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Characteristics of Triple and Quadruple Toe-Loops Performed during The Salt Lake City 2002 Winter Olympics

DEBORAH KING,[1] SARAH SMITH,[2] BRIAN HIGGINSON,[3] BARRY MUNCASY[4] and GARY SCHEIRMAN[5]

ABSTRACT

The purpose of this study was to compare triple (T) and quadruple (Q) toe-loop figure skating jumps and quantify basic characteristics of these jumps to provide information to coaches that will assist them in teaching quadruple toe-loops to elite figure skaters. High-speed video was taken during men's practice and competition sessions at the 2002 Salt Lake City Winter Olympics; three-dimensional analyses of selected triple and quadruple jumps were completed. The most significant difference between triple and quadruple toe-loops was an increase in rotational velocity in the air. Additionally, increased vertical velocity at take-off and subsequent time in the air were also observed. Three main conclusions were developed: 1) The timing of rotation of the hips and shoulders was different for quadruple toe-loops compared to triples with the differences being observed before toe-pick; 2) Increases in rotational velocity occurred primarily as a result of the skaters assuming different body positions from take-off through landing which resulted in tighter rotating positions for longer durations of the jump; 3) Greater vertical velocity was gained during the propulsive phase due to the extension of the legs during the press off the ice.

Keywords: jumping, height, angular velocity, biomechanics, kinematics, figure skating.

INTRODUCTION

To remain internationally competitive in figure skating, athletes must be able to perform jumps consistently and safely. In particular, male skaters hoping to compete successfully must be able to perform quadruple jumps. While the first quadruple jump landed in competition occurred at the 1988 World

[1]Department of Exercise & Sport Sciences, Ithaca College, New York, USA
[2]Coaching & Sport Sciences Division, United States Olympic Committee, USA
[3]Departments of Zoology and Exercise & Sport Science, Oregon State University, USA
[4]Department of Exercise Science, Georgia Southern University, USA
[5]Peak Performance Technologies, Inc.

Championships, it wasn't until late 1997 and 1998 that quadruple jumps were being attempted on a regular basis by the top skaters in the world. However, the completion percentage of quadruple jumps still remained low. At the 2000 State Farm Figure Skating Championships, the completion percentage for quadruple jumps was 54% (King, unpublished data). Given the complexity of executing a quadruple jump, the short time frame in which the jumps are completed, and the often subtle technique differences that distinguish a triple jump from a quadruple jump or a successful jump from an unsuccessful jump, biomechanical analyses can provide objective measurements to assist coaches as they help skaters master this difficult skill.

To date, the majority of biomechanical analyses of figure skating jumps has focused on the Axel jump (Albert and Miller, 1996; Aleshinksy *et al.*, 1988; King *et al.*, 1994; King, 1997), which has been considered traditionally the most difficult jump due to its forward edge take-off. In particular, the triple Axel was one of the crucial jumps for male skaters competing at the national and international level. However, the rapid evolution of quadruple jumps has forced *up and coming* male skaters to add to their repertoires of jumps and to learn at least one quadruple jump in addition to the triple Axel. Presently, two jump types, the toe-loop and Salchow, are being performed as quadruple jumps in competition with the quadruple toe-loop being more prevalent. The toe-loop is a pick jump off the right back outside edge with a left toe-pick (Figure 1).
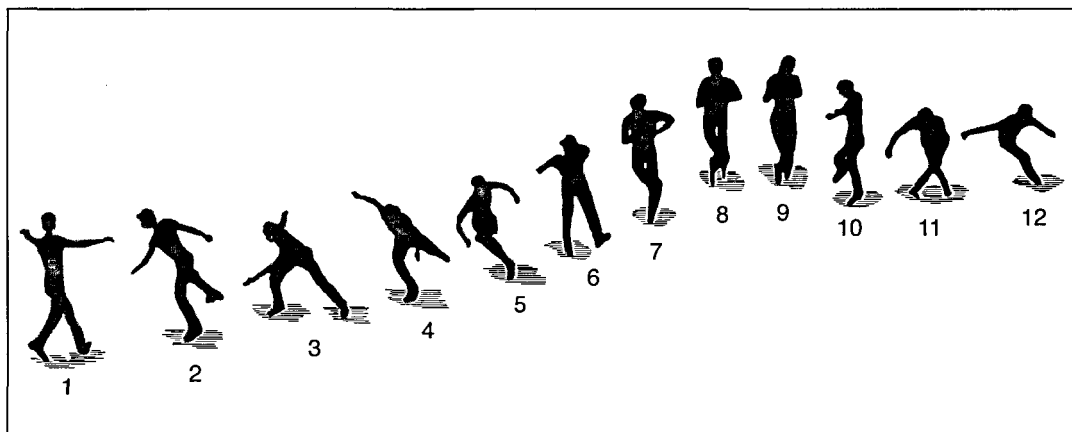
Figure 1 Photo sequence of a quadruple toe-loop illustrating the skater gliding backward on the right foot (4th picture) just prior to placing the left toe-pick on the ice (5th picture) in preparation for take-off (6th picture).

The progression from low to higher revolution jumps in figure skating (e.g. double to triple) has recently focused on the need to increase rotational velocity in the air as opposed to jump height. Researchers have reported the main differences in single to double to triple Axels to be decreases in moments of inertia of skaters about their longitudinal axes (Albert and Miller, 1996; Aleshinsky *et al.*, 1988) with only minor differences in jump heights or times in the air (Albert and Miller, 1996; King *et al.*, 1994). In a study of a minimal number of

quadruple toe-loops performed at the 2000 U.S. Nationals, jump heights tended to be lower for quadruple jumps compared to triples with similar times in the air due to delayed landings during the quadruple jumps (King et al., 2002).

However, a study by King (1997) found an increase in jump height from single to double to triple Axels. When jump heights were compared between groups of skaters of different skill levels, height became a distinguishing factor. Comparing a group of accomplished male skaters who could perform single and double Axels (Albert and Miller, 1996) to a group of elite male skaters who could perform single, double, and triple Axels (King et al., 1994), the skaters who were performing triple Axels had higher single and double jumps.

Thus, the purpose of this study was to determine technique differences in triple and quadruple jumps. Specifically, the goals were to compare kinematic characteristics of quadruple jumps (Q), triple jumps of the skaters who can perform quadruple jumps (T_{yes}), and triple jumps of skaters who can not perform quadruple jumps (T_{no}). The ultimate goal was to provide coaches with information to help them teach skaters this difficult skill.

METHODS

Data were collected at the 2002 Salt Lake City Winter Olympics during the men's short and long programs as well as during particular men's warm-up and practice sessions held at the Salt Lake Ice Center in Salt Lake City, Utah. Basic subject characteristics were obtained from press releases.

Four high speed (120-pictures/second) pan and tilt cameras (Peak Performance Technologies, Inc., Centenial, Colorado) were used to record the entire free and short programs and the approach through landing of selected figure skating jumps during the practice sessions. Two cameras each were placed on both sides of the ice rink approximately 52 m away from centre ice, 26 m past centre ice towards the ends of the rink, and 28 m above ice level (Figure 2). The two cameras on each side of the rink were gen-locked. A calibration was performed prior to each day of testing with two survey poles, each 4.88 m in length, sequentially moved to seven locations on the ice, as was recommended by Peak Performance Technologies (Figure 2). Combinations of three to five poles that gave the best three-dimensional reconstruction were used to establish calibrations for each day of data collection. The three-dimensional reconstruction error, determined by computing the root mean square difference between the actual and computed distances of ice and board markings and the poles not included in the calibrations, averaged 0.023 ± 0.016 m (mean±SD).

In total, 71 quadruple toe-loops or quadruple toe-loop combination jumps were attempted at the Olympics. However, this study was delimited to quadruple toe-loops not performed in combination with another jump, for which 33 were attempted and 13 were landed cleanly. It was not possible to assess whether any of the 20 non-cleanly landed quads would have been quadruple toe-loop combination jumps had they been landed. A clean landing was defined as a jump for which the skater landed on one foot and glided out of the landing without touching down a hand or having to step out of the landing onto the other foot. Of the 13 cleanly landed quadruple toe-loops, eight jumps performed by six
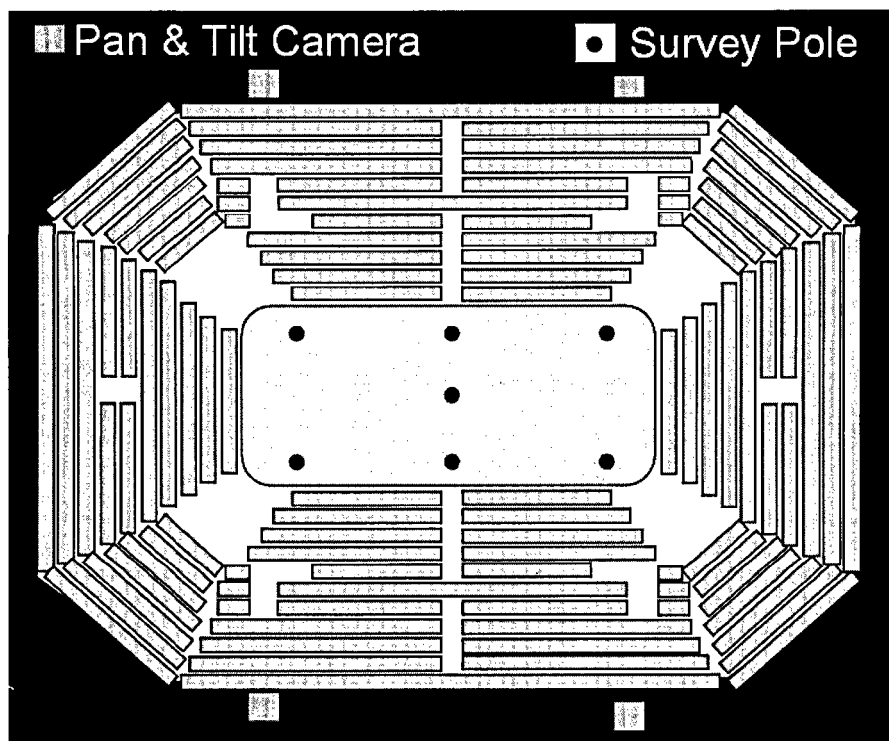
Figure 2 Aeriel view depiction of camera placement around Salt Lake Ice Centre and survey locations used during the calibration.

skaters were in full field of view of at least two cameras from the approach through landing and were chosen for analysis.

Few of the skaters (10) performed triple toe-loops during competition since the triple toe-loop is one of the easier triple jumps and does not elevate the difficulty of the skaters' programs as other triple jumps would. However, many of the skaters performed triple toe-loops in practice, typically as a warm-up to a quadruple toe-loop. Thus, two distinct groups of triple toe-loops were analysed, those completed by skaters who were completing quadruple toe-loops (T_{yes}) and those completed by skaters who were not performing quadruple toe-loops (T_{no}). Skaters qualified for the T_{no} group, if they did not attempt a quadruple jump at the Olympics in either practice or competition and if they had not performed a quadruple jump in international competition during the 2002 competitive season. In total, eight triple toe-loops, performed by six different skaters, were included in the T_{no} analysis and 11 triple toe-loops, performed by seven different skaters, were included in the T_{yes} analysis. A summary of skater characteristics along with number of skaters and jumps analysed in each group is presented in Table 1.

Only two of the four camera views were used in the analysis of each jump. All video data were manually digitised creating a 19 point model of the skater consisting of 11 segments. The head and neck were treated as one segment as

were the forearm and hand. Three dimensional x, y, and z coordinates were calculated from the raw x and y coordinates using the algorithms from the pan and tilt calibration. The position data were then filtered using quintic spline processing with filtering parameters determined automatically using an optimisation algorithm (Motus v.7.1, Performance Technologies Inc.). The first and second derivatives of each landmark were then visually inspected and filtering parameters were adjusted as needed. Final filtering parameters for all landmarks and all coordinates ranged from 0.0008 to 0.003.

Table 1 Subject Characteristics for Skaters Completing Q and T_{yes}, T_{no} Toe-Loops. Age and Height Values are Means ± Standard Deviations.

	Age (years)	Height (m)	# Skaters	# Jumps Analysed
Q	21.8±4.9	1.72±0.03	6	8
T_{yes}	24.1±5.0	1.68±0.07	7	11
T_{no}	22.0±1.7	1.74±0.05	6	8

Data analyses were completed using custom software in LabView (v 5.1, National Instruments, Austin, Texas). Whole body centre of mass (CM) was determined using mass inertia characteristics from deLeva (1996). An average mass for two boots of 2.9 kg was used for all skaters based on boot measurements taken from nine U.S. national and international calibre male skaters. The centre of mass location of the boot was assumed to coincide with the centre of mass of the foot. Relative vertical momentum contributions of the upper and lower extremities to the vertical momentum of CM were determined with the method of Lees and Barton (1996). Selected joint angles were calculated using Eulerian angles (Zatsiorsky, 1998) and velocities were determined using the first order central difference method.

Four key events were identified for each jump: toe-pick (instant the toe-pick was placed into the ice); take-off (last contact with the ice); max height (top of the flight phase); and landing (instant of contact with the ice). Additionally, each jump was divided into three phases: approach; propulsion; and flight (Figure 3). The approach phase began at the initiation of the three turn entering the jump and ended at toe-pick. The propulsion phase began at toe-pick and ended at take-off. The flight phase began at the take-off and ended at landing. In total, 21 kinematic variables describing the position and motion of the skater were calculated along with the times of the propulsive and flight phases (Figure 3).

Average approach speed (AppSpeed) was calculated as the average magnitude of the horizontal velocity during the approach. Knee flexion at toe-pick was calculated for the glide (GlideKnee$_{TP}$) and take-off (TOKnee$_{TP}$) legs and reported such that zero degrees correspond to a fully extended position. For all skaters except one, who jumped the opposite direction, the glide leg was the right leg and the take-off leg was the left. Toe-pick distance (TPDist) was calculated as the horizontal distance between the heel of the glide foot and the toe of the take-off foot at the instant of toe-pick. Vertical (Vel$_{VTO}$) and horizontal
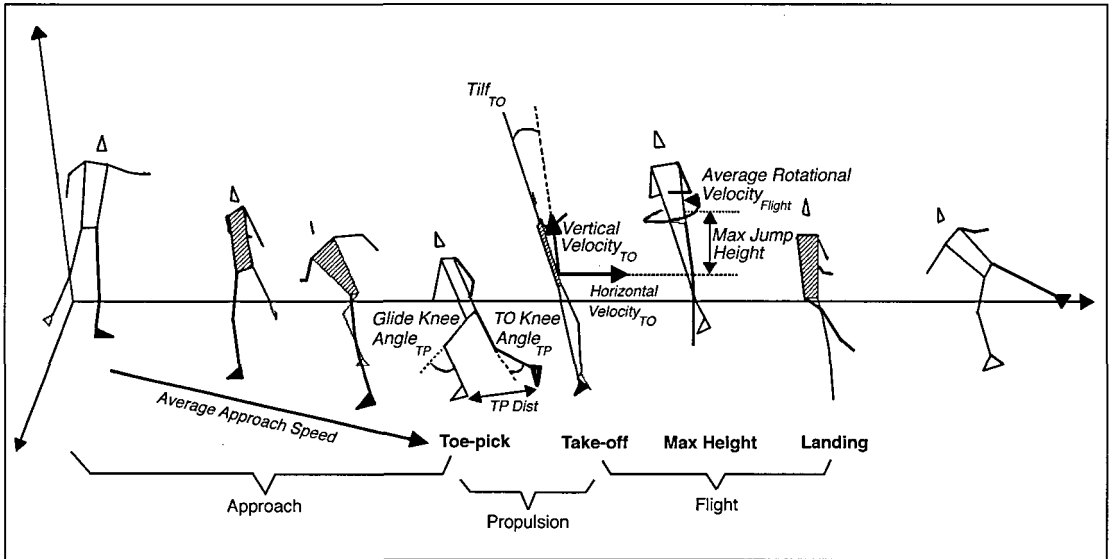
Figure 3 Stick figure representation of quadruple toe-loop depicting key events, phases of the jump, and selected variables.

(Vel_{HTO}) velocities at take-off were calculated for the centres of mass of the skaters. Take-off angle ($Angle_{TO}$) was calculated as the inverse tangent of the Vel_{VTO} divided by the Vel_{HTO}. Backward tilt (Tilt) was defined as the angle between the longitudinal axis of the skater's trunks and a vertical axis that was projected onto a vertical plane parallel to the skater's direction of travel during the flight phase. Average rotational velocity (RotVel) was calculated from the hip segment about the longitudinal axis during the flight phase. Maximum jump height was defined as the maximum vertical displacement of the CM of the skaters during flight. Hip and shoulder rotation angles (Figure 4), measured as the angle between the two hips and shoulders, respectively, and a line perpendicular to the direction of travel of the jump in the horizontal plane, were calculated at toe-pick ($HipRot_{TP}$, $ShRot_{TP}$), take-off ($HipRot_{TO}$, $ShRot_{TO}$) and landing ($HipRot_{LAND}$, $ShRot_{LAND}$). Heights of the CM at the take-off ($Height_{CMTO}$) and at the landing ($Height_{CMLAND}$) were calculated as the vertical position of the CM above the ice surface at these two instances. Lastly, to measure the *openness* or *closedness* of the skaters' positions, in terms of arm and leg position, a variable, body position (BodyPos), was defined. Body position was detemined by averaging the distances of the two wrists and free (glide) leg ankle from the longitudinal axis of the skater in the transverse plane of the skater at take-off, throughout the flight phase, and at landing (Figure 5). This measure was chosen in lieu of reporting the skaters' moments of inertia to provide coaches with a practical measure that is easily visualised in comparison to the body positions that their own skaters assume during these jumps. The measure was adapted from an ankle to ankle position measure reported by Albert and Miller (1996) in a study of double Axels. A comparison the BodyPos variable and the moment of inertia calculated about a skater's longitudinal

axis for a *quadruple toe-loop* is provided in Figure 6. Notice that the two variables follow a similar trend throughout the phases of the jump, but that the scale on BodyPos has a more immediate visual meaning to the non scientist since it is reported in metres. Variables dependent on stature, TPDist, $Height_{COM}$, and BodyPos, were scaled using a ratio to the skaters' heights to the average height of the skaters.
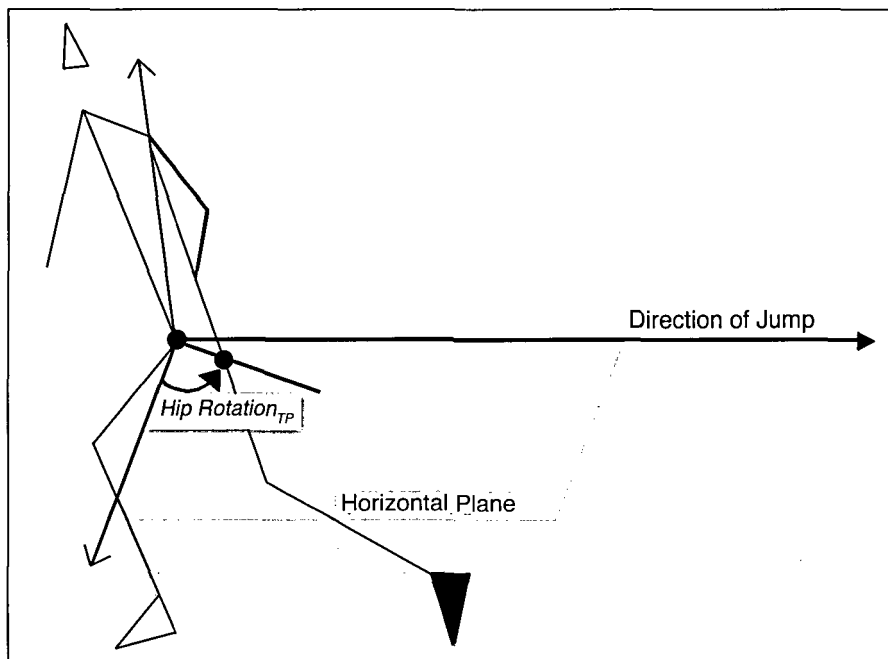
Figure 4 Schematic of how $HipRot_{TP}$ was measured. The same measuring system was used to measure hip and shoulder rotation at toe-pick, take-off, and landing. Landing rotation values, however, are reported as degrees short of square. Negative 90 indicates the skater is 90 degrees short of completing the last rotation.

There were only four skaters whose jumps were analysed in both the Q and T_{yes} group. However, due to the already small number of jumps available for analysis, it was decided to keep the eight Q jumps and 11 T_{yes} jumps even though there was not perfect pairing between the two groups. For skaters who had more than one jump in a particular group (Q, T_{yes}, or T_{no}), the averages of their multiple jumps within that group were used in preparing all summary statistics. Only descriptive summary statistics were performed for the dependent variables.

RESULTS

Approach and Toe-pick

The average horizontal approach speeds were similar for all jumps (Table 2) with the Q jumps on average only 6% slower as compared to the T_{yes} jumps.

L. Arm–COM Distance$_{TO}$

R. Arm–COM Distance$_{TO}$

Free Ankle–COM Distance$_{TO}$
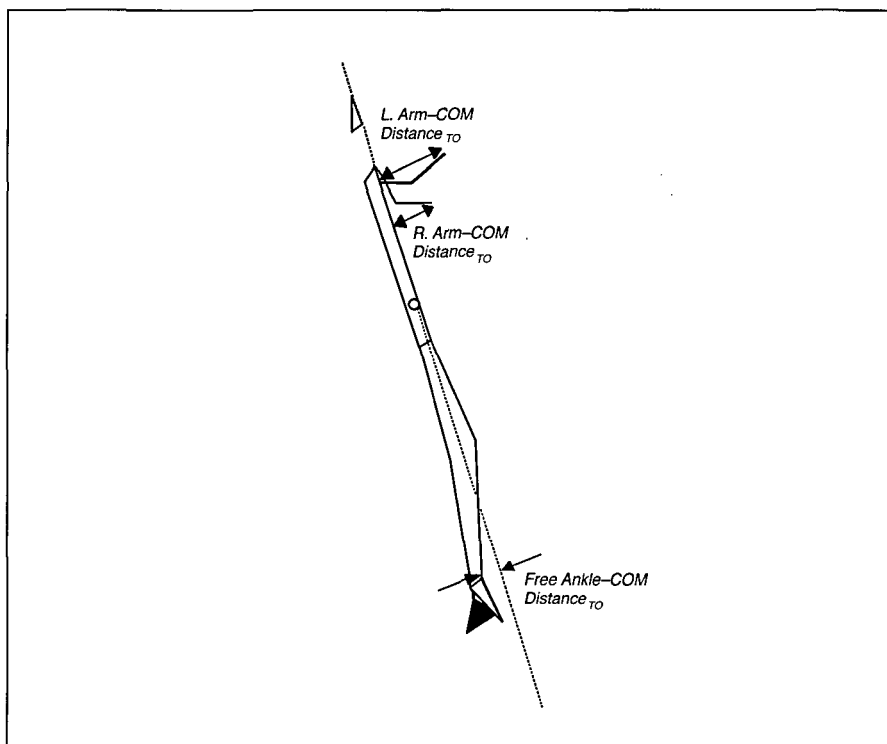
Figure 5 Schematic of how BodyPos$_{TO}$ was measured. The average of L.Arm-CM Distance$_{TO}$, R.Arm-CM Distance$_{TO}$ and FreeAnkle-CM Distance$_{TO}$ were averaged. The same measurement system was used for BodyPos$_{FLIGHT}$ and BodyPos$_{LAND}$.

Through the approach, as the skaters prepared for the toe-pick, there was gradual downward motion of their centres of mass due to flexion of the glide knee. The knees of the glide legs then started to extend on average 0.12 to 0.14 s prior to toe-pick. The toe-pick of the take-off foot was placed into the ice an average of 0.76 m from the glide foot for the Q jumps and generally centred behind the right hip. Toe-pick distance tended to be slightly less for the Q jumps as compared to the T$_{yes}$ jumps. However, TPDist was somewhat variable from jump to jump for individual skaters and not all skaters who completed both quadruple and triple toe-loops consistently had shorter TPDist for their Q jumps.

Both the timing and positioning of the hip and shoulder rotation in this phase was slightly different across groups (Table 2). The T$_{no}$ group opened their hips more during the approach so that by toe-pick the hips were rotated on average 8 degrees farther into the jump as compared to the T$_{yes}$ or Q groups. Additionally, for the T$_{no}$ jumps, the shoulders were lagging on average 26 degrees behind the hips at toe-pick. A similar technique was observed for the T$_{yes}$ jumps, for which shoulder rotation was on average 32 degrees behind hip rotation. However, for the Q jumps, the skaters started rotation of the shoulders earlier in the approach so that at toe-pick the shoulders were on average only 6 degrees behind the rotation of the hips.

Table 2 Approach and Toe-Pick Variables for Q, T_{yes}, and T_{no} Jumps. All Values are Mean ± SD.

	Q	T_{yes}	T_{no}
AppSpeed (m/s)	5.8 ± 0.3	6.2 ± 0.8	5.9 ± 0.7
GlideKnee$_{TP}$ (degrees)	66 ± 14	64 ± 13	66 ± 1
TOKnee$_{TP}$ (degrees)	45 ± 6	43 ± 18	38 ± 3
TPDist (m)	0.76 ± 0.11	0.83 ± 0.10	0.79 ± 0.06
HipROT$_{TP}$ (degrees)	54 ± 27	56 ± 17	63 ± 15
ShRot$_{TP}$ (degrees)	48 ± 24	24 ± 6	37 ± 9

Propulsion and Take-off

The propulsive phases for all groups averaged 0.14 ± 0.03 s in duration. During this phase, the skaters generated the majority of the vertical velocity for the jump and completed the initial on-ice rotations in preparation for their rotations in the air. Vertical velocities at take-off were similar for the Q and T_{yes} jumps
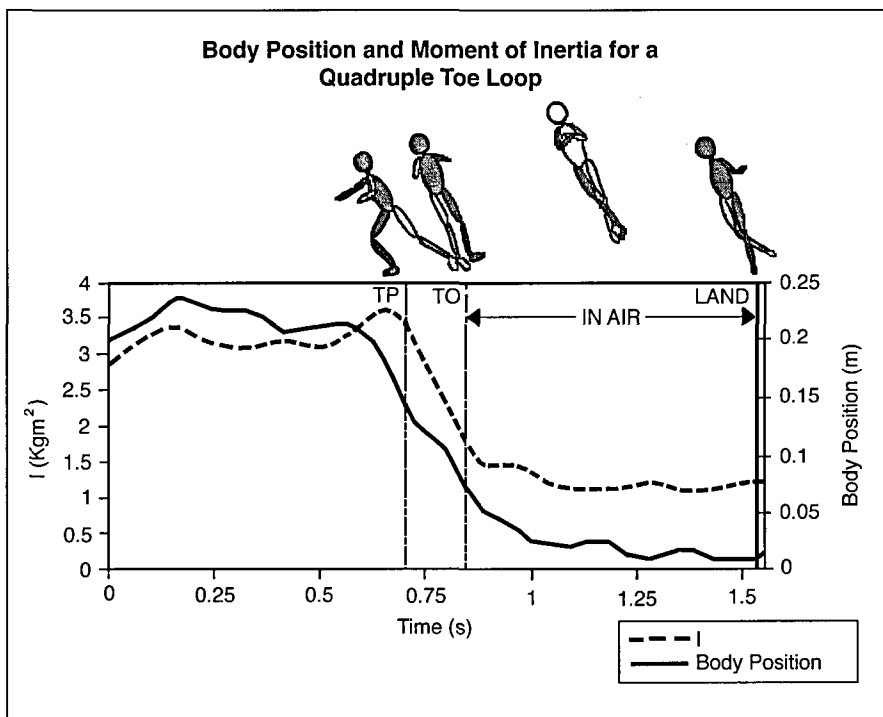
Figure 6 Comparison of the variable BodyPos and a skater's moment of inertia calculated about the longitudinal axis for a quadruple toe-loop. The graph starts just before the three turn during the approach and ends just after landing. The value of BodyPos indicates in metres the average distance the arms and legs are away from the midline of the skater's body (refer to Figure 5 and text). The dark grey leg and arm are the skater's right side, the light grey leg and arm are the left side, a dark trunk is the back of the skater, and a white trunk is the font of the skater.

averaging 3.3 ± 0.2 m/s and 3.2 ± 0.4 m/s, respectively; both Q and T_{yes} vel_{VTO} were consistently higher than vel_{VTO} for the T_{no} jumps which averaged 3.0 ± 0.1 m/s (Table 3). For all jumps, the vertical velocity came predominantly from the extension of the legs pressing the skater off the ice. The relative vertical contribution from the upward drive of the arms or glide leg once off the ice was minimal, averaging $1.4 \pm 1.1\%$ of the total body vertical momentum. During this phase, the skaters also gain vertical velocity from the upward movement of the CM that results from the skaters drawing their feet together and rising over the pick foot. For the Q jumps, the skaters were slightly more vertical at take-off, 15 ± 2 degrees of backward tilt as opposed to 19 ± 4 for the T_{no} jumps and had a higher CM height at the instant of take-off (Table 3).

During this phase, the skaters turned on the toe-pick and the rotations of the hips and shoulders continued. The shoulders turned faster than the hips for all jumps (Table 3), but this difference was small for the Q jumps, 2.7 rev/s for hips versus 2.9 rev/s for shoulders. Recall that for the Q jumps, the hips and shoulders were more aligned in rotation position at toe-pick than for the T_{no} and T_{yes} jumps as well, meaning that the hips and shoulders turned more in unison during the Q jumps than for the other jumps. By the end of the propulsive phase, the shoulders were on average rotated 4 to 6 degrees past the hips for all jumps. In comparing the absolute rotation position of the hips and shoulders at take-off across jumps, the Q jumps had 14 to 25 degrees greater rotation of both the hips and shoulders at take-off as compared to both the T_{no} and T_{yes} jumps with the T_{yes} group having the least rotation (Table 3). There were no differences in the *degree of openness* of the skaters at the instant of take-off, as measured by $BodyPos_{TO}$, but the free leg ankle was closer to the axis of rotation $(0.14 \pm 0.05$ m) for the Q jumps as compared to the T_{no} jumps $(0.18 \pm 0.04$ m).

Table 3 Propulsion and Take-Off Variables for Q, T_{yes}, and T_{no} Jumps. All Values are Mean $\pm$ SD.

|	Q	T_{yes}	T_{no}
Phase Time (s)	0.14 ± 0.04	0.15 ± 0.03	0.14 ± 0.02
Vel_{VTO} (m/s)	3.3 ± 0.2	3.2 ± 0.4	3.0 ± 0.1
Vel_{HTO} (m/s)	4.0 ± 0.4	4.2 ± 1.0	4.1 ± 0.7
$Angle_{TO}$ (degrees)	39 ± 2	38 ± 5	30 ± 14
Tilt (degrees)	15 ± 2	17 ± 7	19 ± 4
$Height_{CMTO}$ (m)	0.98 ± 0.06	0.90 ± 0.07	0.88 ± 0.07
$BodyPos_{TO}$ (m)	0.26 ± 0.04	0.25 ± 0.04	0.26 ± 0.03
$HipROT_{TO}$ (degrees)	187 ± 25	162 ± 29	171 ± 39
$ShRot_{TO}$ (degrees)	191 ± 23	166 ± 27	177 ± 21

Flight and Landing

The greatest difference between the Q, T_{yes}, and T_{no} jumps was the rotational velocity during flight (Table 4). The average rotational velocity as measured from the rotation of the hips was 1.0 rev/s faster for the Q jumps as compared

to T_{yes} jumps and 0.9 rev/s faster than for the T_{no} jumps. The increase in average rotational velocity for the Q jumps came in part from maintaining a tight rotating position throughout the duration of the flight phase (Figure 7). At landing, BodyPos$_{LAND}$ for the Q jumps was 0.17 ± 0.06 m as compared to a more open position of 0.24 ± 0.10 m for the T_{no} jumps and $0.24 \pm .06$ m for the T_{yes} jumps (Table 4). Height$_{CMLAND}$ was lower for the Q jumps as compared to the T_{yes} jumps, but very similar to the T_{no} jumps. Time in the air was also greatest for the Q jumps; on average the Q jumps had only 0.03 seconds more flight time than the T_{yes} jumps (Table 4). The total rotations completed in the air, as measured from the hips, were 3.23 rotations in the air for the Q jumps, 2.42 for the T_{yes} and 2.32 for the T_{no} jumps.

Table 4 Flight and Landing Variables for Q, T_{yes}, and T_{no} Jumps. All Values are Mean $\pm$ SD.

	Q	T_{yes}	T_{no}
RotVel (rev/s)	4.8 ± 0.1	3.8 ± 0.2	3.9 ± 0.1
Height (m)	0.55 ± 0.04	0.55 ± 0.12	0.51 ± 0.07
Time$_{FLIGHT}$ (s)	0.68 ± 0.02	0.65 ± 0.05	0.62 ± 0.03
HipRot$_{TO}$ (degrees)	-90 ± 25	-44 ± 25	-35 ± 16
ShRot$_{TO}$ (degrees)	-115 ± 22	-40 ± 24	-56 ± 17
Height$_{CMLAND}$ (m)	0.93 ± 0.02	0.97 ± 0.04	0.93 ± 0.03
BodyPos$_{LAND}$ (m)	0.17 ± 0.06	0.24 ± 0.6	0.24 ± 0.10
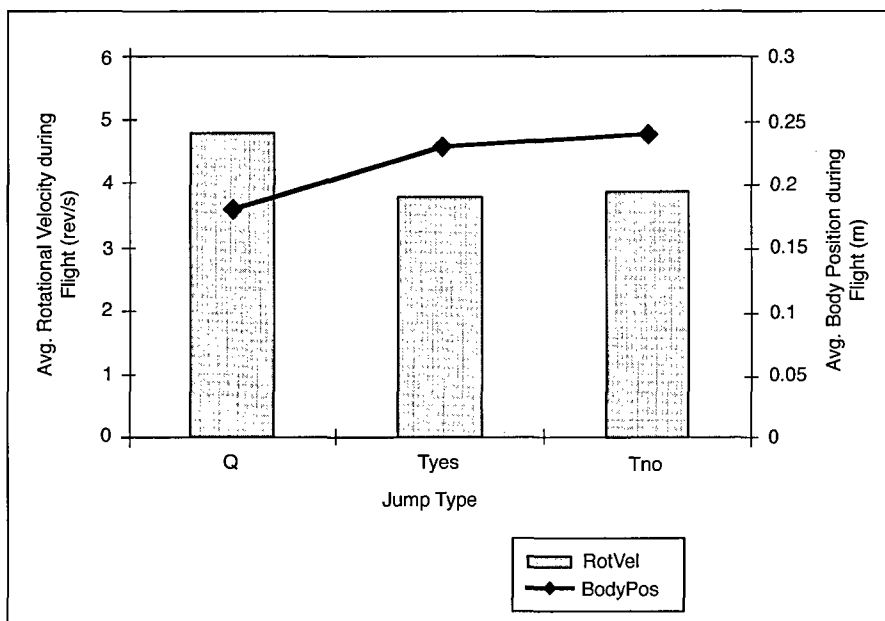
Figure 7 Graph of average rotational velocity during flight and average body position during flight for all three jump types, showing how slower RotVel for the triples corresponds with larger BodyPos$_{FLIGHT}$.

DISCUSSIONS AND IMPLICATIONS

While the most significant aspect for completing a quadruple toe-loop as compared to a triple is being able to increase rotational velocity in the air, which is commonly emphasised by coaches, several other characteristics of the toe-loop are performed differently for quadruple jumps, which cannot be ignored. Firstly, there is a misconception that skaters must skate faster into quadruple jumps as compared to triples. The approach speed for Q and T_{no} jumps were fairly similar, and skaters who were performing quads actually tended to skate slower into their quads as compared to their triples, even though the differences in approach speeds between jumps were small. These results could have more to do with confidence and a feeling of control and timing for the jump than an actual mechanical advantage to slowing down the approach. In fact, from a purely mechanical perspective, obtaining or maintaining a fast approach would appear to have benefits if skaters can take advantage of the speed by translating their kinetic energy during the approach into the generation of more vertical velocity during the propulsive phase through the vaulting action off the toe-pick. In fact, the observation that the T_{yes} jumps do have slightly faster approaches than the T_{no} jumps and slightly greater vertical take-off velocities lends some credence to this hypothesis. However, the mechanism of the greater vertical velocity at take-off could be due to other factors such as a more forceful extension of the legs.

Examining the timing of the extension of the glide leg, relative to toe-pick, in the Q jumps the skaters tended to begin the extension of the knee of the glide leg closer in time $(0.12\pm0.0\,\text{s})$ to toe-pick as compared to the T_{no} $(0.14\pm0.08\,\text{s})$ and T_{yes} $(0.14\pm0.05\,\text{s})$ jumps although the knee moved through similar ranges of motion. This quicker extension could be related to the tendency for the Q jumps to have a smaller TPDist that was also associated with slightly greater knee flexion of the pick leg at the instant of toe-pick. However, a cause and effect relationship has not been established between these three factors. A more thorough analysis of the various components of the generation of vertical velocity during the propulsive phase, perhaps utilising mathematical models, appears warranted.

Secondly, while approach speed was not faster for quadruple toe-loops, vertical take-off velocity was higher for both Q and T_{yes} jumps as compared to skaters who could not do quads (T_{no}). Greater vertical take-off velocity results in higher jumps and more time in the air to complete the extra revolution for the quadruple toe-loop. While skaters who can perform quadruple toe-loops do not need this extra height to complete their triple toe-loops, they do maintain this extra height during their triples, as shown by the greater jump heights observed for the T_{yes} jumps as compared to the T_{no} jumps. Whether these skaters had higher jumps all along, which assisted in their mastering the quadruple toe-loop, or developed higher jumps while learning, or after learning, the quadruple toe-loops is unknown. However, having adequate height and sufficient time in the air to complete four revolutions is obviously important to advancing from a triple to a quadruple jump. All quadruple toe-loops analysed in this study had flight times greater than 0.658 seconds, which is slightly

longer than the minimal flight time observed from four quads analysed from 2000 U.S. Nationals that was 0.625 seconds (King *et al.*, 2002). However, these minimal flight times are still longer than the average flight time observed for the T_{no} jumps in this study, suggesting that jump height or time in the air is an important factor for being able to perform a quadruple toe-loop successfully. Since the $Height_{CMLAND}$ was similar for the Q and T_{no} jumps, skaters needing additional flight time for the Q will need to achieve higher jumps to get this time rather than trying to extend the time at landing by landing in a lower or more flexed body position. This height will come predominantly from a greater vertical velocity due to pressing off the ice with the legs. However, the upward movement of the CM as the skaters draw their feet together and attain a more vertical position, less backward tilt, at the instant of take-off for the Q jumps is also beneficial.

Lastly, the timing of the rotation of the hips and shoulders initiated on the ice was different for quadruple jumps compared to triples. Specifically, skaters who were performing quadruple toe-loops started the rotation of their shoulders earlier, so that by toe-pick their hips and shoulders were more aligned about their longitudinal axes as opposed to the shoulders lagging behind the rotation of the hips. Consequently, during the propulsion phase, the hips and shoulders turned in a more uniform motion for the Q jumps as compared to the T_{yes} and T_{no} jumps. Thus, to advance from triple to quadruple toe-loops, skaters should initiate an earlier rotation of the shoulders so that they have a quick, synchronised turning of the trunk on the pick foot.

At take-off, skaters should expect to be facing just past forward with their arms close into the body and the free leg approximately parallel to the take-off foot. It is a misconception that during the quadruple toe-loop skaters need to drive hard upward with their arms or free leg in an attempt to gain additional vertical velocity and height for the jump. These results are similar to what has been reported for triple Axels as compared to double Axels as compared to single Axels for which there is less upward and outward movement of the free leg and arms during propulsion (Albert and Miller, 1996; King *et al.*, 1994). Keeping the arms and legs close to the body assists the skaters in attaining faster average rotational velocities in the air by allowing them to be in tight rotating positions at the instant of take-off. Overall, the skaters were able to increase their rotational velocities by 1 revolution per second during the flight phase of the quadruple jumps due to a combination of increased rotational velocities at take-off and delayed check-outs which enabled the skaters to maintain fast rotational velocities through the entire flight phase. This increase in rotation speed along with slightly longer flight times and a more pre-rotated take-off position allowed skaters to land quadruple toe-loops successfully. However, this strategy does require skaters to have the strength and ability to check and control their rotation on the ice during landing.

Similar strategies of relying predominantly on increased rotational velocity and greater initial rotation on the ice to increase number of revolutions have been observed when comparing single to double or double to triple axles (Albert and Miller, 1996; King *et al.*, 1994, King, 1997). However, in comparing skaters who can and cannot perform quadruple jumps, this study also reveals

that being able to generate vertical velocity at take-off to achieve adequate time in the air is characteristic of skaters who can complete quadruple jumps. This increase in vertical velocity did not come from differences in upward drive of the arms or free leg, but rather from the press off the ice of the glide and pick leg.

CONCLUSION

Coaches can take three main conclusions from this study to assist them with teaching and critiquing quadruple toe-loops. Of utmost importance is the ability to increase rotational velocity. Beginning before toe-pick, the skaters initiated rotation of the shoulders so that by toe-pick the hips and shoulders were aligned and rotated, with respect to the longitudinal axis, together as the body turned quickly on the toe-pick while the skaters pressed off the ice. Secondly, the movement of the skaters' arms primarily contributed to rotation and were not driven up and through in an attempt to gain more vertical velocity. Skaters then held the tight rotating positions until landing and didn't have noticeable check- outs in the air. And lastly, despite the need to increase rotational velocity, skaters performing quads in this study had greater jump heights and more time in the air than those not performing quads; thus, a greater vertical force production from the legs during the press off the ice is important.

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