A BIOMECHANICAL COMPARISON OF SINGLE, DOUBLE, AND TRIPLE AXELS

D. King, A. Arnold, S. Smith

United States Olympic Committee
Colorado Springs, Colorado, USA

INTRODUCTION

The sport of figure skating has undergone a transition from emphasizing artistry to emphasizing athleticism. To be competitive in national and international competition, figure skaters today must perform complex athletic skills such as triple axels and quadruple toe-loops. While numerous skaters are attempting these jumps in competition, very few are executing them consistently, particularly at the end of their program or in combination with other jumps. This new focus on triple and quadruple jumps has challenged figure skating coaches. The jumps are so quick - less than .65 seconds - that the coaches have difficulty discerning what skaters do differently while executing triple and quadruple jumps as compared to double and single jumps. If figure skating coaches can learn which characteristics of triple and quadruple jumps are critical, they will be able to more successfully teach these difficult skills to developing skaters. Thus, the primary purpose of this study was to compare single, double, and triple axels performed by elite skaters and determine key biomechanical differences between the three jumps.

METHODOLOGY

Five elite male skaters performed a series of single, double, and triple axels in a specified jump zone positioned such that skaters could take their normal approach patterns into their jumps. Three Panasonic 60 Hz video cameras (2 AG450s, 1 D5100) were positioned approximately 100° apart to capture the skaters' take-offs. The jump zone was illuminated with spotlights, and the cameras were set to record with a shutter speed of 1/500.

Three single, double, and triple axels of each skater were recorded with the video cameras. Each jump was rated from fair to excellent by two coaches. Additionally, measurements from the skaters' marks on the ice were recorded to obtain parameters such as jump distance, take-off length, and skid length and width. A PEAK Performance Technologies, Inc. motion measurement system was used to perform a three-dimensional analysis of each skater's best single, double, and triple axel. The trials were manually digitized, creating a twelve segment model. The data from each camera view were smoothed using a Fast Fourier Transform algorithm and then combined using the Direct Linear Transform Theory.

Eight kinematic variables, four at take-off and four in the air were analyzed. A qualitative judgment of the skaters' body position in the air (open or closed) was also made. The parameters for individual skater's single, double, and triple axels were compared, as were the parameters for the group of skaters as a whole. For each parameter, a comparison among different skaters was also performed to determine characteristics typical of the higher rated jumps. Due to the limited number of subjects and trials, no statistical analyses were performed.

RESULTS

Length of take-off, skid length and width, and jump length (Table 1) were measured directly from the skaters' markings on the ice. Length of take-off was defined as the distance that the skaters travelled on their take-off leg during their approach. Take-off lengths for triple axels were consistently less (mean difference 11%) than for single axels, and were frequently less (mean difference 2%) than for double axels. Skid length and width, measurements of the amount of skid the skaters used during take-off, were greatest during the triple axel. Jump length for the triple axel was on average 15% less than for the double axel and 28% less than for the single axel.

Table 1. Single, double, and triple axel ice marking measurements for the five skaters.

	Take-off length (m)			Skid length (m)			Skid width (m)			Jump length (m)		
skater	S	D	T	S	D	T	S	D	T	S	D	T
A	3.8	3.7	3.4	0.0	0.7	0.9	.00	.04	.08	4.3	3.8	3.0
B	4.1	3.8	3.6	0.3	0.7	0.7	.05	.04	.03	4.0	3.4	2.7
C	4.7	4.2	4.3	1.6	1.9	2.1	.04	.10	.10	4.5	3.4	3.6
D	4.2	3.9	4.0	1.5	1.3	1.2	.04	.05	.06	4.0	3.6	3.0
E	5.0	4.4	4.2	0.7	0.8	0.9	.03	.04	.03	3.7	3.2	2.4

Four variables, hip flexion, take-off angle, and vertical and horizontal velocity, were measured at the instant of take-off (Table 2). Hip flexion angles of the free or swing leg were approximately 25% less during the triple axel as compared to the single axel, and 15% less as compared to the double axel. Vertical velocities at take-off demonstrated no trends and were on average similar for the single, double, and triple axel. However, the skaters' horizontal velocities at take-off for the triple axel (mean 3.6 m/s) were lower than for the single axel (mean 5.3 m/s) and for the double axel (mean 4.7 m/s). Accordingly, take-off angles were steepest for the triple axel, on average 43° as compared to 36° for the double axel and 32° for the single axel.

Lastly, four in-air variables, jump height, rotational velocity, time to tightest position, and tilt, were measured (Table 3). Jump height, determined by vertical velocity at take-off, was similar for the single, double, and triple axels, and exhibited no trends across skaters. All skaters demonstrated a consistent increase in rotational velocity from the single axel (mean 2.9 rev/s) to the double axel (mean 4.3 rev/s) to the triple axel (mean 4.9 rev/s), rotating on average 70% faster during the triple axel than during the single axel. Time to tightest position, while not always consistent across skaters, was on average quickest for the triple axel with the arms being quicker than the legs. Tilt in air, a measurement of the skaters' forward/backward tilt from vertical relative to their direction of motion, showed no trends from single axel to double axel to triple axel. However, the most highly rated jumps were all tilted backward between 5 and 10°.

DISCUSSION

In order to increase the number of revolutions completed in a jump a figure skater must increase time in the air and/or rotate faster. While skaters commonly believe that their triple axels are higher than their single and double axels, the results of this study indicate otherwise. Figure skaters' take-off angles were greater in their triple axels. However, due to their lower resultant velocities at take-off skaters actually jumped no higher in their triple axels than in their double or single axels, and thus spent a similar amount of time in the air for all jump types. In a study of four figure skaters performing a variety of single, double, and triple jumps, Aleshinsky (1986) similarly noted a trend of decreasing absolute take-off velocities from single to triple jumps coupled with nearly identical vertical velocity components.

Table 2. Single, double, and triple axel take-off parameters for the five skaters.

	hip flexion (°)			vertical velocity (m/s)			horizontal velocity (m/s)			take-off angle (°)		
skater	S	D	T	S	D	T	S	D	T	S	D	T
A	70	66	60	3.3	3.4	3.1	4.2	4.8	3.8	38	35	39
B	58	45	30	3.1	3.3	3.3	6.8	4.4	4.7	25	37	35
C	105	90	80	3.6	3.6	3.4	6.2	4.7	3.3	30	37	46
D	75	66	66	3.4	3.6	3.4	5.2	5.2	2.9	33	35	49
E	85	75	57	2.8	3.0	3.4	4.2	4.5	3.3	34	34	46

Table 3. Single, double, and triple axel in-air parameters for the five skaters.

	jump height (m)			rotation velocity (rev/s)			time to tightest position legs/arms - (s)			tilt in air (°)		
skater	S	D	T	S	D	T	S	D	T	S	D	T
A	.56	.66	.58	3.6	4.5	5.0	.10/.07	.10/.05	.10/.05	10	6	18
B	.79	.66	.64	2.5	4.1	4.6	.20/.20	.10/.07	.12/.08	8	10	15
C	.79	.73	.81	2.4	4.5	4.7	.13/.13	.13/.07	.08/.05	15	25	22
D	.71	.69	.69	2.8	4.1	5.4	.15/.15	.10/.10	.08/.08	15	11	8
E	.56	.53	.58	3.2	4.1	5.0	.17/.17	.10/.10	.08/.08	12	7	2

Rotational velocity, however, was markedly increased during a triple axel, with the more successful skaters rotating in excess of 5 revolutions/sec. An increase in rotational velocity can come from an increase in angular momentum and/or a decrease in moment of inertia. While neither angular momentum or moment of inertia were directly measured in this study, other variables which were observed suggest that skaters increase their angular momenta at take-off and decrease their moments of inertia in flight. For example, the increased skidding during the triple axel take-off may serve to increase angular momentum by initiating a greater rotation on the ice. Furthermore, the skaters attained a tighter body position and thereby decreased their moments of inertia in the air. The skaters also tended to reach their tightest rotating positions sooner, due in part to their decreased hip flexion at take-off, and they held this position longer. Similar techniques to increase rotational velocity were observed by Aleshinsky (1986), who reported that skaters held a more closed position at the instant of take-off and generated greater angular momentum by starting their rotation on the ice. These observations suggest that strong adductor muscles - needed to quickly attain the rotating position and to resist the large centrifugal forces felt during the rotation - are advantageous if not imperative (Nash, 1988).

Increased skidding during a triple axel may additionally have served to decrease the skaters' horizontal velocities. This would account for the dramatic decreases in jump lengths observed during their triple axels. Another factor which might have contributed to the lower horizontal velocities at take-off is approach velocity. While approach velocity was not able to be measured during this study, by mere observation most coaches believe that skaters' approaches into triple axels are considerably slower than their approaches into single and double axels.

A variable which has not previously been studied is forward/backward tilt in air. It was observed that the highest rated jumps had a backward tilt of 5 to 10°, indicating that there may be an ideal tilt in air regardless of jump type. It would seem that a tilt of 5 to 10° backwards (to the direction of motion) allows the skaters to best maintain a balanced position at landing where the friction between the blade and the ice decelerates the point of support faster than the center of mass.

CONCLUSIONS

Despite an increase in take-off angle during triple axels, skaters tended to jump the same height during all jump types. This is attributed to lower magnitudes of resultant take-off velocities resulting in similar vertical velocities. Thus, the increase in completed revolutions resulted solely from an increase in rotational velocity. This increase in rotational velocity came in part from a greater skid during the triple axel, holding a more closed rotating position, and attaining the tightest rotating position most quickly. Hypothetically, the best technique for maximizing the number of completed revolutions in the air would be to jump as high as possible as well as rotate as quickly as possible. Skaters could theoretically increase the height of their triple axels by having a more open take-off and not skidding, allowing more energy to be utilized for maximizing take-off velocity (Aleshinsky, 1986). However, taking off of a clean edge as opposed to a skid requires greater skill and leaves little room for misstep. Due to the difficulty and great potential for error, this theoretical technique may not be practical for figure skating. Thus, to consistently complete triple axels, skaters must rely on good rotating techniques including a tight rotating position and the ability to attain the rotating position quickly.

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