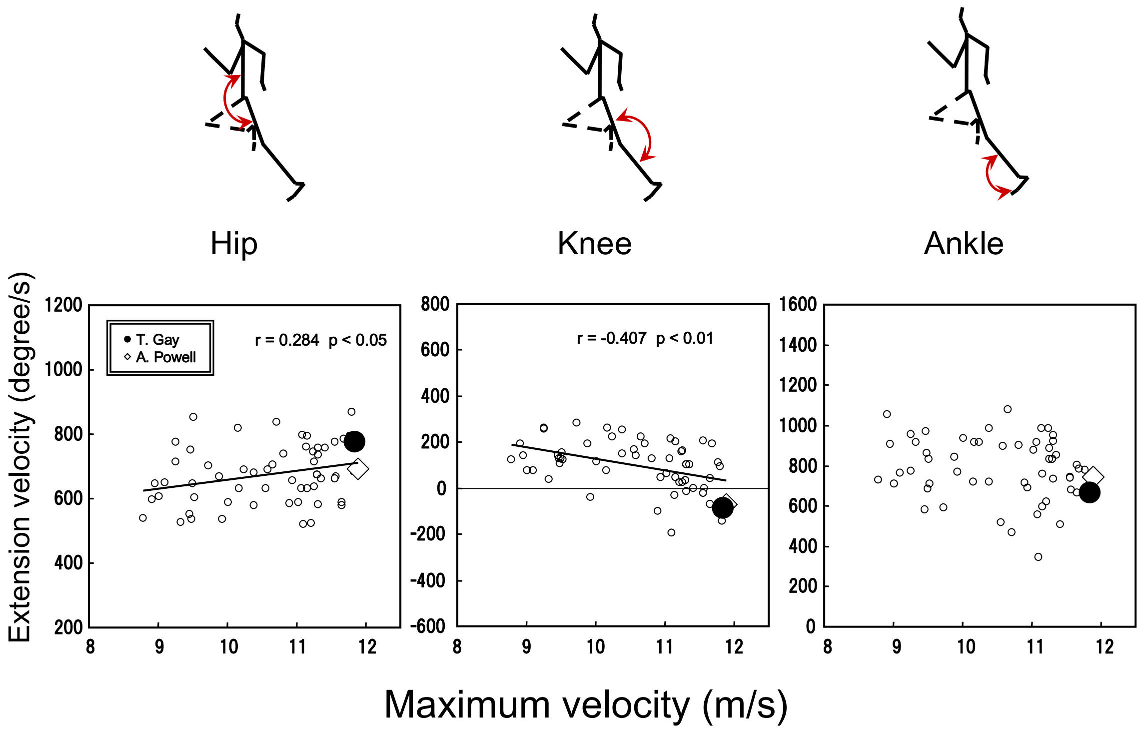

Figure 3 Relationships among sprint running velocity and support leg movements

With regard to knee extension velocity, if the knee joint is fixed like Lewis, then 100% of hip extension can be transferred to drive the leg in the posterior direction, but if the knee joint is bent like Gay and Powell, hip extension velocity is added to the leg, causing the drive velocity of the leg in the posterior direction to exceed 100%. Furthermore, with a driving movement where the knee joint is extended, hip extension velocity is absorbed by knee extension velocity, thus reducing the drive velocity of the leg in the posterior direction.

The maximum hip extension velocity for Gay and Powell was 774 and 693 degrees/s, and the maximum ankle extension velocity 664 and 743 degrees/s, respectively, and these values were mostly comparable to the data obtained by Ito et al. (1998).

4. Guidance recommendations

The results of the present study show that Gay and Powell are world-class sprinters with different characteristics in terms of step length and step frequency, and suggest that caution must be exercised when strongly correcting step frequency and length.

Past studies have shown that the maximum ankle extension velocity is constant and is not related to sprint running velocity, and this suggests that so-called "snapping" movements are due to the spring-like properties of the muscle-tendon complex involving the triceps muscle of the calf and the Achilles tendon. In other words, athletes do not consciously extend the ankle, and guidance should take into account this point.

Training guidance that attempts to increase sprint running velocity by reducing the deceleration associated with landing must be reexamined because the landing distance for Gay and Powell is comparable to that of sprinters who run 100 m in 11 seconds.

What is important here is that Gay and Powell continue to bend the knee of the support leg during the support phase, and training guidance that instructs sprinters to actively extend the knee and ankle joints of the support leg must be reevaluated.

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Analysis of speed patterns in 100-m sprints

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Abstract

The running speed of men's and women's 100-m sprintes, including Tyson Gay (USA), Asafa Powell (JAM) and Veronica Campbell (JAM), at the 11th IAAF Athletic Championships in OSAKA were measued by using laser beam apparatus (LAVEG Sport, JENOPTIK, Germany). The purpose of this brief report was to investigate changes in running speed during the 100-m races and to provide information a sprint training. The highest speed of Gay (USA), who won the men's 100-m, and Powell (JAM) was 11.83 m/s and 11.79 m/s, respectively, and the rate of decrease in speed was 2.2% for Gay and 8.1% for Powell. However, their top speed was slower than that of Carl Lewis at the 3rd IAAF World Championships in Tokyo (12.05m/s, 9.86s of previous WR). In women, the highest speed attained by Campbell (JAM) was 10.56m/s and the rate of decrease in speed was 9.6%. The correlational coefficient between the top speed and goal time was -0.933 for men ($p < 0.0001$) and -0.962 for women ($p < 0.0001$). The rate of decrease in speed ranging from 2% to 13% has a small effect on the goal time. However, it may influence the ranking of the races of both the men's and women's.

1. Introduction

Tyson Gay (USA) won the 100-m world title for men in 9.85 s, followed by Derrick Atkins (BAH) who won the second rank in 9.91s, with world record holder Asafa Powell (JAM) attaining the third position. Powell led the run from the start to a distance of 60 m; however, after 60~70 m, his speed decreased suddenly. Taking the same time of 11.01 s, Veronica Campbell (JAM) defeated the defending champion Lauryn Williams (USA).

In 100-m races, the important factors comprise the acceleration from the start to the top speed, the top speed, and the decrease in speed just before the goal. Analysing 100-m races of the world championship will provide extremely important data for planning the training strategy in a sprint. The speed analyses of 100-m races were conducted by using video cameras or measuring instruments with the laser beam method. This method could measure the running speed from start to finish with a sampling rate of 100 Hz, although we had employed this method for evaluating the speed of the sprinters during 100-m races.

2. Method

In this study, the apparatus using the laser beam (LAVEG Sport, JENOPTIK, Germany) was employed for measuring the running speed. The error of measurement of this device is 7 cm, and the safety of the laser beam is categorised as class 1 by the safety standard. In this study, we positioned the five apparatuses at 64~68 m before the start line and 22~24 m above ground level (Figure 1). We measured the running speeds during sprinting for all races of men and women, from the first to the final round. In each race, five sprinters were selected based on their best performance in the daily programme.

Figure 1. Setting the 5 lavegs in seat in stand.

The measurement tools were positioned at the top of the stand behind the 100-m lanes such that different noises remained in the data, affected by the tilting movement of the device, particularly from the start to a distance of 40 m. These noises were removed by the spine interpolation; other noises were removed by the 1-Hz low pass Butterworth digital filter. Using filtered data, the elapsed time of 10 m from the start to the goal was calculated using the distances-time curves data. From the elapsed time, we calculated the running speed at each interval, the top speed and the rate of the decrease in speed from the top to the last speed, i.e. from 90 m to 100 m. The official results were used in the goal and reaction times.

3. Results

The measuring objects included 75 examples from the first to the final round; we obtained the data of 63 samples for men, with the goal time ranging from 9.85 s to 10.46 s, and the data of 71 samples for women, with the goal time ranging from 10.99 s to 11.98 s. In our opinion, the data loss occurred when the runner did not begin and qualify and when the laser light beam was unable to follow the runners because the device was positioned high on the stand.

Goal time, top speed, the appeared distance of the top speed, the reaction time at the start, the elapsed time of 10 m, the speed of a 10-m interval, the rate of decrease in speed from the top to the speed of the last interval of every man and woman were recorded in table 1. These data represented the data of the 1st, 2nd, 3rd, 5th, and 6th ranked male runners and the 1st, 2nd, 4th, 5th, and 6th ranked female runners and the time of 10.99 s at their semi-final.

Tabel 1. Reaction time, Goal time, top speed, percent of decrease in speed, elapsed time, speed, %max in 100m finals of men and women.

Men 100m Final (Wind;-0.5m/s)

rank	name	reaction time s	goal time s	top speed m/s	top distance m	%Decrease in Speed %	Distance(m)	10	20	30	40	50	60	70	80	90	100
1	Tyson Gay	0.143	9.85	11.83	65	2.2	elapsed time (s)	1.90	2.94	3.86	4.73	5.59	6.44	7.28	8.13	8.99	9.85
	USA						speed(m/s)	5.25	9.70	10.83	11.42	11.72	11.79	11.83	11.80	11.67	11.57
							% max speed	44.4	82.0	91.6	96.6	99.0	99.7	100.0	99.7	98.7	97.8
2	Derrick Atkins	0.137	9.91	11.74	55	1.8	elapsed time (s)	1.89	2.93	3.87	4.75	5.62	6.47	7.32	8.18	9.04	9.91
	BAH						speed(m/s)	5.28	9.65	10.69	11.26	11.57	11.74	11.71	11.70	11.58	11.53
							% max speed	45.0	82.2	91.1	95.9	98.6	100.0	99.7	99.7	98.7	98.2
3	Asafa Powell	0.145	9.96	11.79	55	8.1	elapsed time (s)	1.88	2.91	3.83	4.71	5.57	6.42	7.29	8.16	9.04	9.96
	JAM						speed(m/s)	5.31	9.73	10.83	11.38	11.67	11.79	11.51	11.51	11.34	10.84
							% max speed	45.1	82.5	91.8	96.6	99.0	100.0	97.7	97.6	96.2	91.9
5	Churandy Martina	0.180	10.08	11.67	65	2.6	elapsed time (s)	1.98	3.03	3.98	4.88	5.75	6.62	7.47	8.34	9.20	10.08
	AHO						speed(m/s)	5.05	9.49	10.62	11.09	11.42	11.58	11.67	11.60	11.56	11.37
							% max speed	43.3	81.3	91.0	95.0	97.8	99.2	100.0	99.4	99.0	97.4
6	Marlon Devonish	0.149	10.14	11.48	65	3.9	elapsed time (s)	1.96	3.00	3.95	4.85	5.73	6.61	7.48	8.36	9.23	10.14
	GBR						speed(m/s)	5.11	9.60	10.52	11.09	11.31	11.42	11.48	11.37	11.42	11.03
							% max speed	44.6	83.7	91.7	96.7	98.6	99.5	100.0	99.1	99.5	96.1

Women 100m final (Wind;-0.2m/s), & best time(Wind;-0.1m/s)

rank	name	reaction time s	goal time s	top speed m/s	top distance m	%Decrease in speed %	Distance (m)	10	20	30	40	50	60	70	80	90	100
1	Veronica Campbell	0.167	11.01	10.56	55	9.3	elapsed time (s)	2.01	3.14	4.15	5.11	6.07	7.02	7.97	8.96	9.97	11.01
	JAM						speed(m/s)	4.97	8.84	9.96	10.36	10.46	10.56	10.45	10.12	9.94	9.58
							% max speed	47.1	83.7	94.3	98.0	99.0	100.0	98.9	95.8	94.1	90.7
2	LaurynWilliams	0.145	11.01	10.40	45	6.1	elapsed time (s)	2.01	3.13	4.13	5.10	6.06	7.03	8.00	8.98	9.99	11.01
	USA						speed(m/s)	4.97	8.97	9.95	10.32	10.40	10.37	10.35	10.14	9.95	9.76
							% max	47.8	86.2	95.7	99.3	100.0	99.7	99.5	97.5	95.7	93.9
4	Torri Edwards	0.141	11.05	10.45	45	7.3	elapsed time (s)	2.00	3.12	4.15	5.12	6.08	7.04	8.01	9.00	10.02	11.05
	USA						speed(m/s)	5.01	8.87	9.78	10.25	10.45	10.42	10.34	10.06	9.84	9.68
							% max	47.9	84.9	93.6	98.1	100.0	99.7	98.9	96.2	94.2	92.7
5	Kim Gevaert	0.143	11.05	10.32	55	6.9	elapsed time (s)	1.98	3.10	4.11	5.10	6.08	7.04	8.02	9.01	10.01	11.05
	BEL						speed(m/s)	5.06	8.92	9.86	10.08	10.30	10.32	10.28	10.12	9.97	9.61
							% max	49.0	86.4	95.6	97.6	99.8	100.0	99.6	98.0	96.6	93.1
6	Christine Arron	0.164	11.08	10.41	45	7.9	elapsed time (s)	2.03	3.15	4.16	5.13	6.09	7.06	8.03	9.02	10.04	11.08
	FRA						speed(m/s)	4.93	8.95	9.84	10.30	10.41	10.41	10.29	10.04	9.86	9.59
							% max	47.3	85.9	94.5	98.9	100.0	100.0	98.8	96.4	94.7	92.1
SF	Veronica Campbell	0.144	10.99	10.46	55	9.5	elapsed time (s)	2.00	3.12	4.12	5.10	6.07	7.02	7.98	8.96	9.93	10.99
	JAM						speed(m/s)	4.99	8.94	9.98	10.21	10.37	10.46	10.39	10.30	10.22	9.47
							% max	47.7	85.4	95.5	97.6	99.1	100.0	99.4	98.5	97.7	90.5

The maximum top speed attained by Gay (USA) over a distance of 60–70 m is 11.83 m/s; he was followed by Powell who ranked 3rd with a speed of 11.79 m/s. Lewis (USA) whose goal time was 9.86 s recorded a top speed of 12.05 m/s in the men's 100-m final at the third IAAF World Championships in Tokyo in 1991. Thus, Gay's top speed was 0.22 m/s slower than that of Lewis. With regard to the women's championship, Campbell (JAM) who attained the 1st position in the final was the fastest with a speed of 10.56 m/s, followed by Williams (US) who ranked 2nd with a speed of 10.45 m/s.

The changes in the speed of the top three male sprinters have been recorded in figure 2. From the start to a distance of 60 m, the tendency of changes in speed in Gay and Powell almost exhibited an identical pattern; however, after covering a distance of 60 m, the speed of Powell decreased suddenly. On the other hand, after this point, Gay maintained his speed at the same level, and decreased it slightly just before the goal. The percentage of the decrease in speed was 2.2% in Gay and 8.1% in Powell.

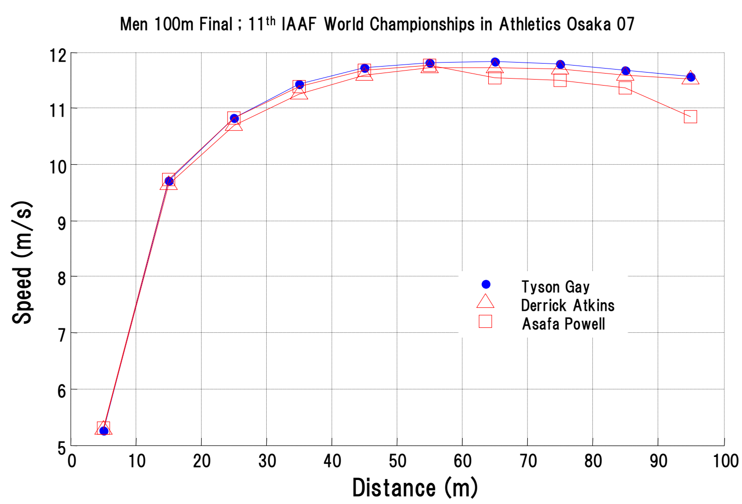

Figure 2. Speed changes in top 3 sprinter at men's 100m final

Figure 3 presents the changes in the speed of the top two female sprinters.　Taking the same time, Campbell defeated the defending champion Williams and attained a top speed of 10.56 m/s in the distance from 50 m to 60 m; however, after this point, her speed decreased.　The top speed of Williams who ranked second was lower than that of Campbell by 10.40 m/s.　However, William's acceleration at the start and the ability of maintaining her speed was higher than that of Campbell. Thus, during the distance from 70 m to the goal, the speed of Williams was higher than that of Campbell.

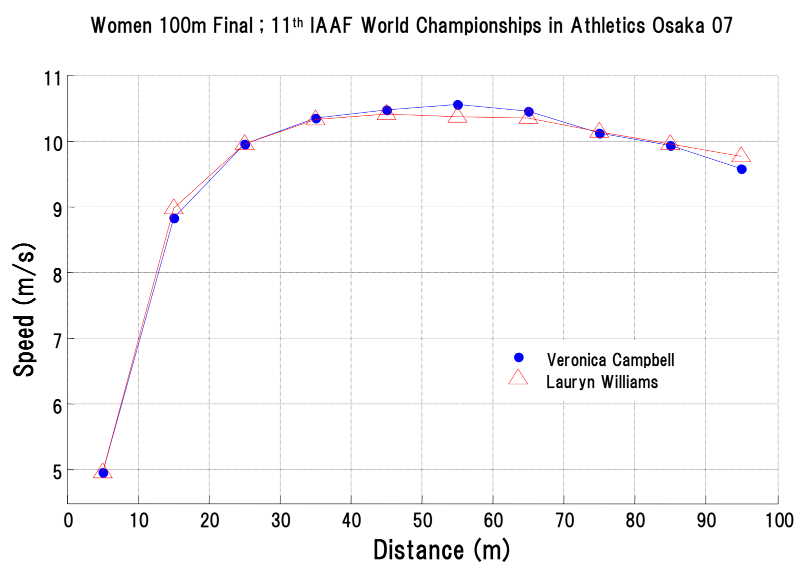

Figure 3. Speed changes in top 3 sprinter at women's 100m final

Figure 4 presents the relationship among the top speed, the elapsed time of 30 m, the percentage of decrease in speed and the goal time.　M represents men, W represents women, JPN is the data collected in Japan which includes the data of the international events held in Japan and 07 Osaka represents the present world championship in athletics.　Among men, the range of the goal time in 101 samples of JPN was from 9.95 s (Gatlin; USA, 2006) to 10.91 s; among women, the range of the goal time in 106 samples was from 11.05 s (Felix; USA, 2005) to 12.89 s.

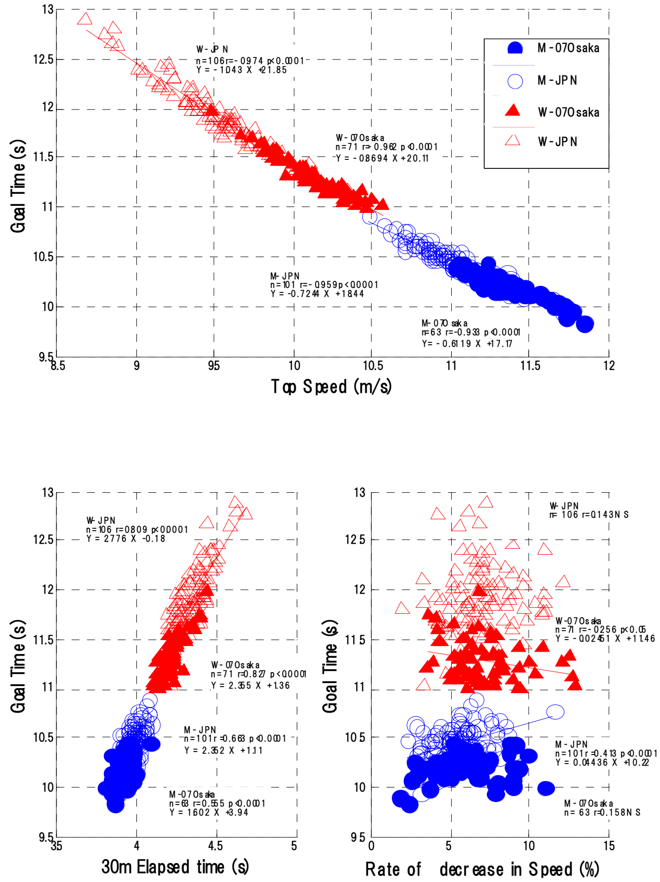

Figure 4. The relationship among top speed, 30m elaped time, and percent of decrease in speed, and goal time.

The top speed and the goal time were inversely related, and significant statistical correlations existed for any group (M-07 Osaka = –0.933, M-JPN = –0.959, W-07 Osaka = –0.962, W-JPN = –0.974, $p < 0.0001$). It has been demonstrated that in 100-m races, the higher the top speed, the better is the performance.

In any group, the elapsed time at 30 m was also statistically related to the goal time. The correlation coefficients were from 0.555 to 0.809, which were lower than the relationship of the top speed with the goal time.

The rate of decrease in speed had been distributed in the range of 2% to 13% in all groups. When we observe the decrease rate of the speed and goal time in each group, we find that there was a positive relation in M-JPN and a negative relation in W-07 Osaka with statistically significant $p < 0.05$, and that in the other group, they had no relationship between them. From these results, it was suggested that there was a small effect of maintaining speed to the goal on a 100-m sprint performance. This is the one of the factors that did not result in any relationship between the goal time and the percentage of the decrease in speed.

4. Conclusion

We obtained the extremely important data for 100-m sprinting in men (63 samples) and women (71 samples) in the 11th IAAF World Championships in Osaka.

The highest speed of Gay (USA), who won the men's 100-m finals, was evaluated to be 11.83 m/s and the rate of decrease in speed was evaluated to be 2.2%. In women, the highest speed attained by Campbell (JAM) was 10.56m/s and the rate of decrease in speed was 9.6%.

Statistically significant relationships exist between the top speed and goal time in men ($r = 0.933$, $p < 0.0001$) and women ($r = 0.962$, $p < 0.0001$).

The value of the rate of decrease in speed distributed from 2% to 13% has a small effect on the goal time; however, it affects the ranking in each race, for example, in both the men's and women's finals.

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Biomechanical analysis of the world's top distance runners of the 10,000 m final in the Osaka 2007 11th IAAF World Championships in Athletics

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Abstract

The purpose of this study was to reveal the biomechanical characteristics of running motion for the world's top distance runners in the men's 10000 m final at Osaka World Championships in Athletics. Bekele showed greater mean power and smaller effectiveness of mechanical energy utilization to running velocity, however increased in effectiveness at the latter of the race. Maximum, minimum and range of the thigh and shank angle showed the difference between the runners but did not change greatly throughout the race. Maximal thigh angular velocity of the recovery leg increased for Bekele, which might be critical motion for distance runners. The world's top distance runners showed a slight change of running motion and few fatigue symptoms. Even a distance runner must perform like a sprinter; it might be necessary to maintain high running speed during a race and spurt at the end. This is not only to utilize mechanical energy efficiently but also to generate more mechanical energy.

Introduction

It is an important task for success in distance running to maintain running speed over an entire race distance, however it was not unusual in those races for the winner and second place to be separated by a second. Therefore race management became a very important factor. The gold medalist not only maintained a high running speed, but in the recent distance races of the World Championships and Olympic Games the champion used two highly effective strategies: (1) changing running speed intentionally throughout the race to cause rivals to waste energy; (2) spurting sharply on the last lap like a sprinter.

From an energetic view point, both the increase in energy generation and effective utilization of energy to running velocity would be critical factors to performance of distance runners. Physiological studies have revealed the relationship of the physiological factors such as $\dot{V}O_2max$, lactate threshold and running economy to distance running performance. However, runners were evaluated by $\dot{V}O_2max$ and running economy in running on a treadmill in a laboratory. Biomechanical study indicated the direct relationship of running motion to the performance in the race. Enomoto et al. (1997) suggested that the elite distance runners showed higher effectiveness of mechanical energy utilization to running velocity in a running cycle.

One of the most interesting factors about distance runners is how they sustain and manage to maintain running speed against fatigue. Elliot and Ackland (1981) showed a few kinematic variables changing during the race as a result of fatigue. Williams et al. (1991) suggested that change in running motion due to fatigue is different by individuals. However, there are few studies about changes in running motion for the world's top distance runners during the race. A study analyzing the change in running motion during the race might give useful information about the running techniques of the world's top distance runners and a new insight into training for distance runners from biomechanical viewpoint.

The purpose of this study was to reveal the biomechanical characteristics of running motion for the world's top distance runners in the men's 10000 m final at Osaka World Championships in Athletics.

Methods

We videotaped the runners at a fixed area on the backstretch in the men's 10000 m final in Osaka World Championships in Athletics using two digital video cameras (60 Hz) from side and front views of a runner. Another video camera was videotaped following the top group from the start to the goal to calculate the split time of each 100 m. The first place finisher of the race was Kenenisa Bekele (ETH) who is the world record holder of 10000 m, the second place finisher was Sileshi Sihine (ETH), the third place finisher was Martin Irungu Mathathi (KEN), whose height, body mass, best time of 10,000 m were 1.60 m, 54 kg, 26:17.53 for Bekele, 1.71 m, 55 kg, 26:39.69 for Sihine, 1.67 m, 52 kg, 27:08.42 for Mathathi, respectively. Running speed and step frequency were derived from the lap time of each 100 m and average time of a cycle (two steps) in each 100 m and step length was divided running speed by step frequency. Running motion of the top three runners were analyzed during a running cycle at the 600 m (stage 1), 3800 m (stage 2), 6200 m (stage 3), 8200 m (stage 4) and 9400 m (stage 5) marks using the three-dimensional motion analysis technique. After calculation of three dimensional coordinates and smoothing the coordinate data using digital Butterworth filter, the center of gravity of the body, angles and angular velocities of the segments and joints of lower limbs, mechanical energy of whole body were calculated. Effectiveness index of mechanical energy utilization to running velocity was calculated by horizontal translational mechanical energy of the body divided by mechanical work in a cycle (Enomoto et al., 1997), which was calculated by sum of energy change of each segment in each time interval (Metzler et al., 2002).

Results ＆ Discussion

Table 1 shows the split and lap time for top three at each 1000 m during the race. Each 1000 m lap times from the start to 9000 m were almost same. There was a small difference between three runners in the last 1000 m, although no difference was found between them until the 9000 m mark. The goal time of the winner was the sixteenth fastest time (his season best time at that time) in 2007 despite the high temperature and humidity (30 degree, 65 %) in Osaka that night.

Table 1 Split and lap time at each 1000m in the race.

	1. Kenenisa Bekele (ETH)		2. Sileshi Sihine (ETH)		3. Martin Irungu Mathathi (KEN)	
Distance	Split time	Lap time	Split time	Lap time	Split time	Lap time
1000	2 : 44.36		2 : 44.53		2 : 45.38	
2000	5 : 27.61	2 : 43.25	5 : 27.79	2 : 43.26	5 : 28.19	2 : 42.81
3000	8 : 13.59	2 : 45.98	8 : 13.79	2 : 46.00	8 : 14.04	2 : 45.85
4000	10 : 58.21	2 : 44.61	10 : 58.36	2 : 44.56	10 : 58.36	2 : 44.31
5000	13 : 43.41	2 : 45.20	13 : 43.62	2 : 45.27	13 : 43.76	2 : 45.40
6000	16 : 29.22	2 : 45.82	16 : 29.39	2 : 45.77	16 : 29.52	2 : 45.77
7000	19 : 13.07	2 : 43.85	19 : 13.32	2 : 43.93	19 : 13.37	2 : 43.85
8000	21 : 55.20	2 : 42.13	21 : 55.42	2 : 42.10	21 : 55.53	2 : 42.16
9000	24 : 35.79	2 : 40.59	24 : 35.96	2 : 40.54	24 : 35.54	2 : 40.01
10000	27 : 05.90	2 : 30.11	27 : 09.03	2 : 33.07	27 : 12.17	2 : 36.63

Figure 1 shows the running speed, step frequency and step length in each 400 m for the top three. Running speed of the top three was almost same until last three laps, while they suddenly sped up around 8800 m mark and time of the final lap were 55.51 s of Bekele, 58.66 s of Sihine and 62.16 s of Mathathi. Bekele was behind Mathathi and Sihine and seemed to exhaust energy before the final lap, but he sped up dramatically and left others behind.

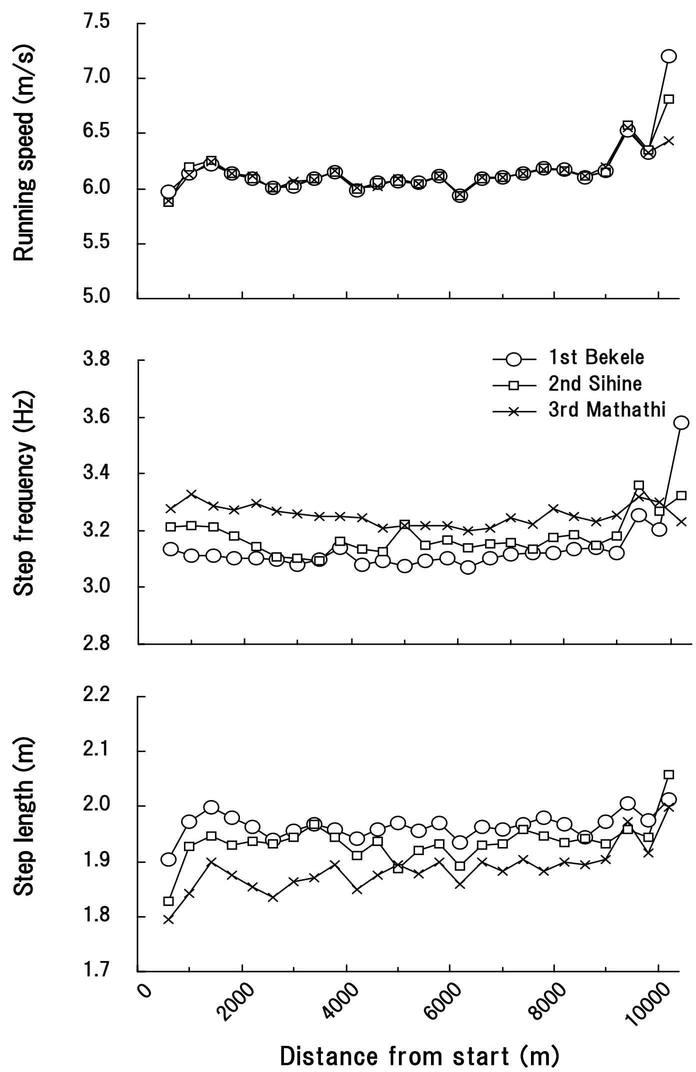

Figure 1 Running speed, step frequency and step length for top three in each 400 m during the race

There was also no change in step frequency and step length until 9000 m. Elliot and Ackland (1981) showed that the decrease in running velocity caused by decrease in step length, while Williams et al. (1991) showed the increase in step length with fatigue eliminating an effect of running speed. Furthermore, the data of this race showed no significant change in the support time (average of right and left foot) during the race. It seems that the top three runners accomplished their best as if they were not fatigued throughout the race despite the hot muggy conditions.

Bekele showed small step frequency and large step length during the race, conversely Methathi showed large step frequency and small step length. Their average step lengths to body height during the race were 1.23, 1.13 and 1.13 for Bekele, Sihine and Mathathi, respectively. Bekele increased running speed by increasing in step frequency largely at the final lap. Correlation coefficients of running speed to step frequency and step length were 0.904 and 0.662 for Bekele, 0.753 and 0.492 for Sihine, and 0.377 and 0.717 for Mathathi. These results suggested that Bekele could maintain large step length during the race and change in running speed by change in step frequency, especially at last spurt.

Figure 2 shows changes in the effectiveness index of mechanical energy utilization to running velocity (EI) and mechanical power which was calculated to divide mechanical work by cycle time of top three from stage 1 to 5. EI of Bekele was smaller than the others at stage 1, then increase at stage 3 and 5. EI of Sihine and Mathathi were greater than Bekele at stage 1, but Sihine decreased in EI from stage4 to 5. Mathathi maintained EI through the race. Mean power of them doesn’t show consistent change through the race. Bekele’s mean power was greater than the others at stage 1 and 2. These results suggest that running motion of Bekele expended more energy but he can increased in effectiveness to maintain the running velocity and speed up at the end of the race. Mathathi may have good running technique to utilize mechanical energy effectively although he can not output more energy to speed up more at end of the race.

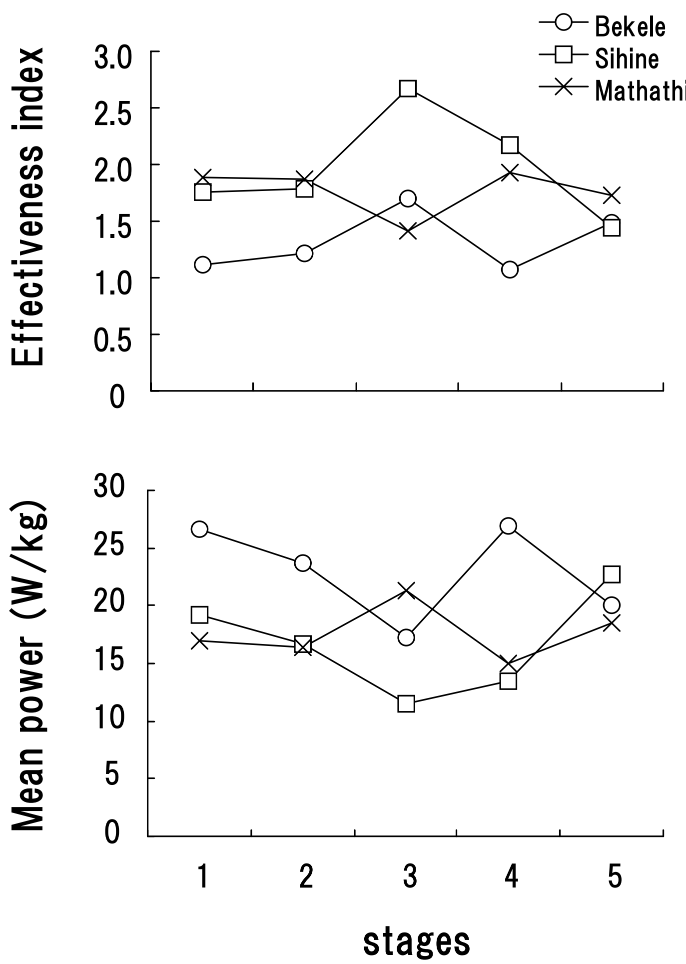

Figure 2 Changes in effectiveness index of mechanical energy and mean power of top three at each stage in the race.

Figure 3 shows the changes in the maximal and minimum thigh and shank angles at each stage for the top three. Thigh and shank angle was defined as angle to the vertical (counter-clockwise is positive). Positive means swinging to the front of the body and negative means backward. The lengths of each bar indicate the range of motion of thigh and shank. The range of shank movement for Bekele was greater than the others, although the range of thigh movement for Mathathi was greater than the others from stage 1 to 5. All three runners showed minor changes in maximal and minimum angles of thigh and shank. Maximal thigh angle and the range of movement of the thigh for Mathathi gradually increased, while those of Bekele and Sihine didn't change. Maximal and minimum shank angles were maintained for Bekele but decreased for Sihine and Mathathi.

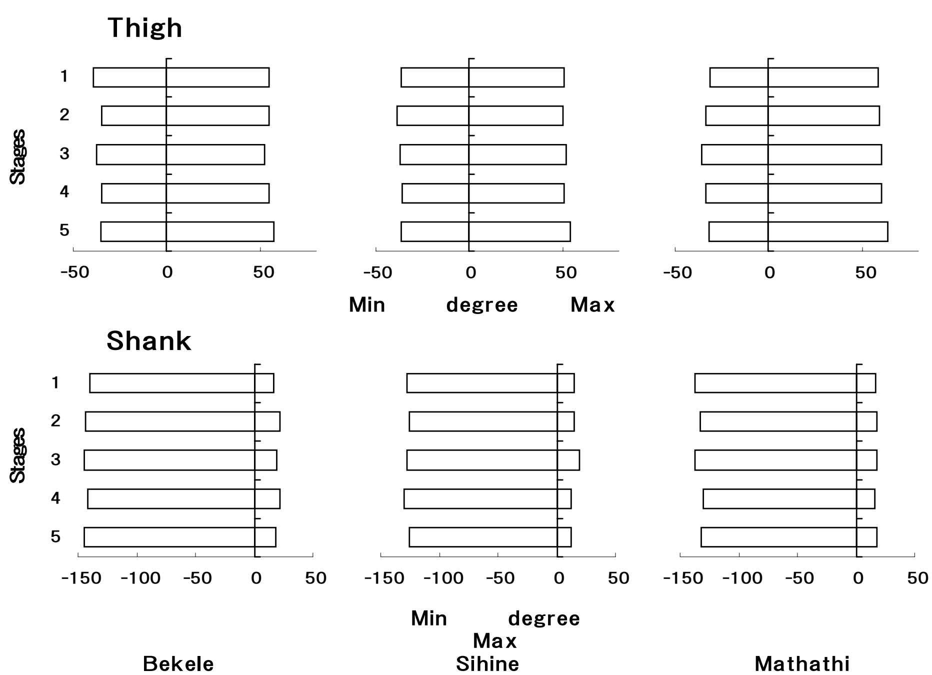

Figure 3 Maximum and minimum angles of the thigh and shank for the top three runners at each stage in the race.

Figure 4 shows stick pictures of the top three runners at 8200 m mark (stage 4) in the race. Thin lines indicate the left side. Bekele shows that his shank was pulled up to the thigh greatly in early recovery phase with the consequence of the decrease in minimum knee angle, and then swung forward greatly before the foot strike.

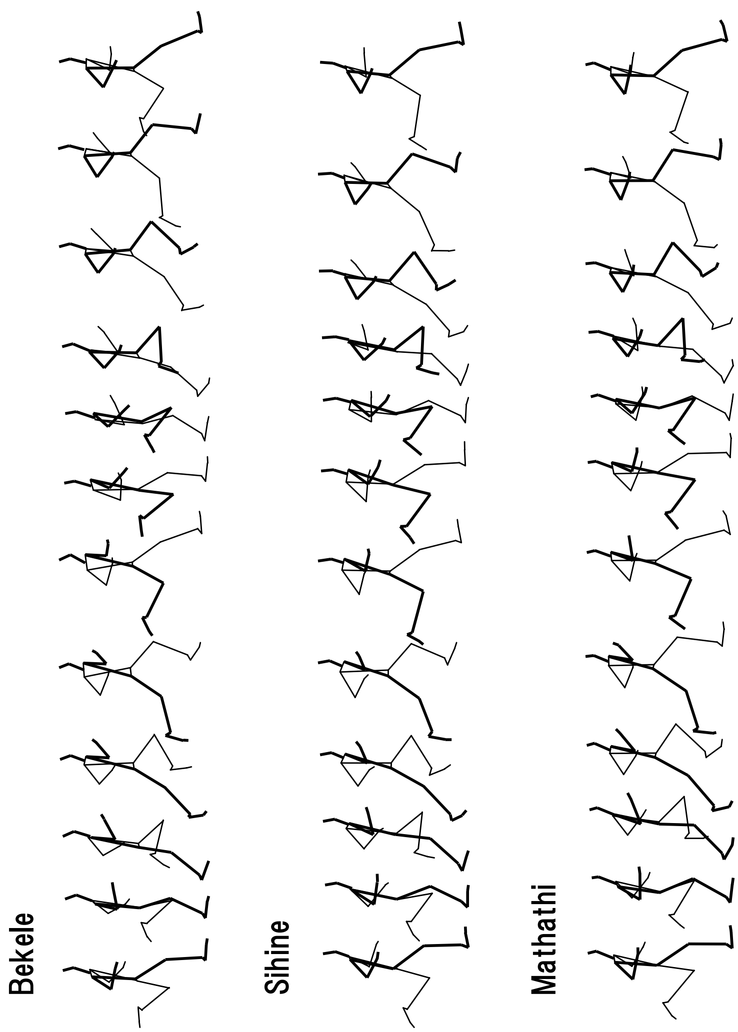

Figure 4 Stick pictures of the top three runners at 8200m mark (stage 4) in the race.

Figure 5 shows changes in maximum thigh angular velocity (MTAV) of the top three runners at each stage in the race. At stage 1 and 2 Mathathi showed greater MTAV than the others. Bekele showed the increase in MTAV gradually from stage 1 to 4. These results imply that Bekele maintain the forward swing velocity of the thigh as a result of the control on the shank motion, which might be characteristic for Bekele. Enomoto and Ae (2005) suggested that Kenyan runners swung the thigh forward faster due to flexing the knee of the recovery leg greatly. These suggested that forward swing of thigh is an important motion for distance runners.

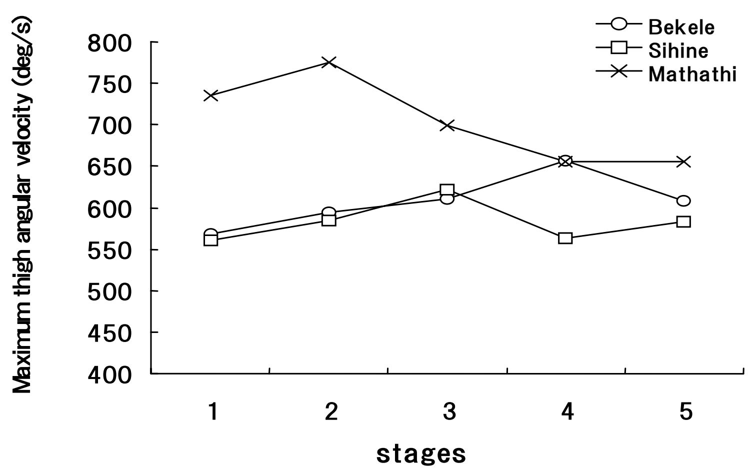

Figure 5 Change in maximum thigh angular velocity of top three runners at each stage in the race.

In conclusion, the world's top distance runners show a slight change of running motion and few fatigue symptoms. The characteristic of Bekele's running motion was greater shank motion, which would need to expend more mechanical energy. Like a sprinters, it might be necessary for distance runners to maintain high running speed during a race and to spurt at the end of a race to not only utilize mechanical energy efficiently but also to generate more mechanical energy.

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Biomechanical analysis of the men's and women's long jump at the 11th IAAF World Championships in Athletics, OSAKA 2007: A brief report

Hiroyuki Koyama, Michiyoshi Ae, Yuya Muraki, Aya Yoshihara, and Kazuhito Shibayama

Abstract

The men's and women's long jumpers at the 11th IAAF World Athletic Championships in Osaka were three-dimensionally analyzed in the preparatory, takeoff, airborne, and landing phases. The purpose of this brief report was to investigate kinematics of the top three long jumpers in Osaka 2007. The results on the preparatory phase indicated that the investigated jumpers increased the run-up speed until the 2nd last stride, and lowered their C.G. in the airborne phase of the 2nd last stride by lengthening the airborne time.

An interesting observation was the lateral foot placement in the 2nd last stride and last stride, and an inward-inclined takeoff leg in the takeoff phase in the frontal plane, which induced effective use of the hip abductors of the takeoff leg to enhance the vertical velocity during the takeoff, as similar to the high jump (Okuyama *et al*., 2003)..

1. Introduction

The finals of the men's and women's long jump at the 11th IAAF World Championships in Athletics Osaka were held in 30th August and 28th August, respectively. The men's winner, Irvine Saladino (PAN) marked his personal best and new African record of 8.57 m. In the women's final, only Tatyana Lebedeva (RUS) jumped over 7.0 m, followed by Lyudmila Kolchanova (RUS) and Tatyana Kotova (RUS). The current world record of the men's long jump was 8.95 m, marked by Mike Powel (USA) at the 3rd World Championships in Athletics Tokyo, 1991. In this game, Carl Lewis (USA) also jumped over 8.90 m, the previous world record by Bob Beamon. These jumps were studied by the biomechanical research project team organized by International Association of Athletic Federations and Japan Association of Athletic Federations. The report of this project provided findings for improving the performance, for example, the run-up speed of Powel and Lewis at the touchdown of the takeoff was over 11.0 m/s, and that of the other finalists was approximately 10.4 m/s; the less knee flexion of the takeoff leg was a very important factor to gain the vertical velocity during the takeoff (Fukashiro *et al*., 1994).

At the 11th World Athletic Championships in Osaka, the biomechanics research project was also organized by International Association of Athletic Federations and Japan Association of Athletic Federations, and videotaped the qualifications and finals of the men's and women's long jump to obtain biomechanical information of the elite athletes and to provide coaches and athletes with findings to improve their performance.

The purpose of this brief paper was to report kinematics data of the top three men and women long jumpers in Osaka, 2007.

2. Methods

2.1 Analyzed jumps

Tables 1 and 2 show the characteristics of the top three men and women long jumpers, which were analyzed in this report.

Table 1. Characteristics of the top three jumpers in the Men's final

Rank	Name	Nation	Height (m)	Weight (kg)	Personal best (m)	Result	Analyzed jump
1	Irving SALADINO	PAN	1.76	70	8.56	6th 8.57 (+0.0)	6th 8.57 (+0.0)
2	Andrew HOWE	ITA	1.84	73	8.41	6th 8.47 (-0.2)	6th 8.47 (-0.2)
3	Dwight PHILLIPS	USA	1.81	81	8.6	1st 8.30 (+0.4)	1st 8.30 (+0.4)

Table 2. Characteristics of the top three jumpers in the Women's final

Rank	Name	Nation	Height (m)	Weight (kg)	Personal best (m)	Result	Analyzed jump
1	Tatyana LEBEDEVA	RUS	1.73	63	7.33	3rd 7.03 (+0.3)	3rd 7.03 (+0.3)
2	Lyudmila KOLCHANOVA	RUS	-	-	7.21	6th 6.92 (-0.3)	6th 6.92 (-0.3)
3	Tatyana KOTOVA	RUS	1.78	57	7.42	6th 6.90 (+0.5)	6th 6.90 (+0.5)

2.2 Data collection and reduction

The men's and women's long jumpers qualified for the finals of the long jump were videotaped with two high-speed video cameras (250 Hz) and two digital video cameras (60 Hz) placed on the top row of the stadium. The two high-speed video cameras covered the 2nd last stride, last stride and takeoff, and the normal digital video cameras videotaped the airborne and landing motions. A calibration pole with seven control points was set at the fourteen locations over the videotaping area to reconstruct the real coordinates of the jumpers' segment endpoints.

Three-dimensional coordinates of twenty-three segment endpoints were reconstructed by using a three-dimensional direct linear transformation (3D-DLT) method, and were smoothed with a Butterworth low-pass digital filter at optimal cut-off frequencies determined by residual analysis, 4.8 to 8.4 Hz.

The official distance was divided into three lesser distances, which were takeoff distance, flight distance and landing distance, as shown in Figure 1. The takeoff distance (L1) is the horizontal distance between the front edge of the takeoff board and the center of gravity (C.G.) of the body at the instant of the toe-off. The flight distance (L2) is the horizontal distance that the C.G. travels while the athlete is in the air. The landing distance (L3) is the horizontal distance between the C.G. at the instant the heels hit the sand and the ultimate mark in the sand made by the jumper. Toe-to-board distance (L4), which is the horizontal distance between the toe of the takeoff foot and the front edge of the board at the instance of the toe-off of the takeoff, was calculated as an indicator of the accuracy of the takeoff.

The C.G., joint angles of the takeoff leg, hip and shoulder rotation angles, and trunk angle were calculated. The leg angle between the line connecting the hip to ankle joint of the takeoff leg and horizontal line was calculated in the sagittal and frontal planes.

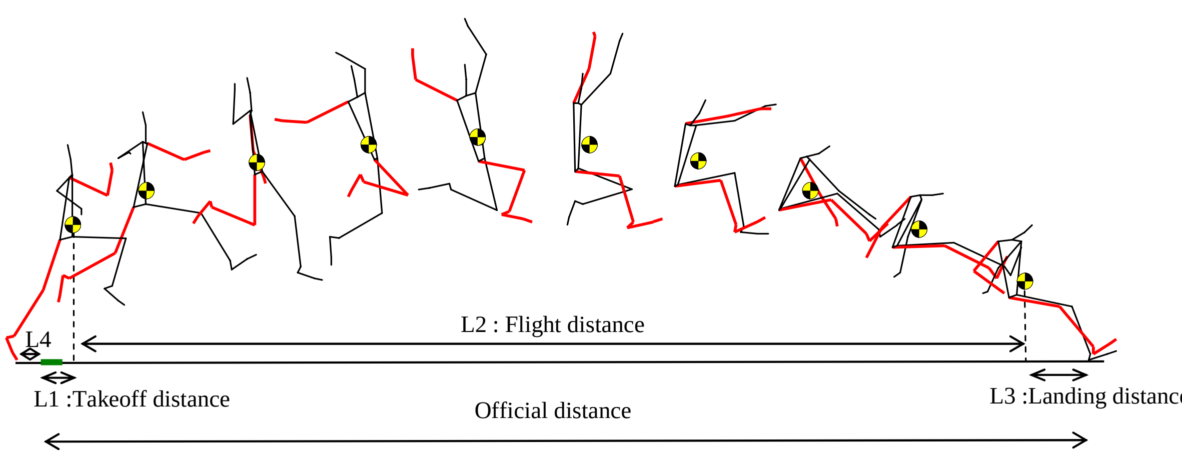


Figure 1. Definitions of components of jumping distance of the long jump

3. Results and Discussion

3.1 Men's Final

3.1.1 Performance descriptors

Table 3 shows the competition result of the men’s long jump. Table 4 shows components of jumping distance of the long jump. The toe-to-board distance of the top three jumpers were ranging from 1.0 to 3.0 cm, which indicated that the run-up accuracy of the best jump was quite good in these jumpers. The takeoff distance (L1) was approximately 0.40 m and the percentage of that to the total distance was about 5.0 %, and the contribution of the flight distance (L2) to the official distance was over 90 % (91.0~91.8 %). These results were similar to the previous report of the elite male long jumpers by Hay (1986). The flight distance of Saladino was 7.80 m (91.0 %) and longer than those of Howe (7.70 m) and Phillips (7.62 m), and the landing distances of the top three finalists were 0.39 m for Saladino, 0.36 m for Howe, and 0.26 m for Phillips, respectively. These distances were smaller than those of the finalist at the World Championship in TOKYO 1991 (0.47±0.09 m). The shorter landing distance in this final seems to result from their landing motion. The data of this study indicated that the apparent landing distance, the horizontal distance between the C.G. and the heel at the instant of heel landing in the sand, was 0.51 m for Saladino and 0.48 m for Phillips, and these values were similar to that of the previous report of Tokyo. The mark of the heel of Phillips made in the sand was 8.53 m and further than that of Howe (8.51 m), indicating Phillips had a large loss of the distance by poor avoiding motion after landing.

Table 3. Results of the final of the men's long jump

RANK	NAME	NAT	RESULT	1st	2nd	3rd	4th	5th	6th
1	Irving SALADINO	PAN	**8.57**	x *1.1m/s*	8.30 *0.5m/s*	8.46 *0.0m/s*	x *0.0m/s*	x *-0.3m/s*	**8.57** ***0.0m/s***
2	Andrew HOWE	ITA	**8.47**	x *1.1m/s*	8.13 *-0.1m/s*	x *0.2m/s*	8.12 *0.7m/s*	8.20 *0.2m/s*	**8.47** ***-0.2m/s***
3	Dwight PHILLIPS	USA	**8.30**	**8.30** ***0.4m/s***	x *0.0m/s*	x *-0.1m/s*	8.02 *0.3m/s*	x *0.1m/s*	8.22 *0.0m/s*
4	Olexiy LUKASHEVYCH	UKR	**8.25**	x *0.0m/s*	8.17 *0.4m/s*	x *0.5m/s*	8.05 *0.7m/s*	8.13 *0.4m/s*	**8.25** ***0.2m/s***
5	Godfrey Khotso MOKOENA	RSA	**8.19**	7.98 *0.2m/s*	7.86 *-0.1m/s*	**8.19** ***0.4m/s***	8.18 *0.7m/s*	8.15 *0.0m/s*	**8.19** ***-0.1m/s***
6	James BECKFORD	JAM	**8.17**	8.09 *0.3m/s*	8.03 *0.6m/s*	8.03 *0.6m/s*	**8.17** ***0.0m/s***	8.17 *0.1m/s*	x *0.0m/s*
7	Ndiss Kaba BADJI	SEN	**8.01**	7.90 *0.6m/s*	**8.01** ***0.1m/s***	x *-0.1m/s*	7.90 *0.4m/s*	x *0.0m/s*	7.64 *0.1m/s*
8	Ahmed Faiz BIN MARZOUQ	KSA	**7.98**	x *0.8m/s*	**7.98** ***0.0m/s***	7.70 *-0.3m/s*	x *0.4m/s*	-	x *0.1m/s*

Table 4. Distances within the long jump - Men's final

Parameter	Saladino	Howe	Phillips	1991 Tokyo World Championship*
Official dist. (m) (L1+L2+L3)	8.57	8.47	8.30	8.15±0.17
Takeoff dist. (L1) (m) (%)	0.39 (4.5)	0.41 (4.8)	0.42 (5.1)	-
Flight dist. (L2) (m) (%)	7.80 (91.0)	7.70 (91.0)	7.62 (91.8)	-
Landing dist. (L3) (m) (%)	0.39 (4.5)	0.36 (4.2)	0.26 (3.1)	0.47±0.09
Toe-to Board dist. (L4) (m)	0.01	0.03	0.01	-
Heel displacement @ landing (L5) (m)	8.69	8.48	8.52	-
Loss dist. by landing (m)	0.12	0.01	0.22	-
Actual jump dist. (L4+L5) (m)	8.70	8.51	8.53	-

* Fukashiro *et al*. (1994)

3.1.2 Velocity of the C.G.

Table 5 shows the horizontal and vertical velocities of the 2nd last stride, last stride and takeoff phases and takeoff angle. The run-up speed of the 2nd last stride was 10.65 m/s for Saladino, 10.99 m/s for Howe, and 11.01 m/s for Phillips, and then the speed decreased toward the takeoff. The data indicated that although Phillips reached the largest run-up speed at the touchdown of the 2nd last stride in the top three, the decrease in the speed from the 2nd last stride to the takeoff was the largest (-0.63 m/s), resulting in the smallest horizontal velocity at the touchdown of the takeoff (Saladino, 10.52 m/s; Howe, 10.87 m/s; Phillips, 10.38 m/s). Contrary, the decrease in the run-up speed for Saladino and Howe were smaller, -0.13 m/s for Saladino and -0.12 m/s for Howe, implying that their preparation for the takeoff were superior to Phillips's one.

The horizontal velocity at the touchdown for the top three was similar to the average of the reports on World Championship in Tokyo and Athens (Fukashiro *et al*., 1994; Arampatzis *et al*., 1999), with exception of M. Powel (11.00 m/s) and C. Lewis (11.06 m/s). The data represented that the horizontal velocity at the toe-off for Saladino was the smallest of the three, but his vertical toe-off velocity was the largest and contributed to gain the longest flight distance of the three. It is interesting that although the decreases in the horizontal velocity for Saladino and Howe were approximately same (Saladino, -1.63 m/s; Howe, -1.61 m/s), the gained vertical velocity was very different (Saladino, 3.75 m/s; Howe, 3.46 m/s), indicating that the velocity conversion technique from the horizontal to the vertical for Saladino was superior to Howe.

Table 5. Horizontal and vertical velocities of the center of gravity (C.G.) of athletes and takeoff angle - Men's final

Parameter	I. SALADINO	A. HOWE	D. PHILLIPS	1991 TOKYO WC*			1997 Athens WC**
				M. POWEL	C. LEWIS	Other Athletes	
Official distance	8.57	8.47	8.30	8.95	8.91	8.15±0.17	8.11±0.18
Horizontal vel. (m/s)							
HV_{TDL2}	10.65	10.99	11.01	-	-	-	-
HV_{TDL1}	10.53	10.89	10.94	-	-	-	-
HV_{TD}	10.52	10.87	10.38	11.00	11.06	10.39±0.14	10.65±0.19
HV_{MKF}	9.23	9.56	8.97	-	-	-	-
HV_{TO}	8.90	9.26	8.96	9.09	9.72	8.80±0.12	8.77±0.22
ΔHV_{TD-TO}	-1.63	-1.61	-1.41	-1.91	-1.34	-1.59±0.10	-1.88±0.32
Vertical vel. (m/s)							
VV_{TD}	-0.28	-0.46	-0.06	-	-	-	-
VV_{MKF}	2.61	2.42	2.70	-	-	-	-
VV_{TO}	3.75	3.46	3.67	3.70	3.22	3.44±0.19	3.42±0.26
VV_{MKF} / VV_{TO} (%)	69.6	69.9	73.5	-	-	-	-
Takeoff angle (deg)							
Y-Z plane	22.9	20.5	22.3	22.1	18.3	21.4±1.5	21.3±1.5
X-Y plane	1.9	-2.5	0.5	-1.4	3.3	1.6±1.4	-

* Fukashiro *et al*. (1994) ** Arampatzis *et al*. (1999)

3.1.3 Pathway of the C.G.

Figure 2 shows pathways of the C.G. from the 2nd last stride to the takeoff for the three jumpers. The long jumpers lower the C.G. in the final stage of the run-up to make the body prepared to obtain the vertical velocity during the takeoff phase (Hay, 1986). The top three jumpers gradually lowered the C.G. from the 2nd last stride to the instant of the takeoff foot touchdown. The largest decrease in the C.G. height was achieved in the airborne phase of the 2nd last stride, which were 6.3 cm for Saladino, 8.6 cm for Howe, and 9.1 cm for Phillips. The phase time analysis indicated that the support time of the 2nd last stride was shorter and airborne time was longer, compared with the 3rd last stride. These data confirmed that the top three finalists changed the running motion and prepared for the takeoff during the support phase of the 2nd last stride.

There were remarkable differences in the technique of lowering the C.G. during the last stride among the three athletes. Phillips continued lowering of the C.G. until the toe-off of the last stride. However, Saladino and Howe took off, raising the C.G. slightly during the second half of the support phase. It should be worthy to note that although Phillips's large decrease in the C.G. height led the low position at the touchdown of the takeoff, his decrease in the horizontal velocity from the 2nd last stride to the takeoff was the largest of the three (Phillips, -0.63 m/s; Saladino, -0.13 m/s; Howe, -0.12 m/s).

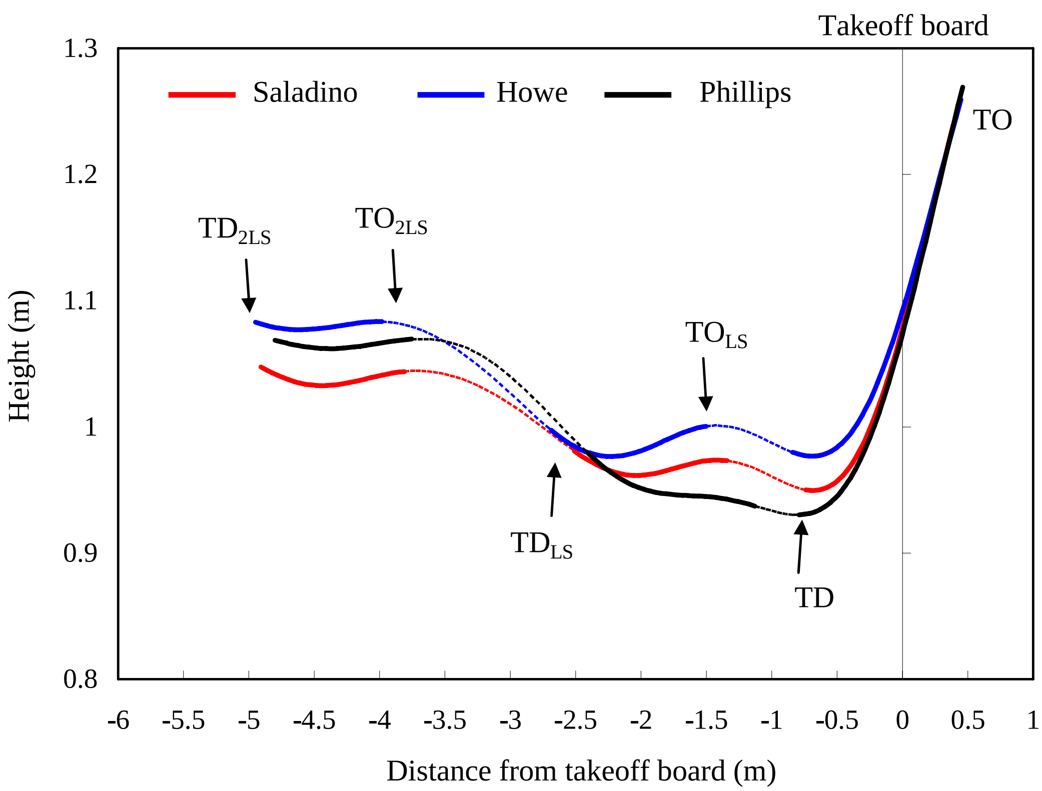


Figure 2. Pathway of the center of gravity of the body from the touchdown (TD) of the 2nd last stride to the toe-off (TO) of the takeoff.

3.1.4 Joint and leg angles during the takeoff phase

Table 6 shows angles of the takeoff leg joints, trunk, hip and shoulder rotation at the touchdown and toe-off of the takeoff phase. Figure 3 shows the overhead views of the pathways of the C.G. from the 2nd last stride to the takeoff and the footprint of each support phase.

The results on the knee joint indicated that the knee flexion and the maximum knee flexion velocity for Saladino were the smallest. Fukashiro *et al*. (1994) reported that the less knee flexion of the takeoff leg was a crucial factor to enhance the vertical velocity during the takeoff. The result of this final and previous report of Tokyo confirm that the less flexed takeoff leg helps to gain the vertical velocity in the takeoff phase.

The hip rotation angles at the touchdown and toe-off of the takeoff phase were 1.1° and 39.1° for

Saladino, -12.6° and 21.9° for Howe, and -5.8° and 17.8° fir Phillips. The range of the hip rotation was 38.0° for Saladiono, 33.5° for Howe, and 23.6° for Phillips. These results indicated that the top three jumper rotated the hip of the lead leg forward in the swing of the lead leg during the takeoff, and the hip forward rotation of Saladino was the largest of the three. The previous report of Tokyo indicated that the range of the twist of the hip and shoulder during the takeoff positively correlated with the jump distance (r=0.86), and that of Powel and Lewis was 74° and 70°, respectively. As shown in table 6, the twist range of Saladino and Howe was 71.1° and 68.0° and similar to that of Powel and Lewis. The results of this study and previous report indicated that the twist of the hip and shoulder was an important motion during the takeoff phase to obtain the jumping distance.

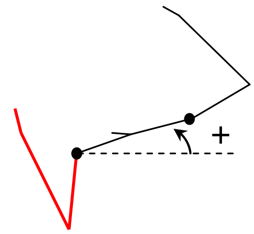
The leg angle (hip-ankle) in the frontal plane at the touchdown of the takeoff was -2.6° for Saladino, -4.7° for Howe, and -1.3° for Phillips, respectively., which indicated that the top three jumpers slightly inclined the takeoff leg inward at the touchdown of the takeoff. As shown in Figure 3, although the top three placed their support foot in the lateral position at the 2nd last and last strides, they placed their takeoff foot nearly under the C.G in the takeoff phase. Especially Howe's takeoff foot was placed in much medial position to the C.G. during the takeoff phase. These results indicated that these jumpers placed their takeoff foot in the medial side, which resulted in a slight inward lean of the takeoff leg during the takeoff phase. Okuyama *et al*. (2003) suggested that the use of the hip abductors of the inward inclined takeoff leg in the high jump was an important factor to enhance the vertical velocity during the takeoff. The behavior of takeoff leg of the top three jumpers with the previous study (Okuyama *et al*., 2003) imply that the elite long jumpers may have used their hip abductors of the takeoff leg to gain the vertical velocity during the takeoff phase.

Table 6. Joint angles of the takeoff leg, trunk angle, hip and shoulder rotation angles, and leg angles at the touchdown (TD) and toe-off (TO) of the takeoff

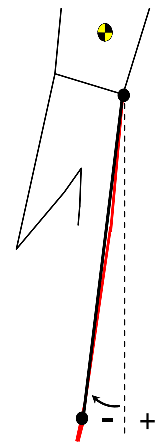
Parameter	Saladino	Howe	Phillips	1991 Tokyo World Championship*
$Knee_{TD}$ (deg)	160.2	160.2	165.4	166.7±3.5
$Knee_{MKF}$ (deg)	143.2	140.7	138.4	145.6±5.3
$Knee_{TO}$ (deg)	168.4	165.2	159.8	172.0±2.3
Flex. / Ext. (deg)	-17.1 / 25.2	-19.4 / 24.5	-27.0 / 21.5	-21.1±4.3 / 26.4±4.8
Maximum Knee Flex. Vel. (deg/s)	-423.2	-452.8	-570.7	
Trunk - Sagittal plane $_{TD}$ (deg)	-2.3	-2.1	-10.1	-4.4±3.9
Trunk - Sagittal plane $_{TO}$ (deg)	5.6	8.0	7.3	5.8±3.7
Shoulder rotation TD (deg)	32.6	14.9	17.8	20.6±5.3
Shoulder rotation TO (deg)	-0.5	-18.6	-13.5	-10.3±8.0
Hip rotation TD (deg)	1.1	-12.6	-5.8	-9.0±4.9
Hip rotation TO (deg)	39.1	21.9	17.8	17.0±10.1
Twist angle (deg)	71.2	68.0	54.9	56.9± 10.6
Leg angle Sagittal plane $_{TD}$ (deg)	37.3	36.1	37.2	-
Leg angle Sagittal plane $_{TO}$ (deg)	-25.3	-31.0	-28.3	-
Leg angle Frontal plane $_{TD}$ (deg)	-2.6	-4.7	-1.3	-
Leg angle Frontal plane $_{TO}$ (deg)	-5.1	-5.7	-7.1	-

* Fukashiro *et al*. (1994)

Rotation angle (shoulder)



Leg angle (sagittal plan



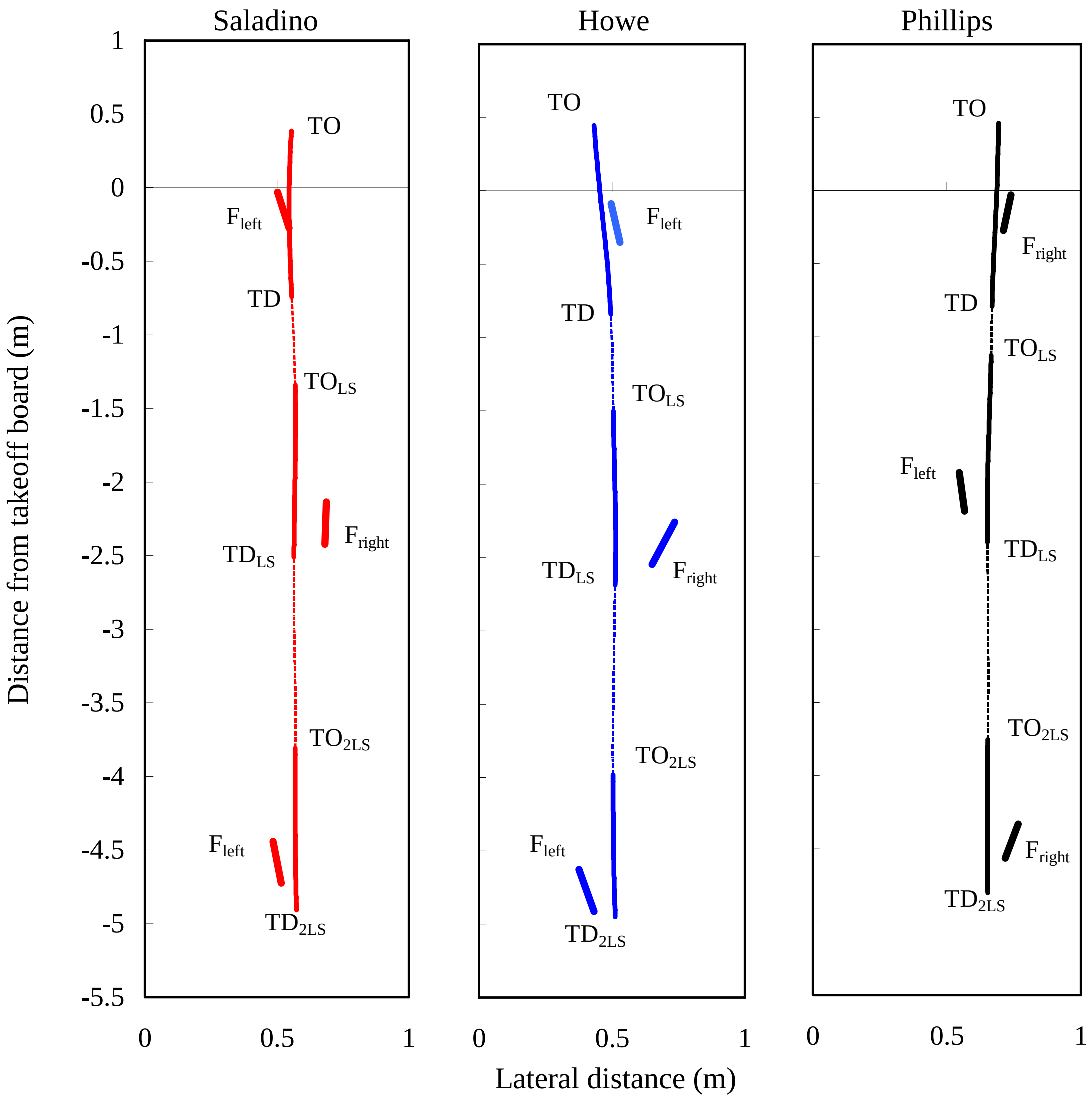


Figure 3. Overhead views of paths of the center of gravity of the body from the 2nd last stride to the takeoff and footprint of each support phase.

3.2 Women's final

3.2.1 Performance descriptors

Table 7 shows the competition result of the women's long jump. Table 8 shows components of jumping distance of the long jump. Lebedeva marked the longest actual jump distance of the top three (7.08 m). The second longest actual jump was marked by the 3rd jumper, Kotova, and her jump was 10 cm longer than Kolchanova (Kotova, 7.05 m; Kolchanova, 6.95m). The distance results indicated that Kolchanova's second position may have attributed to the accuracy of the takeoff foot placement and landing. The landing distance of the top three was longer than that of the men's finalists.

Table 7. Results of the final of the woen's long jump

RANK	NAME	NAT	RESULT	1st	2nd	3rd	4th	5th	6th
1	Tatyana LEBEDEVA	RUS	**7.03**	6.73 *-0.7m/s*	**7.03** ***0.7m/s***	**7.03** ***0.3m/s***	x *0.7m/s*	6.98 *0.1m/s*	**-**
2	Lyudmila KOLCHANOVA	RUS	**6.92**	x *-0.2m/s*	6.84 *0.4m/s*	x *-0.1m/s*	6.71 *0.7m/s*	6.63 *1.0m/s*	**6.92** ***-0.3m/s***
3	Tatyana KOTOVA	RUS	**6.90**	6.80 *-0.6m/s*	x *0.0m/s*	6.75 *1.0m/s*	6.70 *0.7m/s*	x *2.7m/s*	**6.90** ***0.5m/s***
4	Natide GOMES	POR	**6.87**	**6.87** ***0.7m/s***	6.75 *0.3m/s*	6.61 *-0.5m/s*	6.86 *0.9m/s*	6.85 *0.4m/s*	6.80 *-0.3m/s*
5	Bianca KAPPLER	GER	**6.81**	**6.81** ***-0.7m/s***	6.66 *0.5m/s*	6.78 *0.3m/s*	6.55 *-0.4m/s*	x *0.6m/s*	6.49 1.0*m/s*
6	Maurren Higa MAGGI	BRA	**6.80**	6.41 -2.1*m/s*	6.64 0.7*m/s*	6.73 *0.1m/s*	**6.80** **1.2*m/s***	6.62 *0.4m/s*	6.76 -0.2*m/s*
7	Keila COSTA	BRA	**6.69**	**6.69** ***0.0m/s***	6.44 -1.1*m/s*	6.66 *0.2m/s*	6.66 *-0.5m/s*	x *1.9m/s*	6.61 1.1*m/s*
8	Brittney REESE	USA	**6.60**	x *0.1m/s*	**6.60** ***-1.5m/s***	6.58 *-0.3m/s*	x *0.7m/s*	x *0.8m/s*	6.29 *-0.3m/s*

Table 8. Distances within the long jump - Women's final

Parameter	Lebedeva	Kolchanova	Kotova
Official dist. (m) (L1+L2+L3)	7.03	6.92	6.90
Takeoff dist. (L1) (m) (%)	0.31 (4.4)	0.34 (5.0)	0.34 (5.0)
Flight dist. (L2) (m) (%)	6.20 (88.2)	6.12 (88.5)	6.07 (88.0)
Landing dist. (L3) (m) (%)	0.52 (7.4)	0.46 (6.6)	0.49 (7.1)
Toe-to Board dist. (L4) (m)	0.05	0.00	0.06
Heel displacement @ landing (L5) (m)	7.03	6.95	6.99
Loss dist. by landing (m)	0.00	0.03	0.09
Actual jump dist. (L4+L5) (m)	7.08	6.95	7.05

3.2.2 Velocity of the C.G.

Table 9 shows the horizontal and vertical velocities of the C.G of the 2nd last stride, last stride and takeoff phases and takeoff angle. The run-up speed of the 2nd last stride was 9.52 m/s for Lebedeva, 9.23 m/s for Kolchanova, and 9.12 m/s for Kotova, and then slightly decreased until the touchdown of the takeoff, resulting in the 9.37 m/s for Lebedeva, 9.13 m/s for Kolchanova, and 9.08 m/s Kotova at the touchdown of the takeoff. The horizontal velocity at the toe-off for Lebedeva and Kolchanova was same (7.73 m/s). However, there was significant differences in the vertical toe-off velocity between these top two athletes (Lebedeva, 3.50 m/s; Kolchanova, 3.23m/s), indicating that Lebedeva's longer jump resulted from larger gain of the vertical velocity during the takeoff. Kotova's jump was very different from other two. The horizontal velocity at the toe-off was the largest of the three (8.14 m/s) because of the much less decrease in the horizontal velocity during the takeoff (Kotova, -0.94 m/s; Lebedeva, -1.64 m/s; Kolchanova, -1.40 m/s), and her toe-off vertical velocity was the smallest (3.18 m/s). Compared with the previous World Championships of the Tokyo and Athens (Fukashiro *et al*., 1994; Arampatzis *et al*., 1999), the run-up speed of the top three in Osaka was small, but there were no differences in the official distance among these competitions, with exception of J.J. Kersee and H. Drechsler. The results on the C.G. velocity indicated that the larger gain of the vertical velocity and the high takeoff angle for Lebedeva and Kolchanova and less decrease in the horizontal velocity for Kotova contributed to obtain their longer jump distance.

The gain of the vertical velocity until the maximum knee flexion of the takeoff leg (MKF) was 60.8 % for Lebedeva, 57.1 % for Kolchanova, and 39.1 % for Kotova, respectively. Previous studies of Lees *et al*. (1993, 1994) reported that the vertical velocity which long jumpers obtained until the MKF was a crucial factor for successful jump and over 64 % of the final vertical velocity for women and about 70 % for men. These indicated that the vertical velocity obtained until the MKF for the top three was smaller than that of the previous elite athletes. As mentioned above, Kotova obtained only 40 % of the final vertical velocity until the MKF even in the her best jump, however, she finally obtained the vertical velocity of 3.18 m/s, which were within the average of the elite female long jumper. These results indicated that Kotova might use different technique for the velocity conversion from the horizontal to the vertical during the takeoff.

Table 9. Horizontal and vertical velocities of the center of gravity (C.G.) of athletes and takeoff angle - Women's final

Parameter	Lebedeva	Kolchanova	Kotova	1991 TOKYO WC*			1997 Athens World Championship**
				J. J.Kersee	H.Drechsler	Other Athletes	
Official distance	7.03	6.92	6.90	7.32	7.29	6.95± 0.43	6.86± 0.12
Horizontal velocity (m/s)							
HV_{TDL2}	9.52	9.23	9.12	-	-	-	-
HV_{TDL1}	9.63	9.11	9.39	-	-	-	-
HV_{TD}	9.37	9.13	9.08	9.85	9.86	9.53± 0.11	9.62±8.08
HV_{MKF}	7.95	8.17	8.16	-	-	-	-
HV_{TO}	7.73	7.73	8.14	8.09	8.49	7.92± 0.31	8.08±0.26
ΔHV_{TD-TO}	-1.64	-1.40	-0.94	-1.76	-1.37	-1.61± 0.29	-1.54± 0.25
Vertical Velocity (m/s)							
VV_{TD}	-0.38	-0.42	-0.40	-	-	-	-
VV_{MKF}	2.13	1.84	1.24	-	-	-	-
VV_{TO}	3.50	3.23	3.18	3.46	2.80	3.05± 0.24	3.10±0.23
VV_{MKF} / VV_{TO} (%)	60.8	57.1	39.1	-	-	-	-
Takeoff angle (deg)							
Y-Z plane	24.4	22.7	21.3	23.2	18.3	21.1± 2.0	20.9±1.7
X-Y plane	-0.8	-1.1	3.0	-	-	-	-

* Fukashiro *et al* . (1994) ** Arampatzis *et al* . (1999)

3.2.3 Pathway of the C.G.

Figure 4 shows pathway of the C.G. from the 2nd last stride to the takeoff for women's final. The lowering the C.G of the women's top three was similar to the pattern of the men. However, the absolute value of the decrease in the C.G. height in the 2nd last airborne phase was smaller (Lebedeva, 5.0 cm; Kolchanova, 6.8 cm; Kotova, 3.9 cm).

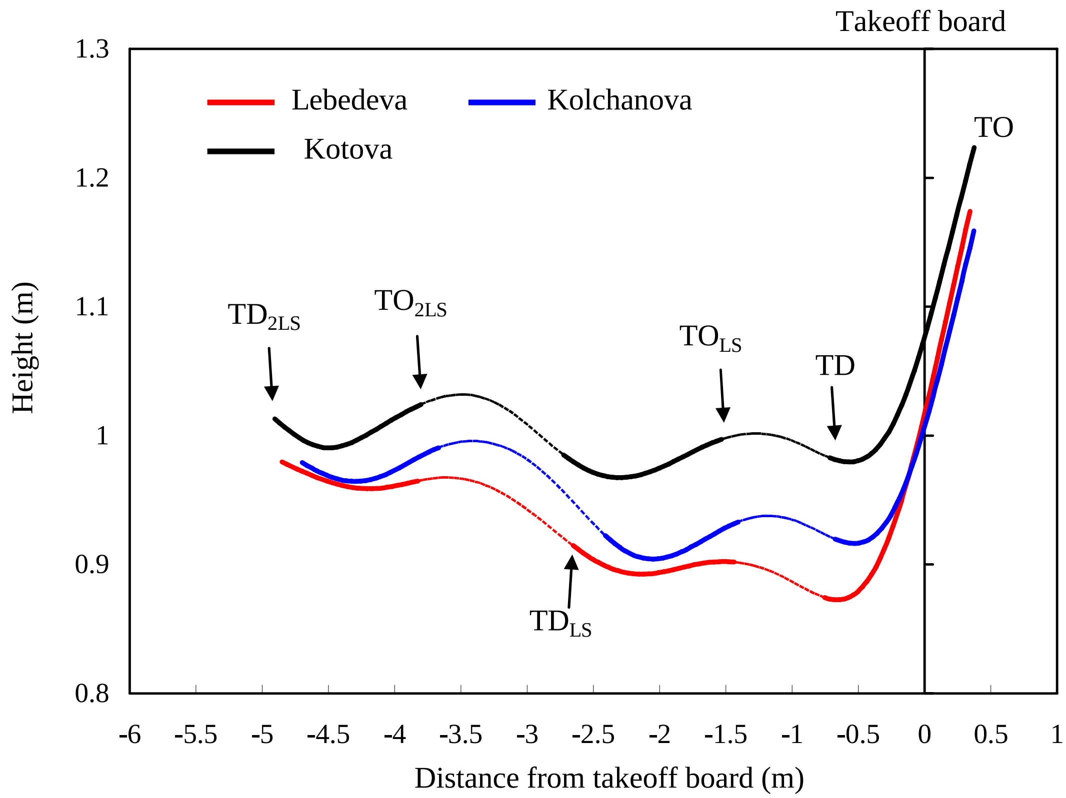


Figure 4. Path of the center of gravity of the body from the touchdown (TD) of the 2nd last stride to the toe-off (TO) of the takeoff

3.2.4 Joint and leg angles during the takeoff

Table 10 shows angles of the takeoff leg joints, trunk, hip and shoulder rotation at the touchdown and toe-off of the takeoff phase. Figure 5 shows the overhead views of the paths of the C.G. from the 2nd last stride to the takeoff and the footprint of each support phase.

The knee flexion of the takeoff leg during the takeoff phase was 14.5° for Lebedeva, 15.4° for Kolchanova, and 6.5° for Kotova, and the minimum knee angle of the takeoff leg was approximately 143° to 146°. Compared with the top three men's jumpers, the knee flexion and maximum knee flexional velocity of the women's were much smaller than those of the men's jumpers. The report of the Tokyo WC indicated that the knee flexion of the takeoff leg was smaller in women's jumper than in the men's jumper (Women, 19.5±3.7°; Men, 21.1±4.3°). The less flexion of the takeoff leg of women may be caused by the small muscular strength of the takeoff leg than men.

The leg angle (hip-ankle) in the frontal plane at the touchdown of the takeoff was -6.1° for Lebedeva, -7.7° for Kolchanova, and -4.3° for Kotova, and those at the toe-off of the takeoff were also the negative values (-8.1° for Lebedeva; -5.2° for Kolchanova; -6.2° for Kotova). These results indicated that the top three of the women inclined the takeoff leg inward over the takeoff phase as the men adapted. Additionally, the inward inclination of the takeoff leg was larger in the women than those of the men's jumpers. As shown in figure 5, the women's top three placed their takeoff foot much medially, and these led the inward-inclined takeoff leg during the takeoff. These motions of the takeoff leg imply the use of the hip abductors of the takeoff leg for enhancing the vertical velocity in the takeoff phase, as previously described.

Table 10. Joint angles of the takeoff leg, trunk angle, hip and shoulder rotation angles, and leg angles at the touchdown (TD) and toe-off (TO) of the takeoff

Parameter	Lebedeva	Kolchanova	Kotova	1991 Tokyo World Championship*
$Knee_{TD}$ (deg)	159.5	159.4	152.4	163.6±3.7
$Knee_{MKF}$ (deg)	145.0	143.9	145.8	144.1±2.7
$Knee_{TO}$ (deg)	163.9	163.5	164.5	170.4±4.1
Flex. / Ext. (deg)	-14.5 / 18.9	-15.4 / 19.6	-6.5 / 18.6	-19.5±3.7 / 26.3±3.3
Maximum Knee Flex. Vel. (deg/s)	-360.9	-392.4	-181.7	
Trunk - Sagital plane $_{TD}$ (deg)	-2.2	-3.9	-4.1	-2.4±2.7
Trunk - Sagital plane $_{TO}$ (deg)	8.3	6.2	-1.3	-0.7±2.8
Shoulder rotation TD (deg)	13.7	23.7	33.1	23.0±3.8
Shoulder rotation TO (deg)	-7.9	-7.5	0.8	-18.9±9.1
Hip rotation TD (deg)	-12.9	-4.9	4.1	-5.3±4.8
Hip rotation TO (deg)	19.8	14.3	15.3	6.4±4.1
Leg angle Sagittal plane $_{TD}$ (deg)	41.1	37.9	32.2	-
Leg angle Sagittal plane $_{TO}$ (deg)	-26.6	-25.2	-27.5	-
Leg angle Frontal plane $_{TD}$ (deg)	-6.1	-7.7	-4.3	-
Leg angle Frontal plane $_{TO}$ (deg)	-8.1	-5.2	-6.2	-

* Fukashiro *et al* . (1994)

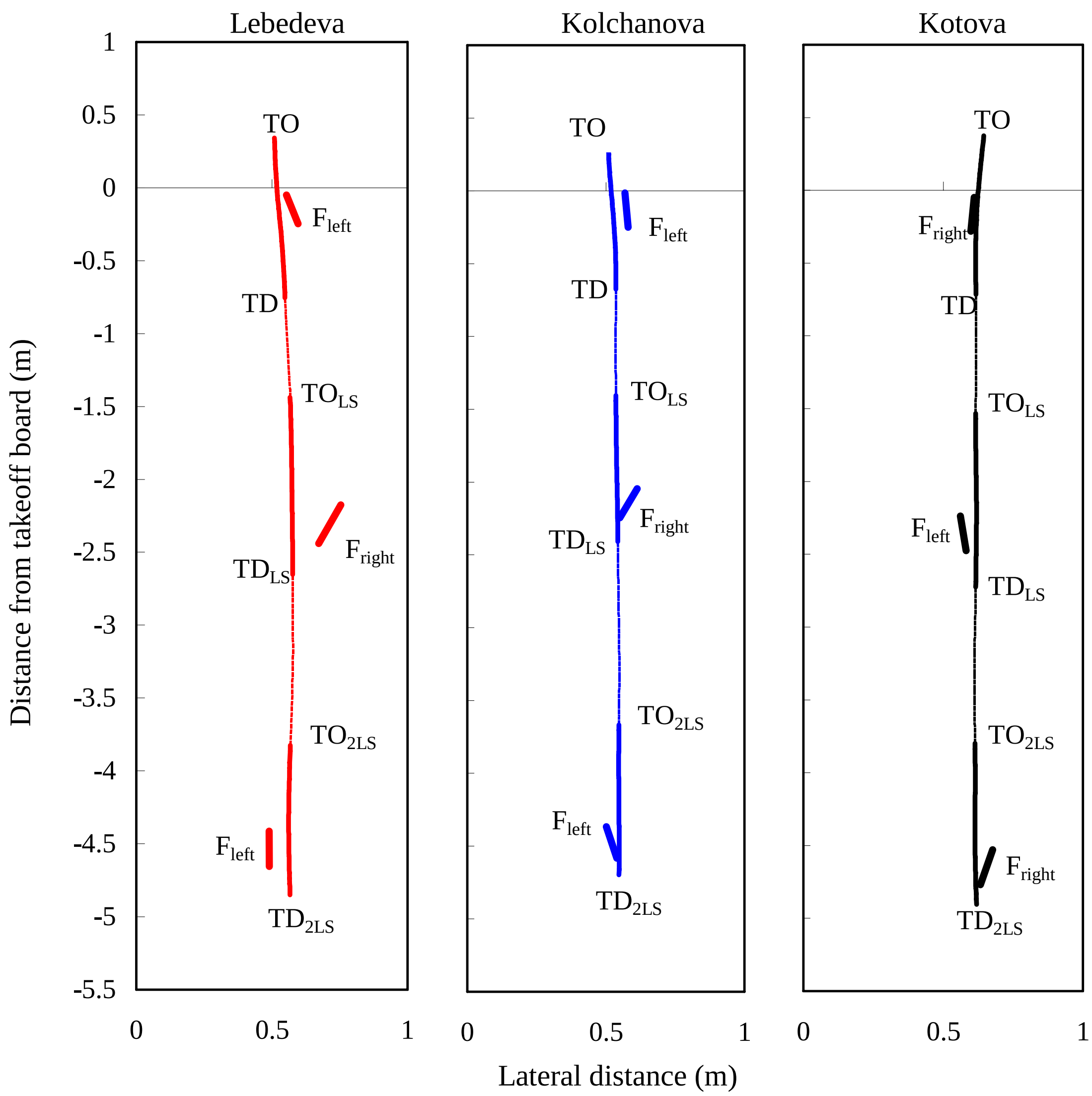


Figure 5. Overhead views of paths of the center of gravity of the body from the 2nd last stride to the takeoff and footprint of each support phase

4. Summary

The results on the preparatory phase indicated that the investigated jumpers increased the run-up speed toward the 2nd last stride, and lowered their C.G. in the airborne phase of the 2nd last stride by lengthening the airborne time. They placed their takeoff foot in the medial side, which resulted in a slightly inward lean of the takeoff leg at the TD of the takeoff, which induced effective use of the hip abductors of the takeoff leg to enhance the vertical velocity during the takeoff, as similar to the high jump (Okuyama *et al.*, 2003).

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Run-up Velocity in the Men's and Women's Triple Jump at the 2007 IAAF World Championships in Athletics in Osaka

Muraki, Y., Koyama, H., Ae, M., Shibayama, K., and Yoshihara, A.

Abstract

The purpose of this report is to present the jumping distance and run-up velocity data from the men's and women's triple jump finals at the 2007 IAAF World Championships in Athletics in Osaka.

The instantaneous run-up velocities of all attempts of all athletes were measured by a laser distance measurement device (LAVEG by Jenoptik). The best record jumps of each athlete were included in an analysis.

Comparing with the past World Championships, the average performance in the men's triple jump did not improve remarkably. In the women's triple jump, the average jumping distance at the 2007 World Championships was greatest among the past World Championships. Therefore, the women achieved 86.0% of the men's jumping distances. While the women's run-up velocities reached 89.6% of the men's at the 2007 World Championships.

The run-up velocity was significantly related to the jumping distance in the men's and women's triple jump finals at the 2007 World Championships. These relationships indicated that one of the most important determinant of the triple jump performance would be the run-up velocity in both men's and women's finals at this competitions.

Introduction

The 11th IAAF World Championships in Athletics 2007 was held at Osaka, Japan, from August 26th to September 2nd. In the men's triple jump, Nelson Évora of Portugal broke his own record by 23 cm and won the gold medal with a record of 17.74 m. While Yargelis Savigne of Cuba showed a big jump of 15.28 m at the first attempt and captured the victory in the women's triple jump.

In the horizontal jumps, the run-up velocity is of major importance for a successful performance. The changes in world records of the men's triple jump also imply the importance of the approach speed. In 1960s, Jozef Schimidt of Poland, who was former Olympic champion and world record holder, was the first to break the 17 m barrier with a jump of 17.03 m. Schimidt's technique involved a low and fast hop and step in order to minimize the reduction of run-up velocity and energy loss during the hop and step.

Moreover, Jonathan Edwards of United Kingdom improved the world record considerably and became world champion in 1995 with 18.29 m. One of the greatest characteristic of Edwards' jump was high run-up velocity.

In this report, the purpose is to present the jumping distance and run-up velocity data from the men's and women's triple jump finals at the 2007 IAAF World Championships in Athletics in Osaka.

Methods

Data were collected at the men's and the women's triple jump finals at the 2007 IAAF World Championships in Athletics in Osaka. The best valid jumps from each of the twelve finalists of the men's and women's competitions were selected for further analysis. The official distances of the selected jumps of each athlete were shown in Table 1 for male athletes and table 2 for female athletes.

Rank	Name	Nat.	Result	Wind	MAX m	MAX m/s	0 m m/s	Diff. m/s
1	N. Évora	POR	17.74	+1.4	4.25	10.49	10.22	-0.27
2	J. Gregório	BRA	17.59	+0.3	7.02	10.45	10.05	-0.40
3	W. Davis	USA	17.33	+1.0	3.25	10.23	10.07	-0.16
4	O. Tosca	CUB	17.32	+1.1	3.64	10.43	10.27	-0.16
5	A. Wilson	USA	17.31	+0.6	6.51	10.51	10.13	-0.38
6	P. Idowu	GBR	17.09	-0.9	5.53	10.26	9.92	-0.35
7	D. Giralt	CUB	16.91	+0.7	4.28	10.12	9.83	-0.30
8	A. Martínez	SUI	16.85	+1.3	6.32	10.49	10.08	-0.41
9	D. Kim	KOR	16.71	+1.1	5.67	9.94	9.70	-0.24
10	A. Petrenko	RUS	16.66	+0.8	3.34	9.89	9.73	-0.15
11	M. Zhong	CHN	16.66	+1.5	5.54	10.31	9.97	-0.34
12	D. Tsiámis	GRE	16.59	-1.1	4.09	9.77	9.53	-0.24
	Average		17.06		4.95	10.24	9.96	-0.28
	±SD		0.39		1.30	0.26	0.22	0.09

Table 1 Jumping distance (official), run-up velocity at the maximum point and 0 m point of the approach distance (foul line), location of the maximum run-up velocity and velocity change from the maximum point to the 0 m point of the approach distance for the best valid jumps from each of the twelve male finalists

Rank	Name	Nat.	Result	Wind	MAX m	MAX m/s	0 m m/s	Diff. m/s
1	Y. Savigne	CUB	15.28	+0.9	3.53	9.49	9.26	-0.24
2	T. Lebedeva	RUS	15.07	+0.8	3.50	9.59	9.39	-0.20
3	H. Devetzí	GRE	15.04	-0.2	3.27	9.22	9.00	-0.22
4	A. Pyatykh	RUS	14.88	+0.3	2.64	9.10	8.96	-0.14
5	M. Šestak	SLO	14.72	+0.2	3.30	8.96	8.81	-0.15
6	M. Martínez	ITA	14.71	+1.3	4.19	8.98	8.72	-0.26
7	O. Saladuha	UKR	14.60	+0.7	3.23	8.96	8.73	-0.23
8	L. Xie	CHN	14.50	+0.9	5.64	9.22	8.61	-0.60
9	K. Costa	BRA	14.40	+1.1	4.08	9.55	9.20	-0.35
10	O. Bufalova	RUS	14.39	+0.7	3.59	9.03	8.84	-0.19
11	O. Rypakova	KAZ	14.32	+1.4	3.54	8.97	8.79	-0.18
12	D. Veldáková	SVK	14.09	-0.1	4.46	8.97	8.78	-0.19
	Average		14.67		3.75	9.17	8.93	-0.24
	±SD		0.35		0.77	0.24	0.24	0.12

Table 2 Jumping distance (official), run-up velocity at the maximum point and 0 m point of the approach distance (foul line), location of the maximum run-up velocity and velocity change from the maximum point to the 0 m point of the approach distance (foul line) for the best valid jumps from each of the twelve female finalists

The instantaneous run-up velocities of the athletes were measured by a laser distance measurement device (LAVEG by Jenoptik), which operated at 50 Hz and was installed before the runway at the top of the stadium. The operator of the LAVEG targeted the athlete's chest and followed during the entire approach run. The position time history data were smoothed by the fourth-order low-pass Butterworth digital filter with a cut-off frequency of 0.5 Hz. From the position time history data, the object's run-up velocity was calculated by the first time derivative.

Consequently, we provided the maximum run-up velocity and its location from the 0 m point of the approach distance (foul line) and the run-up velocity at 0 m point of the approach distance of all the male and female finalists, and the run-up velocity curves of the male and female top three athletes for the analysis.

Results and Comments

Jumping distance

Table 1 and 2 presents jumping distance (official), run-up velocity at the maximum point and 0 m point of the approach distance (foul line), location of the maximum run-up velocity and velocity change from the maximum point to the 0 m point of the approach distance for each of the twelve male and female finalists, respectively. Figure 1 and 2 shows changes in ratios of the average jumping distances in the men's and women's triple jump finals at all the World Championships to those at the 1st World Championships (100%) for the male and the 4th World Championships (100%) for the female, respectively.

At the World Championships 2007, six male athletes jumped further than 17.00 m and three female athletes broke 15.00 m. The average jumping distance of the male changed little throughout the past World Championships (Figure 1). Comparing with the past World Championships, the average jumping distance was greatest in the women's triple jump at the World Championships 2007 (Figure 2). On average, the women reached 86.0% of the men's jumping distances at the 11th World Championships.

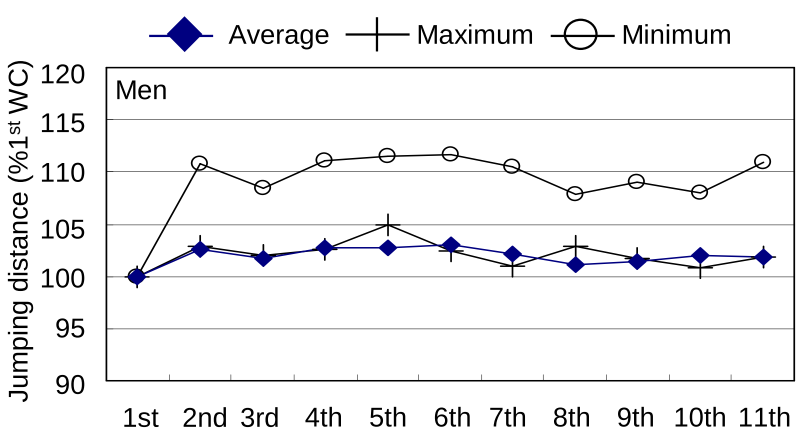

Figure 1 Changes in ratios of the average, maximum and minimum official distances in the men's triple jump finals at all the World Championships to those at the 1st World Championships (100%)

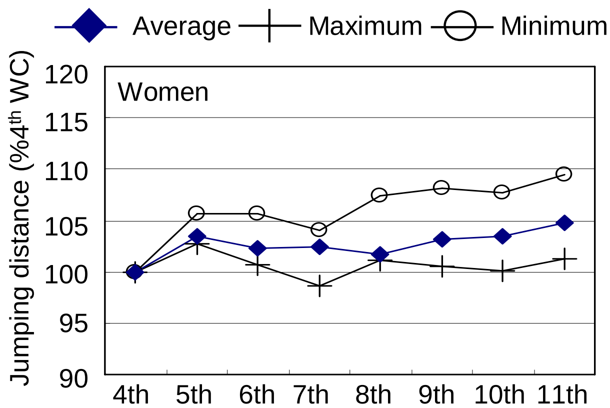

Figure 2 Changes in ratios of the average, maximum and minimum official distances in the women's triple jump finals at all the World Championships to those at the 4th World Championships (100%), in which the event was first included

Run-up velocity

The maximum run-up velocity and run-up velocity at 0 m point of the approach distance were 10.24±0.26 m/s and 9.96±0.22 m/s for the male and 9.17±0.24 m/s and 8.93±0.24 m/s for the female at the World Championships 2007 (Table 1 and 2). There were six male and four female athletes who kept the run-up velocity faster than 10.00 m/s for male and 9 m/s for female, respectively, from the maximum point to the 0 m point of the approach distance. The correlation coefficients between the maximum run-up velocity and the run-up velocity at 0 m point of the approach distance were highly significant for the men ($r = 0.93$, $p < 0.001$) and women ($r = 0.87$, $p < 0.001$). The women's run-up velocities at the maximum and 0 m point of the approach distance were both calculated to be 89.6% of the men's.

Relationships between jumping distance and run-up velocity

Figure 3 illustrates the relationships of the jumping distance to the run-up velocity at the maximum and 0 m point of the approach distance for the men's and women's triple jump finals.

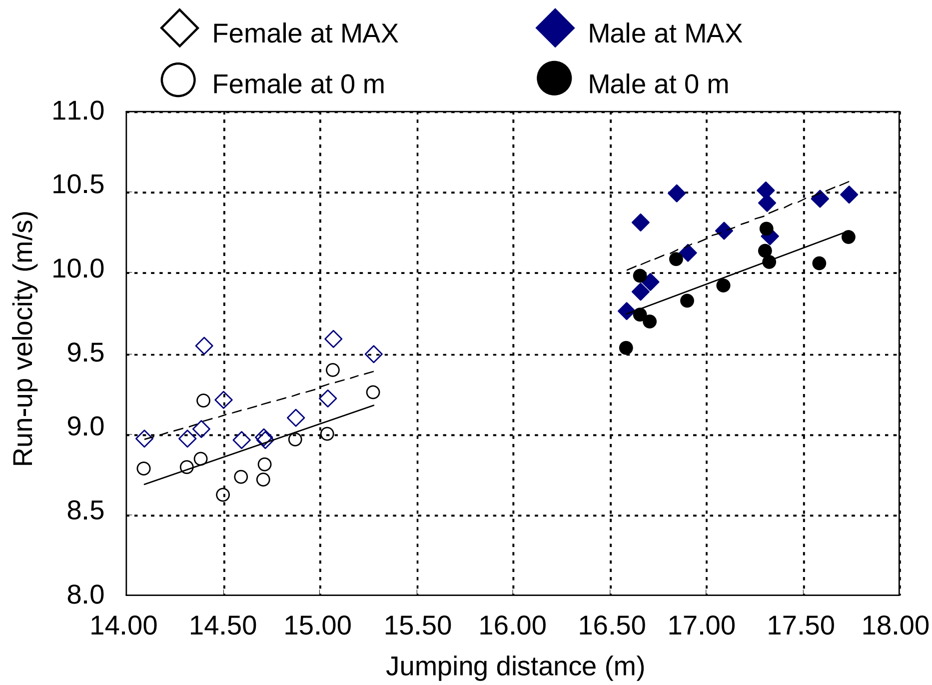

Figure 3 Relationships of jumping distance (official) to the run-up velocity at maximum and 0 m point of the approach distance (foul line) for the men's and women's triple jump finals

In the men's finalists, there were significant relationships of the jumping distance to the maximum run-up velocity ($r = 0.72$, $p < 0.01$) and the run-up velocity at 0 m point of the approach distance ($r = 0.78$, $p < 0.01$). While in the women's finalists, significant correlation was found only between the jumping distance and the run-up velocity at 0 m point of the approach distance ($r = 0.59$, $p < 0.05$). However, considering the Costa's jumping distance (Table 2), her run-up velocity was extremely large in the women's finalists. These data of Costa indicated that she would failure to use her energetic potential in the triple jump. If Costa's data was excluded, the relationships of the jumping distance to the maximum run-up velocity and the run-up velocity at 0 m point of the approach distance turned to be significant (maximum point, $r = 0.74$, $p <0.01$; 0 m point, $r = 0.75$, $p < 0.01$).
These relationships underline the great importance of run-up speed for men not only for women.

Characteristics of the run-up velocities of the top three athletes

Figure 4 and 5 depicts the developments of the run-up velocities of the top three athletes of the men's and women's triple jump finals, respectively.

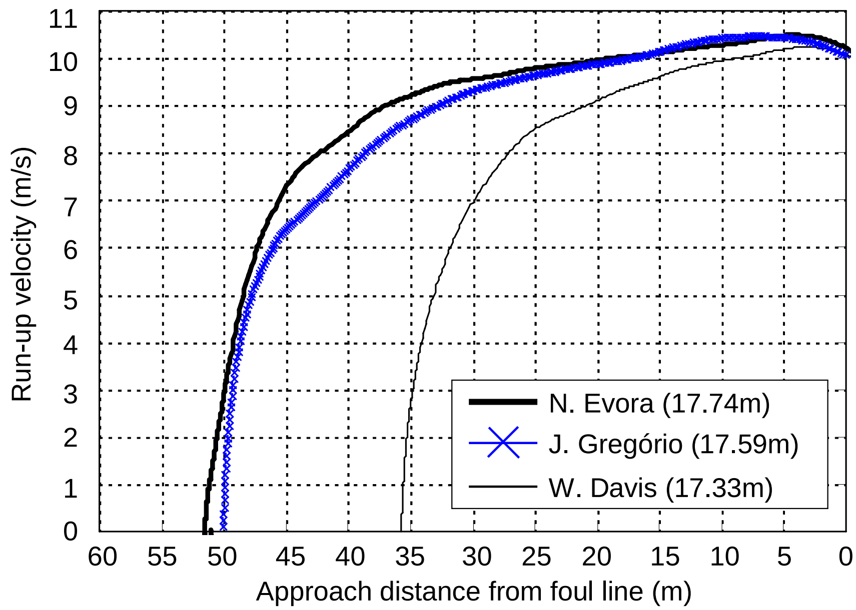

Figure 4 Development of the run-up velocity of the top three athletes of the men's triple jump final: N. Évora (17.74m), J. Gregório (17.59m) and W. Davis (17.33m)

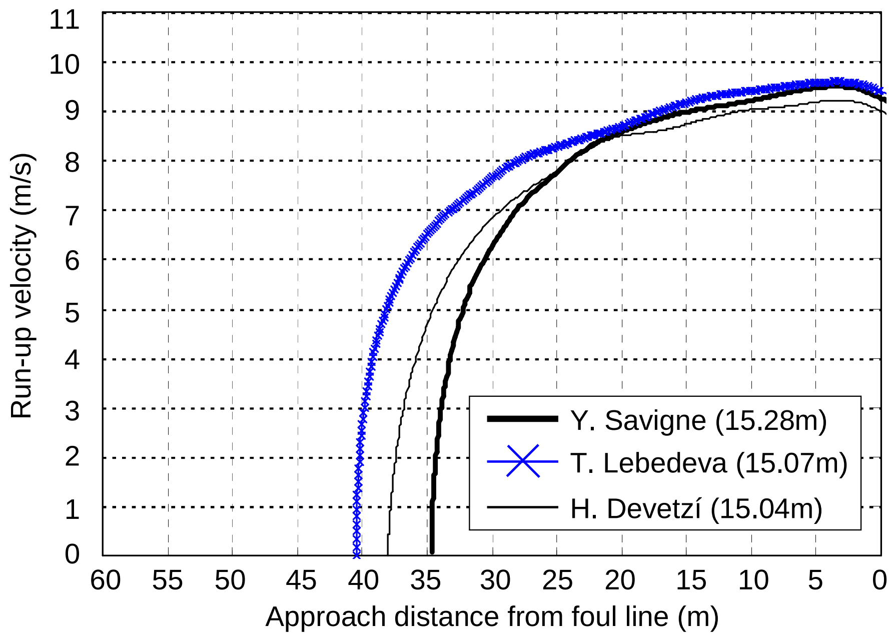

Figure 5 Development of the run-up velocity of the top three athletes of the men's triple jump final: Y. Savigne (15.28m), T. Lebedeva (15.07m) and H. Devetzí (15.04m)

Évora showed large run-up velocity almost entire points of the approach, and the run-up velocity at the end of the approach distance (0 m) was greatest among the top three athletes. Although Gregório exceeded Évora in the run-up velocity from 15 to 5 m points before the take-off, his location of the maximum run-up velocity was earlier than that of Évora and the loss of the run-up velocity became greater before the takeoff (Table 1). While Davis used shortest approach distance among three athletes, around 35 m point of the approach distance. However, his run-up velocity immediately increased and reached its peak of 10.23 m /s at 3.25 m point of the approach distances, which was nearest among the three athletes.

Savigne started the approach from about 35 m point of the approach distance. She accelerated immediately and the maximum run-up velocity reached the second largest among the women's finalists (Table 2). Lebedeva showed the greatest run-up velocity throughout the approach from about 40 m point of the approach distance. Although she could produce the greatest kinetic energy (increase run-up velocity) before the take-off, she was unable to improve the jumping distance within six attempts. The maximum run-up velocity of Devetzí was smallest among the three athletes.

Summary

Run-up velocities of the best attempts of the twelve male and female finalists in Osaka 2007 were measured using a laser distance measurement device. We analyzed the maximum run-up velocity and its location from the 0 m point of the approach distance (foul line) and the run-up velocity at 0 m point of the approach distance.

The average performance in the men's triple jump did not improve remarkably throughout the past World Championships. While in the women's triple jump, the average jumping distance at the World Championships 2007 was greatest among the past World Championships.

The women reached 86.0% of the men's jumping distances and 89.6% of the men's run-up velocities at the 11th World Championships.

The run-up velocity was significantly related to the jumping distance in the men's and women's triple jump finals at the 2007 World Championships. These relationships indicated that one of the most important determinant of the triple jump performance was the run-up velocity in both men's and women's finals at this competitions.

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A biomechanical analysis of the men's shot put finalists in the Osaka Athletics World Championship 2007 -An overview of finalists and comparisons of top three putters

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Abstract

The purpose of this study was to present the overview of finalists' performances and to make comparisons of the technique of top three putters including the two rotators and a glider. Data were collected in the IAAF world championships for athletics in Osaka 2007. One motion of best record about every top ten athletes in the Men's shot put final was analyzed. The main findings are as follows;

While the release velocity is the main determinant of performance, some fluctuations can be related to other factors such as angle and position of release.

There is the technical variation even within the rotational style. Hoffa utilizes both of linear and angular momentum of body in higher extent. In contrast, Nelson seems to have emphasis especially on angular momentum. Mikhnevich of glider keeps higher level of linear momentum of whole body from the push off of glide to just before the final thrust.

These results suggest that shot velocity alone is not enough to explain the process of acceleration. Because whole body momentum is gained or maintained even in the concomitance of marked decrease of shot velocity during flight and transition phase of rotation. To ensure the source of energy for delivery, acceleration of athlete-shot system is suggested to be the key factor.

Introduction

Unlike the Fosbury flop of high jump, both style of glide and rotation coexists as mainstreams in the shot put. This world championship is not the exception. The process reaching the common delivery from a totally different preparation is the matter of great interest among coaches and athletes.

Preceding researchers and coaches have pointed out that the advantage of rotational shot put technique is characterized by long path of shot acceleration (Heger, 1974; Zatsiorsky, 1990; Pyka, 1991). On the other hand, unfavorable depression of shot velocity during flight and transition phase has been reported frequently as a disadvantage (Grigalka, 1985; Luthanen et al., 1997). However, in spite of the shot deceleration, it has been expected that putters body can move forward and it can be favorable for delivery (Zatsiorsky, 1990; Hay, 1992). But experimental evidence has not been presented yet sufficiently. In terms of potential momentum within the athlete-shot system, apparent loss of shot velocity itself cannot necessarily be considered as a critical problem. Actually about discus throw, Schluter and Nixdorf (1984) reported that the amount of discus acceleration during the transition phase, the last half of preparation, is negatively correlated to the discus velocity at release. In other words, the temporary inappropriate state of the implement is not the problem if the system is ready to ensure the final delivery with translating the momentum to the implement.

In this study we will focus especially on the acceleration profile with special reference not only to the shot itself but to the athletes body. The sequence from system acceleration to the final acceleration of shot in the delivery will be analyzed.

The purpose of this study was to present the overview of finalists' performances and to make comparisons of the technique of top three putters including the two rotators and a glider. The technical difference not only between rotation and glide but within rotation are discussed.

Methods

Data were collected in the IAAF world championships for athletics in Osaka 2007. One motion of best record about every top ten athletes in the Men's shot put final was analyzed. All of these putters were right handed. Two digital video cameras (HVR-A1J , SONY) were used to record the putters’ motion at 60fps and exposure time was set at 1/1000sec. One camera was fixed backward and the other at the right side of the throwing circle.

The shot of all ten putters and end points of each body segment of top three putters were manually digitized about every frame with motion analysis system (Frame-Dias; DKH Inc.) from video images. A 14-segment model comprising hands, forearms, upper arms, foot, shanks, thighs, head, and trunk was constructed. Three-dimensional coordinates of 24 points were obtained using a Direct Linear Transformation (DLT) technique (Abdel-Aziz and Karara., 1971), and smoothed by a fourth- order Butterworth low-pass digital filter cutting off at 2.4 to 7.8Hz, determined by residual analyses (Winter, 1990). Standard errors in the constructed coordinates of the control points were 0.006 m (x- axis), 0.004m (y-axis), and 0.007 m (z-axis).

The locations of the center of mass and the moments of inertia for the each body segment of athletes were estimated from the body segment inertia parameters developed by Ae et al. (1992).

For analysis and description of data, putting motion was divided into several phases (Figure 1). The phases of preparation, flight, transition and delivery were assigned with respect to the information of foot contact.

To analyze the motion, a global reference frame was set. The Y-axis was aligned to the putting direction (pointing at front). The Z-axis was the vertical direction (pointing at the top), and the Y-axis was perpendicular to the Y- and Z- axes (pointing at the right). In particular, trunk twist and tilt angle were calculated on the local reference frame fixed on the pelvis. These parameters indicate relative precedence of pelvis rotation to the shoulder axis rotation about longitudinal axis of trunk and tilting angle of trunk within saggial plane respectively.

Results

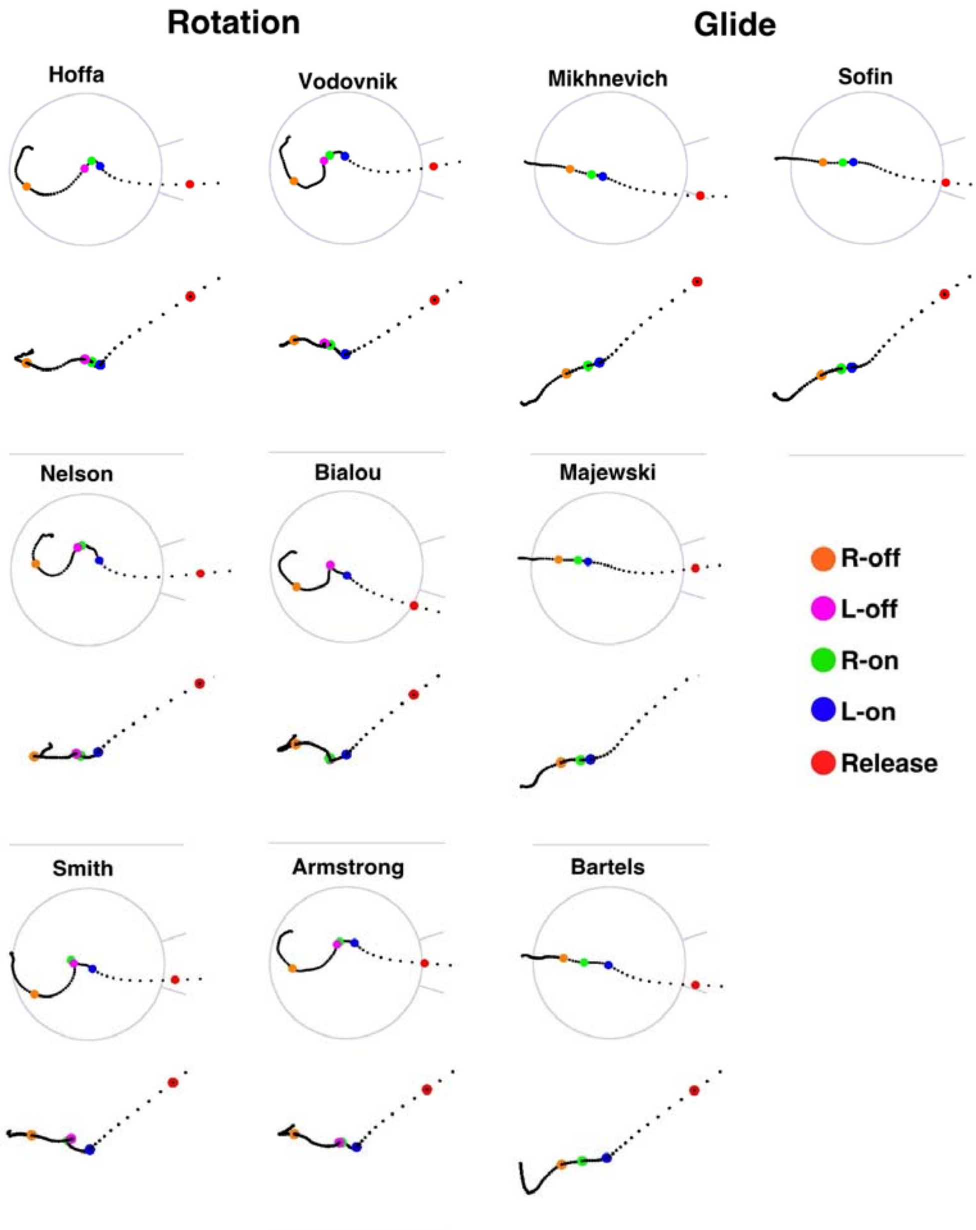
Among ten putters, six adopt the rotational technique and the other four use the glide. Table.1 shows the condition of shot at the release. Official record correlates significantly with the velocity at release ($r=0.87$, $p<0.01$).

Table1. Official records and release conditions of shot.

Rank	Athlete	Official Record (m)	Nation	Rotation/Glide	Velocity (m/sec)	Angle (degree)	Height (m)
1	Hoffa	22.04	USA	Rotation	14.07	32.35	2.34
2	Nelson	21.61	USA	Rotation	14.06	30.77	2.38
3	Mikhnevich	21.27	BLR	Glide	13.44	37.48	2.56
4	Smith	21.13	NED	Rotation	13.34	37.66	2.35
5	Majewski	20.87	POL	Glide	12.99	37.55	2.58
6	Vodovnik	20.67	SLO	Rotation	13.42	33.63	2.26
7	Bartels	20.45	GER	Glide	13.31	35.10	2.11
8	Bialou	20.34	BLR	Rotation	13.24	36.70	2.22
9	Armstrong	20.23	CAN	Rotation	13.18	34.29	2.10
10	Sofin	19.62	RUS	Glide	12.83	35.31	2.39

Shot trajectory on X-Y plane and Y-Z plane of ten putters are showed in Figure 1. About X-Y plane four gliders show almost linear trajectory. The shot of rotators show circle-shaped path in the first half of turn. However "loop" portion of trajectory during flight and transition phase is seen only in Smith.

Figure 1. Shot trajectory on X-Y plane (top view) and Y-Z plane (side view) of ten putters



The time courses of shot velocity of ten putters are represented on Figure 2. Regardless of preparation style, the most of acceleration takes place in the phase of delivery. Before flight phase, while rotation shows two or more peaks, glide shows single peak corresponding to the push off of right leg and the swing of left leg. During flight and transition phase, both of rotation and glide indicates velocity fall. The fall during the flight and transition phase is more remarkable in rotation than glide.

Figure 2. The time courses of shot velocity of ten putters (Only the resultant velocity is shown.)

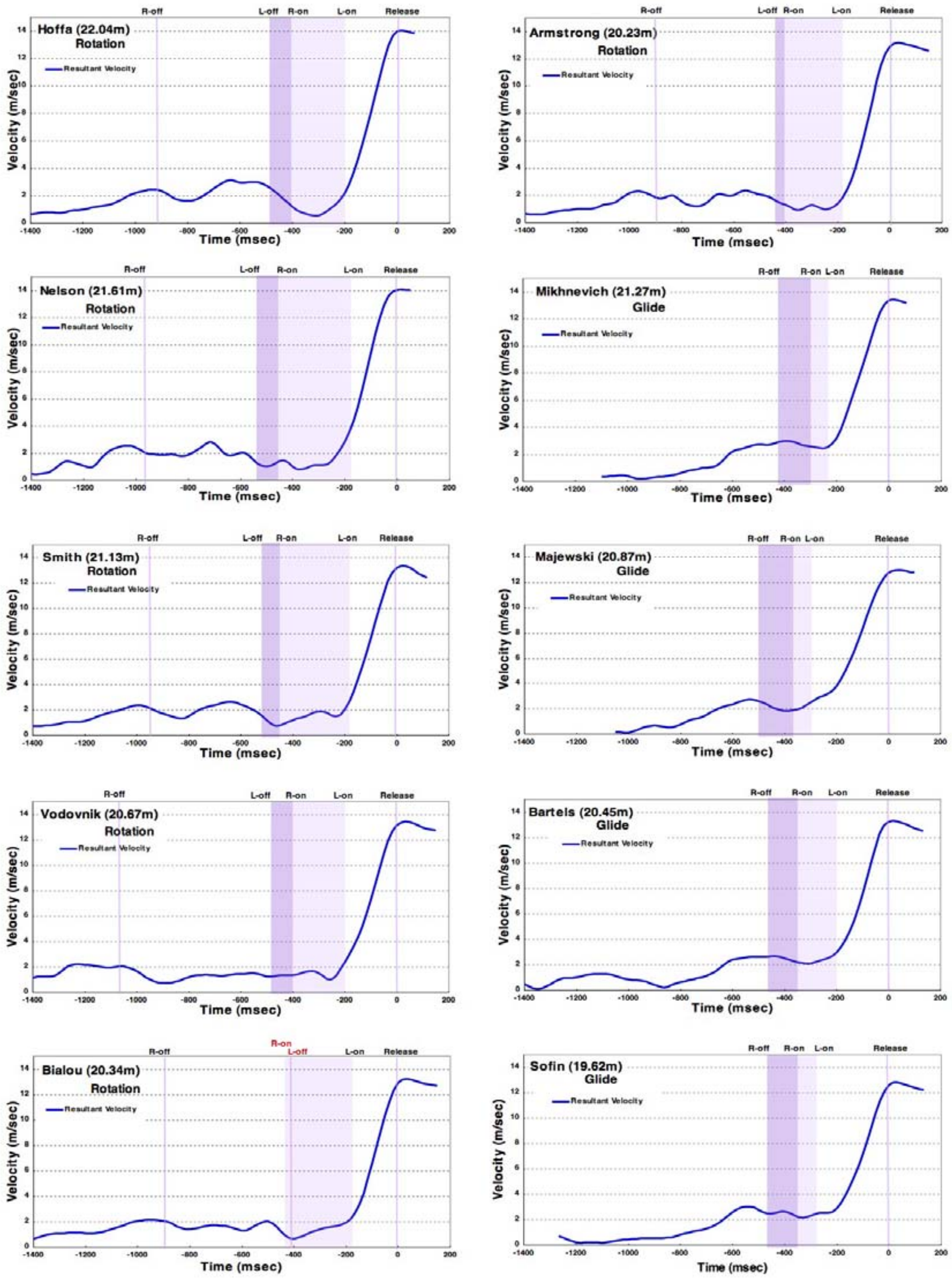
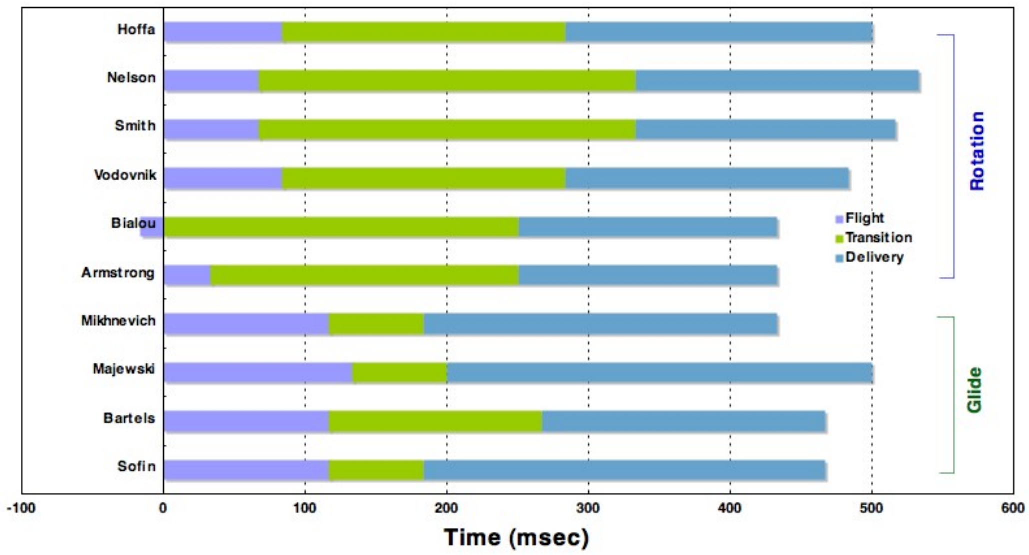


Figure 3 shows the duration of each phase from flight phase to release. Flight phase is longer in gliders than rotators. Especially in rotators, Bialou shows no flight phase. While transition phase is extremely longer in rotators, delivery is longer in gliders. The only rotator who secure the long delivery same as gliders is Hoffa.

Figure 3. Duration of each motion phase from flight phase to release



Further analyses were conducted about the top three putters. Hoffa of 1st and Nelson of 2nd adopt the rotational technique. 3rd Mikhnevich uses glide technique. Their shot velocity showed a typical time change pattern as already described. In this study, we will try to get insight about the cause of shot acceleration with special references to putters' motion and momentum generation.

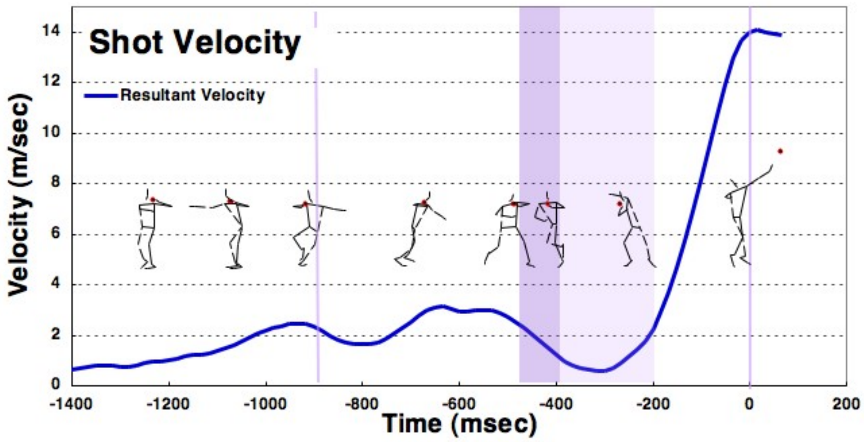
Fig.4a, 4b, 4c show the time course of shot velocity, linear momentum and angular momentum about center of mass (CM).

Linear Momentum of the putter

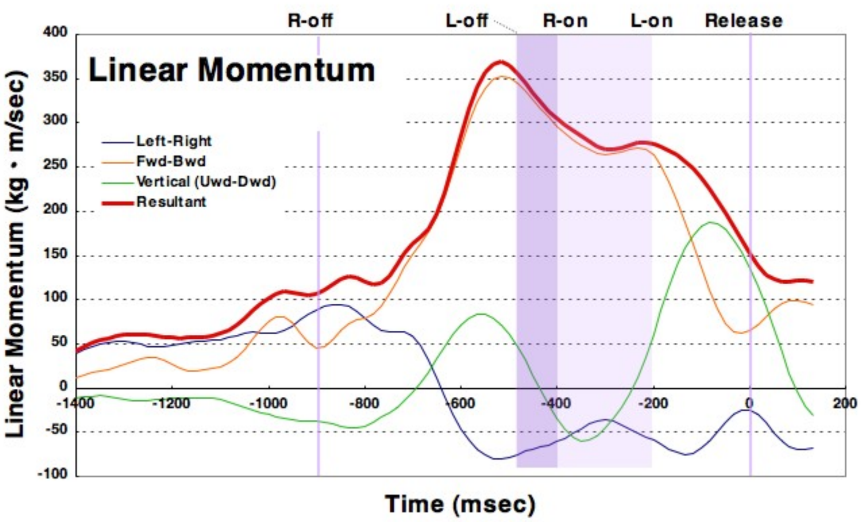
Resultant linear momentum increases gradually and peaks at the last of preparation phase about Hoffa and Mikhnevich. Nelson alone shows the peak during the transition phase. After the peak, it decreases toward the delivery (Fig.??). The peak value of resultant linear momentum of rotational Hoffa (368.9 kg m/sec) surpassed that of Nelson (297.5 kg m/sec) and even Mikhnevich (346.9 kg m/sec) of glide. Nelson shows a notch-like depression just before the L-on, corresponding to the reverse action of upper body during transition phase. On the other hand, Mikhnevich of glide maintains the linear momentum throughout the preparation for the final thrust. Hoffa showed a middle pattern of the other two putters. Two rotator shows second peak of linear momentum around L-on.

Figure 4a. Time course of shot velocity, linear momentum and angular momentum of athlete (Hoffa)

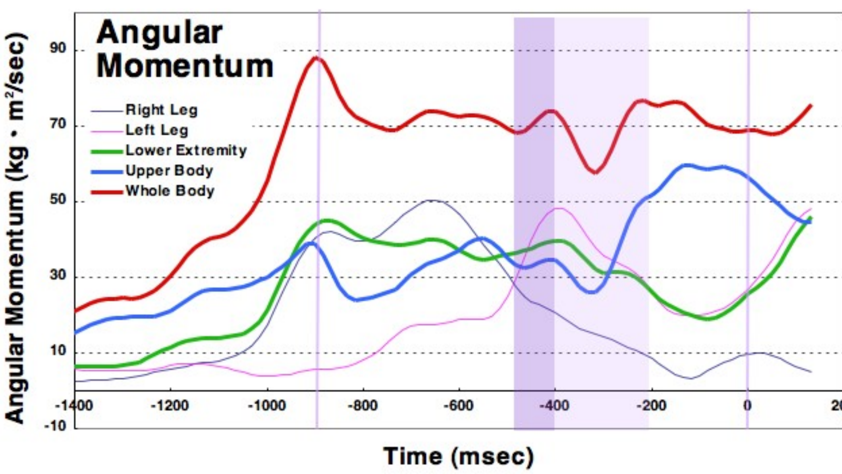
Hoffa (22.04m)



Shot Velocity
Resultant Velocity
Velocity (m/sec)
0
2
4
6
8
10
12
14
-1400
-1200
-1000
-800
-600
-400
-200
0
200
Time (msec)



R-off
L-off
R-on
L-on
Release
Linear Momentum
Left-Right
Fwd-Bwd
Vertical (Uwd-Dwd)
Resultant
Linear Momentum (kg • m/sec)
400
350
300
250
200
150
100
50
0
-50
-100
-1400
-1200
-1000
-800
-600
-400
-200
0
200
Time (msec)



Angular Momentum
Right Leg
Left Leg
Lower Extremity
Upper Body
Whole Body
Angular Momentum (kg • m²/sec)
90
70
50
30
10
-10
-1400
-1200
-1000
-800
-600
-400
-200
0
200
Time (msec)

Figure 4b. Time course of shot velocity, linear momentum and angular momentum of athlete (Nelson)

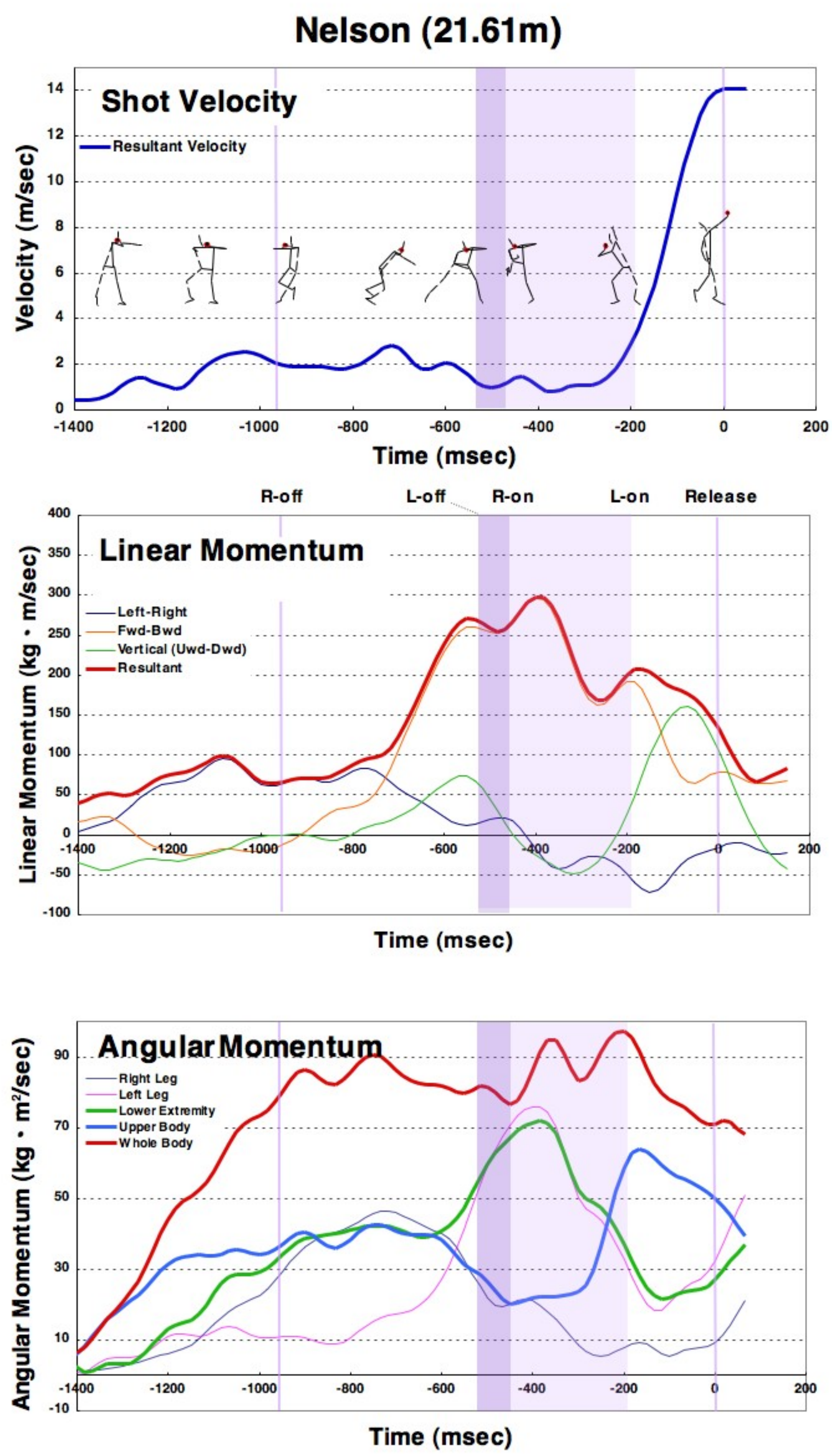
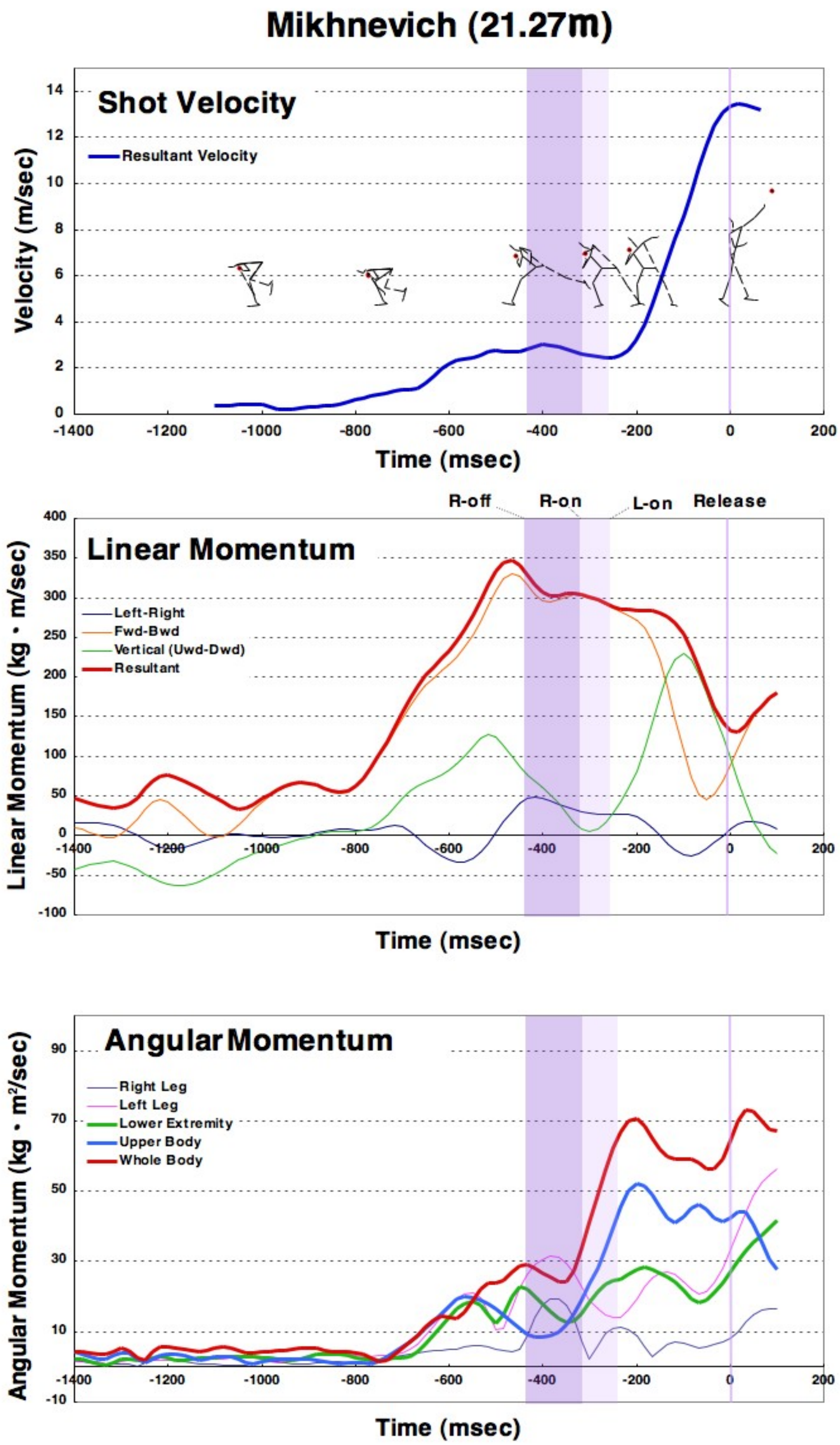


Figure 4c. Time course of shot velocity, linear momentum and angular momentum of athlete (Mikhnevich)



At the start of weight shift and acceleration of body during preparation phase, individual difference is seen in the contribution of each component of the linear momentum. The two rotators can be characterized by the rightward component during the most of preparation phase. While Hoffa makes forward (putting direction) drive, Nelson shows small backward component. Nelson shows a small upper component in the start and downward in the latter half. As for Hoffa, downward component is remarkable in the middle of preparation phase. Mikhnevich of glide is characterized by the starting with downward to forward with upward component before the R-off.

Commonly about both of the rotators and the glider, vertical component shows moderate peak just before the flight phase and remarkable highest peak just before the delivery.

Angular Momentum of putter

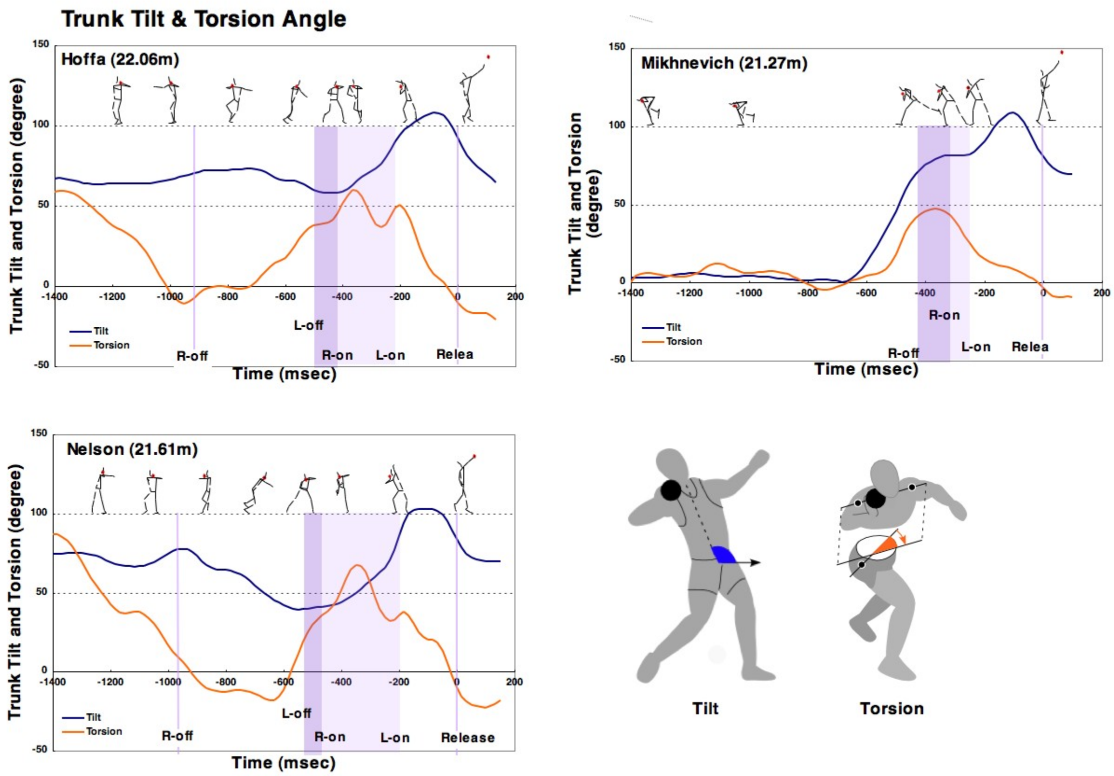
Before R-off, two rotators increase whole body angular momentum about CM mainly by upper body. After R-off, two rotators maintain higher level of angular momentum throughout the motion. On the other hand, as for the Mikhnevich of glide keeps low level of angular momentum in contrast with the linear momentum. Only Mikhnevich shows rapid uniform increase of angular momentum in transition. During preparation, Hoffa keeps the level of angular momentum of lower extremity with balanced generation from both of right and left leg. For contrast, while angular momentum of the right leg of Nelson was almost same level as Hoffa, that of the left leg is remarkably higher and the sudden increase of left leg angular momentum is corresponding to the marked peak of lower extremity and increase of whole body angular momentum.

Trunk inclination and torsion angle

Fig.5 shows the forward - backward inclination within saggital plane and the angle of torsion of the trunk. As for Mikhnevich, both of inclination and torsion angle are gradually increase from about 100msec before the R-off. Then the trunk inclination changes in wide range from horizontal to upright and reached to its peak at just before the release. The torsion angle peaked during flight phase.

Hoffa and Nelson started turn in more upright trunk position. Their trunk tilt forward mostly around the flight phase and increases to the peak just before the release. Nelson leans more forward during preparation than Hoffa and Mikhnevich. It is common among three putters that trunk inclines backward before release beyond and it rapidly reverses toward the release.

Figure 5. Forward - backward trunk inclination and the angle of torsion of the trunk. These parameters indicate tilting angle of trunk within saggital plane relative to the horizontal axis and relative precedence of hip axis rotation to the shoulder axis rotation about longitudinal axis of trunk.



The trunk torsion of Hoffa reaches minimum before R-off. On the other hand, Nelson reaches minimum at late in flight phase. Hoffa and Mikhnevich's winding motion (increase of torsion) progresses at 121.3degree/sec and 141.7degree/sec respectively and that of Nelson increase more rapidly at 285.2degree/sec. The recoil of torsion begins at flight phase in Mikhnevich and in the first half of transition phase in Hoffa and Nelson. The timing of increase of torsion coincides with the It is more intensive in rotation than glide. Especially, Nelson indicates more rapid recoil (221.2degree/sec) than Hoffa (190.8degree/sec) and Mikhnevich (140.8degree/sec).

Discussion

It is reported that body height of Hoffa who won the championship is 182cm, the second Nelson and the third Mikhnevich is 183cm and 201cm respectively (IAAF, 2007). Probably, Hoffa is the shortest world champion of men's shot put so far. It is clearly disadvantageous to be short to secure the acceleration range of the shot. The thought that rotation is suitable for small putters have been shown. Hoffa and Nelson embodied it in form by winning the gold and silver. As a matter of course, there should be the background of the technical excellence in their success.

Official record correlates significantly with the velocity at release. Some fluctuations can be related to other factors such as angle and position of release.

Because most of shot acceleration is executed in delivery, the precedence phases should be aimed at ensuring the final acceleration. To satisfy this condition, not only the preparation of body position and the state of musculature incorporated in the final acceleration, but also the energy storage within athlete-shot system as the source of final acceleration must be critical. The acceleration never occurs by shot alone. It needs the source of energy. In the past study, the researchers' attention has been paid mainly to the acceleration of shot itself even about the flight and transition phase. Luhthanen et al. (1997) pointed out the need of achieving an increase in the speed of the shot during the flight phase. From the viewpoint of reduction of loss of shot velocity, Coe and Stuhec (2005) recommended keeping flight phase shorter. But the argument of how to secure the energy for acceleration has been hardly done. Although, a few researchers mentioned the importance of the momentum of the athlete-shot system (Zatsiorski, 1990; Hay, 1993; Bartnietz, 1994), we cannot find the study that showed it experimentally.

In the present study, the fall of shot velocity during the flight and transition phase is more remarkable in the rotation than the glide. This supports the result of the precedent reports. This slowdown of shot velocity is corresponding to right foot grounding. Especially in rotation, this breaking motion and backward returning motion of the upper trunk coincides. This seems to result in the dissipation of the shot velocity. However, simultaneous generation of angular momentum and preparative configuration of body segments can be seen.

Analyzing the system acceleration about top three in detail, Mikhnevich, in the nature of glide, depends on the linear momentum to storage energy in the whole system. On the other hand, amongst two rotators, Hoffa shows the same level of peak resultant linear momentum as Mikhnevich. It is suggested that linear momentum has great importance as well as angular momentum even in rotational style. Both of the two rotators show higher angular momentum than Mikhnevich.

Hoffa generates higher linear momentum from the effective weight shift to the putting direction and push off. Then he skillfully suppressed the loss of the linear momentum that he got in the preparation phase and reaches the delivery. Two rotator shows second peak of linear momentum around L-on. It seems to be related to the left leg swing of transition phase. Actually, Nelson, indicating marked second peak, is characterized by intensive wide swing of left leg.

Also, from the time course of each component of momentum, the higher angular momentum of rotators after the second half of preparation phase seems to be related to the motion of lower extremity. In particular, Nelson keeps higher angular momentum throughout the preparation. Nelson who shows marked dissipation of linear momentum during transition phase adversely increases the angular momentum. It seems to be closely related to the intensive swing of left leg during the transition. The deepest forward leaning angle of trunk from before R-on to transition seems to secure the range of motion of left leg for wide whipping motion. It is suggested that the leg movement causes the conversion of momentum from leg to the trunk and steep increase of angular momentum of lower extremity and provides trunk torsion as a result. Actually, the velocity of trunk torsion increase of Nelson is more than two times of that of Hoffa and Mikhnevich. The torsion can stretch the abdominal and back muscles just before the final thrust and ensure the intensive upper trunk rotation during the last phase of delivery. Nelson seems to be dependent more upon trunk torsion than Hoffa and Mikhnevich. It is speculated that Nelson most actively utilizes the stretch-shortening cycle of trunk musculature. The remarkable wide swing of left leg of Nelson seems to be the source of kinetic energy of this intensive torsion.

The participation of angular momentum and sideward acceleration, the advantage of rotational technique, can be considered as disadvantage to coordinate the body balance. Hoffa eliminates this kind of tradeoff with continuous linear acceleration of CM from the back of the circle to the release point standing comparison with glide technique without much dissipation of angular momentum of body. Actually, his linear momentum reach to higher level, which exceed not only Nelson but Mikhnevich of glider.

The backward trunk inclination during the delivery is caused by precedence of driving pelvis, but it rapidly reverses toward the release. It is suggested that this forward-backward rotation of trunk reinforces the final trust, cooperating with the linear translation and the recoil of trunk torsion.

Conclusions

The results of the present study shows:

1) While the release velocity is the main determinant of performance, some fluctuations can be related to other factors such as angle and position of release.

2) Appearing in system acceleration, technical variation even within the rotational style. Hoffa utilizes both of linear and angular momentum of body in higher extent. In contrast, Nelson seems to have emphasis especially on angular momentum.

3) Mikhnevich of glider keeps higher level of linear momentum of whole body from the push off of glide to just before the final thrust.

4) Shot velocity alone is not enough to explain the process of acceleration. Because whole body momentum is gained or maintained even in the concomitance of marked decrease of shot velocity during flight and transition phase of rotation. To ensure the source of energy for delivery, acceleration of athlete-shot system is suggested to be the key factor. It can be proposed that the preparation for the delivery seems to be the process to accelerate whole body and secure the favorable body configuration rather than to accelerate the shot itself.

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Biomechanical analysis of elite javelin throwing technique at the 2007 IAAF World Championships in Athletics

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Abstract

The purpose of this study was to investigate the biomechanical parameters that influence the javelin throwing distance only among elite javelin throwers and to indicate the averaged motion pattern of elite javelin throwers. The best competition throws of twelve male finalists at the 2007 IAAF World Championships in Athletics were analyzed. The biomechanical parameters that affect throwing distance for elite javelin throwers were release velocity, and vertical release velocity in particular, and approach run velocity at final right foot contact on the ground. These results suggested that elite javelin throwers who began thrusting the javelin at a higher approach run velocity and obtained some horizontal release velocity (required at least 22-23m/s) but who also obtained higher vertical release velocity obtained better throwing distances. In addition, it was observed from averaged motion of World championships finalists that the better javelin throwers showed more flexion at the right knee angle, we called “knee down” motion, during final preparatory phase.

Introduction

In the past, several biomechanical studies have analyzed the throwing movement of elite javelin throwers in the Olympic Games (OG) or World Championships (WCh). To the extent known, these studies were as follows: the 1985 OG in Los Angeles (Komi and Mero, 1985), the 1991 WCh in Tokyo (Ueya, 1992), the 1992 OG in Barcelona (Mero et al., 1994), the 1995 WCh in Gothenburg (Morriss et al., 1997), the 1999 WCh in Seville (Campos et al., 2004) and the 2005 WCh in Helsinki (Murakami et al., 2006). Most of the studies noted above have reported release parameters (release velocity, release height, release angle, attitude angle, attack angle). Although they also described the characteristics of the throwing technique in individual throwers, few studies elucidated the common characteristics of the throwing techniques among elite javelin throwers. Murakami et al. (2006) investigated kinematic determination of javelin throwing performance for many throwers from the novice to elite level (included WCh finalists) by clarifying the relationship between kinematics of the throwing movement and the distance thrown. However, no studies have tried to investigate kinematic determination of javelin throwing performance only among elite javelin throwers.

The purpose of this study was to investigate the biomechanical parameters that influence the javelin throwing distance only among elite javelin throwers and to indicate the averaged motion pattern of elite javelin throwers.

Methods

Subjects were twelve male javelin throwers who advanced to the male javelin final at the 2007 IAAF World Championships in Athletics in Osaka, Japan. All subjects were right-handed throwers. The best throw for each subject during the competition was analyzed.

The throwing movements were videotaped by two video cameras from the left side and rear of the throwing area. The camera speed was 60fps, and shutter speed was 1000Hz. We calibrated the photographic field of the throwing area (throwing direction: 6m, lateral direction: 4m, vertical direction: 2.5m) for the following three-dimensional analysis. We recorded a pole with six landmarks set on a runway with nine control points.

Twenty-three landmarks on each athlete's body and two reference landmarks on the javelin (tip and grip) were digitized using a digitize system (Frame-DIASII, DKH). The three-dimensional coordinates were calculated using the direct linear transformation (DLT) method. These three-dimensional coordinates were smoothed with a digital filter with cutoff frequency set at 10Hz.

In this study, analysis of the javelin throwing movement focused on the final preparatory and delivery phases. The preparatory phase was defined as the period from when the right foot lands on the ground (R-on) to when the left foot lands on the ground (L-on), and the delivery phase was defined as the period from L-on to release of the javelin (REL).

The calculated parameters were as follows (figure 1):

- Release parameters of the javelin (release velocity, release height, release angle, attitude angle and attack angle)
- Velocity of the body center of gravity (V_{CG}) at R-on, L-on and REL
- Reduction in REL—percent reduction of V_{CG} from L-on to REL
- Duration of the preparatory and delivery phases
- Pull distance—the moving distances of the grip during the preparatory and delivery phases
- Step length—the length between right toe at R-on and left toe at L-on
- Right and left knee joint angle

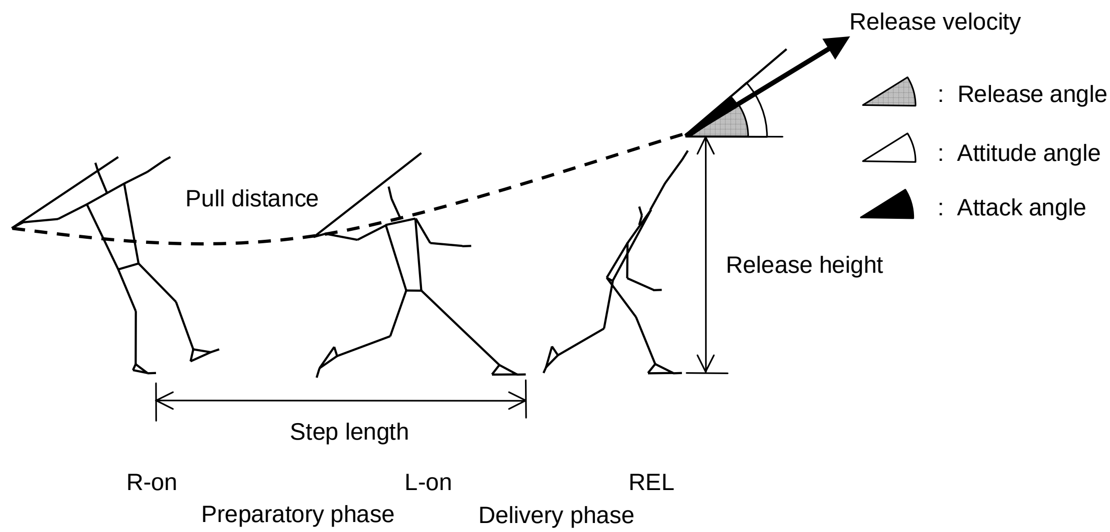

Figure 1 The representation of the measurement parameters

Table 1 Distance and release parameters of the javelin

Rank	Name	Distance (m)	Release Velocity (m/s)				Release height (m)	Release angle (deg)	Attitude angle (deg)	Attack angle (deg)
			Lateral	Horizontal	Vertical	Resultant				
1	Pitkämäki	90.33	-4.5	22.8	18.8	29.9	1.99	39.9	45.6	5.7
2	Thorkildsen	88.61	1.0	24.3	17.2	29.8	1.86	35.9	39.4	3.5
3	Greer	86.21	2.4	24.0	16.6	29.3	1.71	35.6	37.1	1.5
4	Vasilevskis	85.19	1.6	24.7	15.3	29.1	1.81	33.4	37.1	3.7
5	Ivanov	85.18	2.2	24.6	14.9	28.8	1.89	34.3	35.9	1.5
6	Oosthuizen	84.52	2.2	23.5	15.9	28.5	1.91	34.6	38.2	3.6
7	Janik	83.38	2.6	24.4	14.8	28.7	1.87	32.5	34.2	1.7
8	Järvenpää	82.10	2.1	24.6	14.4	28.6	1.78	32.2	38.3	6.0
9	Martínez	82.03	-1.3	24.3	14.9	28.5	2.03	32.9	37.5	4.6
10	Arvidsson	81.98	-0.3	24.4	14.3	28.3	1.99	31.9	33.0	1.2
11	Rags	80.01	1.2	22.6	16.8	28.2	1.96	38.7	40.5	1.8
12	Wirkkala	78.01	0.9	23.9	14.9	28.2	1.84	32.8	42.5	9.7
	Average	83.96	0.8	24.0	15.7	28.8	1.89	34.6	38.3	3.7
	SD	3.48	2.0	0.7	1.4	0.6	0.10	2.6	3.5	2.5

In addition, we showed the averaged motion pattern of the javelin throwing movement for visual feedback in order to consider good throwing technique. The averaged motion was calculated by normalizing the three-dimensional coordinates of the segment endpoints by the thrower's body height and the time elapsed during each movement phase. For details on calculations of averaged motion, refer to Ae et al. (2007). In this study, the averaged motion was compared between six high rank throwers and six low rank throwers. But Greer (Rank 3) was excluded from the six high rank throwers' averaged motion because his leg motion differed markedly from all the other throwers. His legs motion will be described in detail later.

The correlation coefficients (r) between throwing distance and each measured parameter were calculated using the method of least squares. The significance level was set at 5% and 1%.

Results

Distance and release parameters

The distance and release parameters are presented in Table 1. The distance was 83.96±3.48m (Range : 90.33m-78.01m). The highest horizontal release velocity was Vasilevskis (Rank4: 24.7m/s), and the gold medalist Pitkämäki ranked 11th (22.8m/s). However, Pitkämäki had the highest vertical release velocity (18.8m/s); furthermore, he had the highest values in both release angle and attitude angle. Although significant positive correlations were observed between the distance and resultant release velocity (r=0.938, p<0.01) and vertical release velocity (r=0.672, p<0.05), the other release parameters showed non-significant correlations with the distance (Table 2).

Table2 Correlation coefficients between distance and release parameters of the javelin

Parameter	r	significance
Release velocity		
Lateral	-0.325	ns
Horizontal	-0.057	ns
Vertical	0.672	p<0.05
Resultant	0.938	p<0.01
Release height	-0.059	ns
Release angle	0.495	ns
Attitude angle	0.187	ns
Attack angle	-0.247	ns

ns: not significance

The velocity of the body center of gravity, duration, pull distance, and step length

The velocity of the body center of gravity (V_{CG}), duration of preparatory and delivery phases, pull distance, and step length are presented in Table 3. V_{CG} decreased slightly from R-on (6.52±0.33m/s) to L-on (5.98±0.47m/s), and then the velocity rapidly decreased to release (3.44±0.36m/s). Horizontal step lengths for most throwers were the same as their body height or less. Although a significant positive correlation was observed between the distance and V_{CG} at R-on ($r=0.596$, $p<0.05$), the other parameters showed non-significant correlations with the distance (Table 4).

Table 3 Velocity of the body center of gravity (V_{CG}), duration, pull distance and step length.

Rank	Name	V_{CG} (m/s)			Reduction in REL (%)	Duration (s)		Pull distance (m)			Step length (m)	
		R-on	L-on	REL		Preparatory	Delivery	Preparatory	Delivery	Total	Lateral	Horizontal
1	Pitkämäki	6.93	6.48	3.55	45.3	0.183	0.117	1.33	2.06	3.39	-0.75	1.72
2	Thorkildsen	6.91	6.19	3.72	39.9	0.150	0.117	1.13	2.07	3.20	-0.48	1.64
3	Greer	6.72	6.37	3.67	42.3	0.167	0.117	1.26	1.98	3.24	-0.35	1.88
4	Vasilevskis	6.48	6.06	2.71	55.3	0.217	0.117	1.45	2.06	3.52	-0.66	2.14
5	Ivanov	6.90	6.04	3.37	44.2	0.233	0.100	1.71	1.75	3.46	-0.11	2.35
6	Oosthuizen	6.33	4.94	2.73	44.7	0.233	0.133	1.51	2.03	3.54	-0.35	1.98
7	Janik	5.97	5.41	3.72	31.2	0.233	0.150	1.40	1.94	3.34	-0.58	1.96
8	Järvenpää	6.63	6.57	3.77	42.6	0.167	0.117	1.10	2.00	3.10	-0.32	2.00
9	Martínez	6.19	5.75	3.59	37.5	0.233	0.133	1.44	2.20	3.64	-0.81	1.76
10	Arvidsson	6.25	5.61	3.40	39.4	0.200	0.133	1.28	2.10	3.37	-0.46	1.72
11	Rags	6.65	6.21	3.55	42.9	0.167	0.117	1.18	2.06	3.24	-0.16	1.72
12	Wirkkala	6.31	6.09	3.52	42.2	0.150	0.133	1.02	1.99	3.01	-0.48	1.72
Average		6.52	5.98	3.44	42.3	0.194	0.124	1.32	2.02	3.34	-0.46	1.88
SD		0.32	0.47	0.36	5.6	0.034	0.013	0.20	0.11	0.19	0.22	0.22

1. Reduction in REL was percent reduction of V_{CG} from L-on to REL

Table 4 Correlation coefficients between the distance and each parameter

Parameter	r	significance
V_{CG}		
R-on	0.596	$p<0.05$
L-on	0.194	ns
REL	-0.058	ns
Reduction in REL	0.221	ns
Duration		
Preparation	0.056	ns
Delivery	-0.385	ns
Pull distance		
Preparation	0.310	ns
Delivery	-0.062	ns
Total	0.290	ns
Step length		
Lateral	-0.247	ns
Horizontal	0.087	ns

ns: not significance

Visual feedback by averaged motion

In backward viewing, throwers ranked 7–12 tended to show more rightward rotation of the trunk (the grip was placed further backward) during the preparatory phase, so they tended to delay the timing of pulling the javelin during the delivery phase compared to throwers ranked

1–6 (Figure 2, 3).

In side viewing, throwers ranked 1–6 tended to show more flexion at the right knee angle (Figure 4, left upper) and bending of the trunk backward slightly during the preparatory phase compared to throwers ranked 7–12 (Figure 2). Both throwers ranked 1–6 and throwers ranked 7–12 tended to show nearly full extension at the left knee angle after slightly flexing during the delivery phase (Figure 4, right bottom). However, bronze medalist Greer showed a very different style from the other eleven throwers; he kept greater flexion at his right and left knee angle during the delivery phase (Figure 5). Therefore, he was excluded from averaged motion of throwers ranked 1–6.

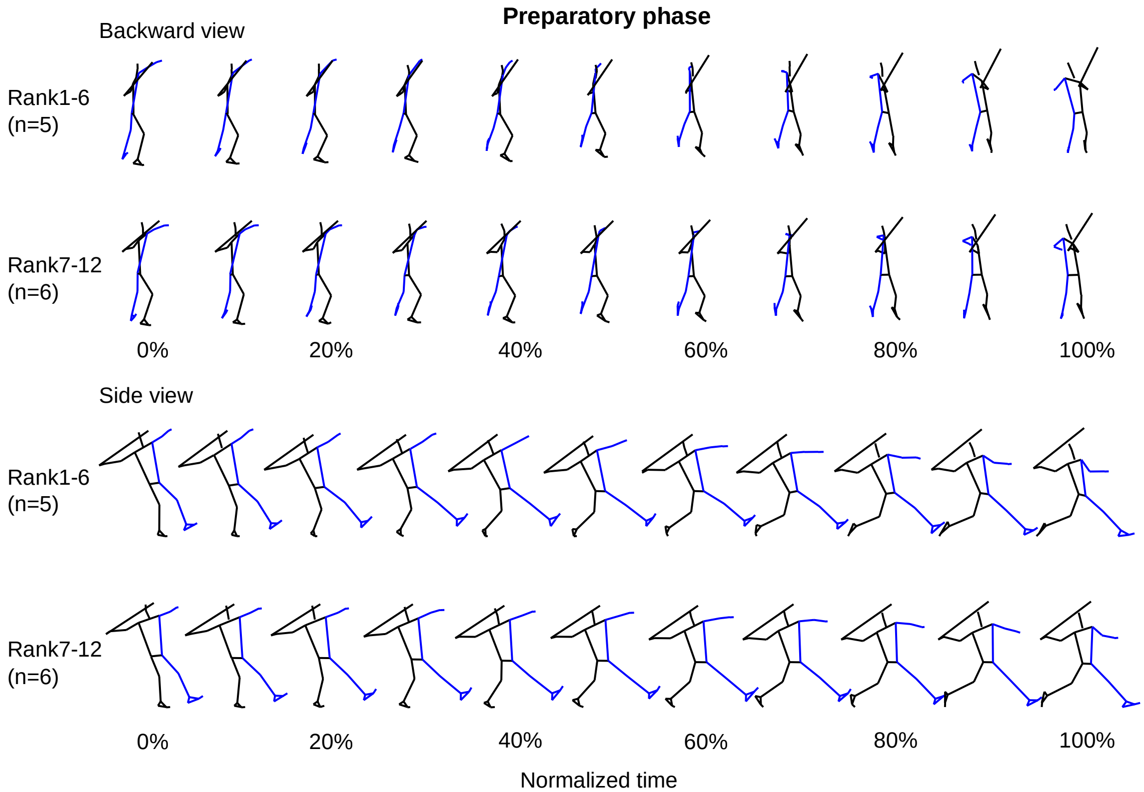

Figure 2 Averaged motion during preparatory phase in elite javelin throwers

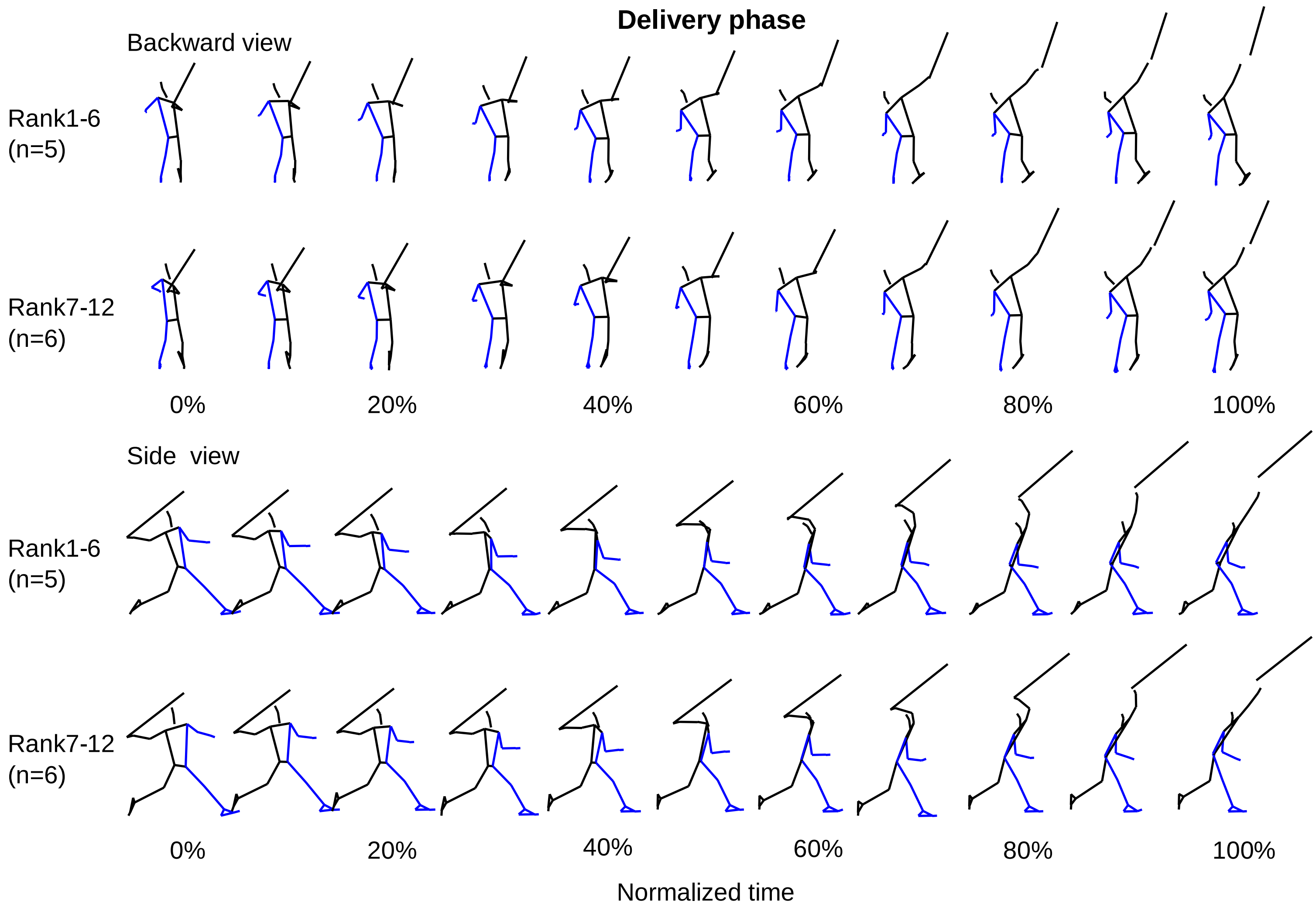

Figure 3 Averaged motion during delivery phase in elite javelin throwers

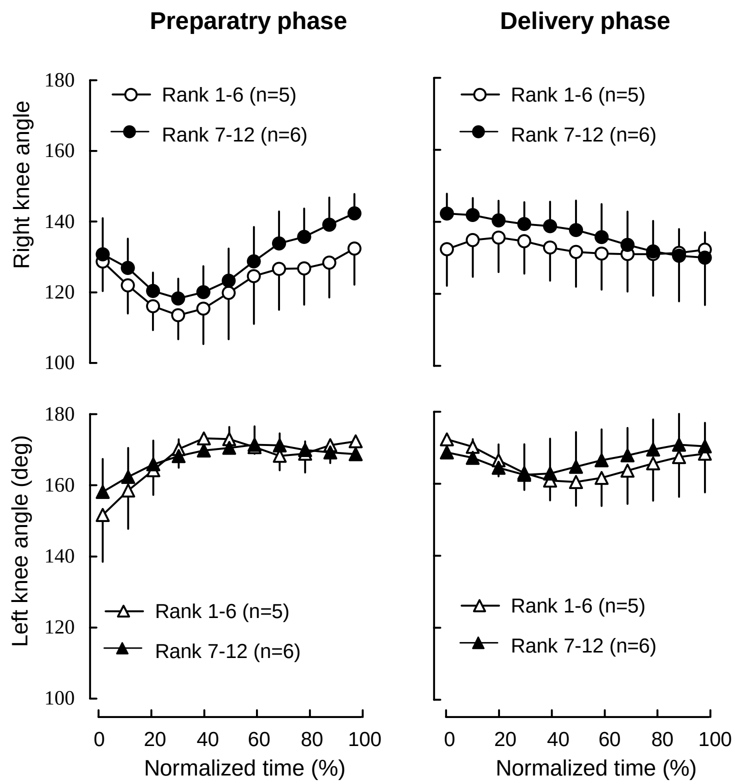

Figure 4　Angle displacement of the knee joint

Figure 5　Stick pictures of the throwing motion during delivery phase in Greer (Rank 3)

Discussion

The release parameters presented in this study (Table 1) were similar to those in previous studies (Mero et al., 1994; Morriss et al., 1997 ; Campos et al., 2004). In relationship to distance, there was a significant positive correlation coefficient between the distance and resultant release velocity; other release parameters showed non-significant correlation with the distance (Table 2). These results were supported by previous studies (Bartonietz, 2000; Murakami et al., 2006). In each component of release velocity, there was no significant correlation between the distance and horizontal release velocity which was most highest mean values in three components, but there was a significant correlation between the distance and vertical release velocity. This result suggested that vertical release velocity was a determination of rank (distance) as a prerequisite for obtaining a horizontal release velocity of about 23–24m/s among elite javelin throwers.

Murakami et al. (2006) has reported that there was a significant positive correlation between the distance and approach run velocity at R-on for a wide range of performance levels. We also obtained the same result (Table 3), which proved the importance of starting to thrust the javelin at a higher approach run velocity in elite javelin throwers. However, the other parameters regarding approach run velocity were not significantly correlated with the distance. Although the reduction in REL is considered to relate to the kinetic energy transfer from the whole body to the javelin (Böttcher and Kühl, 1998; Bartonietz, 2000; Morriss et al., 2001), the amount of reduction was not a factor that decided the javelin throwing performance in elite javelin throwers. It may have influenced this result with different strategies to accelerate the javelin in individuals.

Furthermore, Murakami et al. (2006) have reported that the distance and the pull distance had a linear relationship, and the pull distance values here (in WCh finalists) were similar, but this relationship was not confirmed by this study. This result suggested that pull distance was not a determinative factor in deciding the javelin throwing performance in elite javelin throwers. The duration and step length also were not determinative factors for their ranking.

This study was not able to adequately clarify the determinative factors for ranking in elite javelin throwers, instead indicating only basic biomechanics parameters. Therefore, we must analyze the kinematics and kinetics like angular velocity, momentum, and kinetic energy at each joint and body segment. In order to obtain some hints for future analysis of the throwing techniques in elite javelin throwers, we tried to visually determine how elite javelin throwers move and indicate the averaged motion in five high rank throwers (ranked 1–6) and six low rank throwers (ranked 7–12) among World Championship finalists. This approach will be able to provide highly useful information for javelin throwers and their coaches without showing many biomechanical parameters.

Most interesting was the angle displacement of the both right and left knee joint. In Side viewing, the right knee joint tended to be flexed more in throwers ranked 1–6 than in throwers ranked 7–12 during the preparatory phase (Figure 4, left upper). We describe this motion as ‘right knee down’ in this study. It was conceivable that this ‘right knee down’ motion makes the pelvis rotate without bending the trunk forward, which leads to a body position thrusting the javelin during the former half of delivery phase (Figure 2, 3). In contrast, an incomplete ‘right knee down’ motion was observed in throwers ranked 7–12, who tend to keep bending the trunk forward slightly through the preparatory to delivery phase (Figure 2, 3). We surmise that such differences in motion are caused by more elite throwers producing a higher vertical release velocity for the javelin.

Many previous studies have reported the importance of keeping extension at the left knee joint during delivery phase (Morriss and Bartlett, 1996; Bartonietz, 2000; Murakami et al., 2006). Most elite javelin throwers in this study also showed nearly full extension at the left knee angle after slight flexion during the delivery phase. This left knee motion was found to be an important motion common to elite javelin throwers. However, bronze medalist Greer showed greater flexion at his left knee angle during the delivery phase (Figure 6). This study was unable to clarify whether this was a technique unique to him or whether he had practiced correctly but failed during the competition. Further investigation of this point is probably needed.

Conclusion

This study sought to study biomechanical parameters that affect throwing distance for elite javelin throwers and indicate the averaged motion patterns of throwing motion for elite javelin throwers.

Based on the current results, biomechanical parameters that affect throwing distance for elite javelin throwers are release velocity, and vertical release velocity in particular, and approach run velocity at R-on. This leads to the conclusion that elite javelin throwers who began thrusting the javelin at a higher approach run velocity and obtained some horizontal release velocity (required at least 22-23m/s) but who also obtained higher vertical release velocity obtained better throwing distances.

In addition, throwing movement may differ among upper- and lower-level groups even among elite javelin throwers, a fact that became apparent as a result of visual feedback data. In the future, standardized models will be created and amassed to cover a wide range of javelin throwers, thus identifying more valid findings and perspectives on coaching.

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