EFFECTIVE EXECUTION OF THE FLIGHT IN QUADRUPLE JUMPS IN FIGURE SKATING

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For a high final score figure skaters need quadruple jumps (QJ) with perfect execution. QJ are very difficult and have a high risk of falling. Therefore the purpose of this study was to identify reserves in the flight phase for a safe execution of jumps with more than three rotations. The complete number of turns in the flight phases is necessary to perform a safe landing. Perfect quadruple jumps in different competitions with international participation of 12 world class athletes have been selected for the study and analysed with a 3D kinematic analysis. The primary aim of the study has been to identify reserves for a perfect execution on the basis of moment of inertia. In addition the study aimed at characterizing the movement when preparing the landing movement with only a very short time available for the skater, especially in jumps with more than three turns.

KEY WORDS: landing solutions, moment of inertia, flight time, kinematics.

INTRODUCTION: One major aim in figure skating competitions is to perform difficult jumps almost perfectly for a high Basis Value (BV) with high Grade of Execution (GOE). Jumps with more than three rotations have the highest BV and three of them can be presented in the men's free skating competition. Jump combinations in the second half of the free program get a factor 1,1 in BV. The flight time for QJ is a limiting factor.

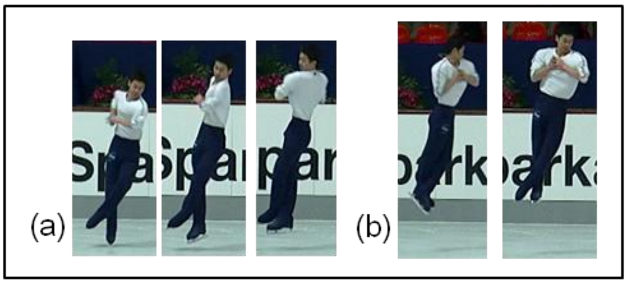

Figure 1: Positions with the minimum moment of inertia during the flight (b) and before the first contact to the ice (a) of the 4S

Several studies (Sakurai, Ikegami, Akiya & Asano, 1999; Knoll, 2004a) found differences in flight time for multi-revolution jumps between training, the first and the second jump in free skating competition programs. The highest flight times were measured in training and the smallest flight times in the second jumps. The flight time is determined by vertical velocity in the take off (King, 1999), and flight time in QJ is greater when compared with the same jump, but three rotations only (King, Smith, Higginson, Muncasy und Scheirman, 2003). But the same flight time in QJ can be generated with different angular momentum (Knoll, 2004b). Knoll and Härtel (2005) found differences between generated maximum value during take-off and the angular momentum for the flight in the last contact on ice.

To present jumps with more than three turns is very challenging including a high risk of falling. The reasons for falls are different, but if the last rotation is not completed and the blade of the landing leg is 90° or more transverse to the jump direction, falling is indispensable. Therefore the aim of the study was to identify reserves on the basis of moment of inertia (MOI) with respect to an actual flight execution. For an effective flight phase, the minimum moment of inertia should be achieved quickly and should be maintained as long as possible. The beginning of the flight phase is determined by the position at the last contact on the ice. All investigated jumps; the Triple Axel (3A), the Quadruple Toeloop (4T) and the Quadruple Salchow (4S) have a different execution of the take off. They can also have different positions during the last contact on ice. From this position the skater switches to the closed position in the air with a small moment of inertia (Figure 1b). Studies on 3A have identified different landing positions at the end of the flight phase.

Knoll (2004a) identified three possible landing solutions, one of them against rotation (AR) (Figure 1a). The AR is defined as active rotation of the upper body against the lower body while preparing for landing. This solution of landing preparation allows the skater to perform the last turn in QJ in a very short time.

METHODS: For the study we selected the best solutions with clean landing of 3A, 4S and 4T performed by world class skaters between 2000 and 2013 in the following competitions: Grand Prix in Gelsenkirchen, World Championships 2004 in Dortmund, Junior World Championships 2007 in Oberstdorf, Nebelhorn Trophy 2012 in Oberstdorf and national events. A clean landing was defined according to King et al. (2004) as a jump which was landed on one foot at the backward-outside edge. Therefore 12 jumps of 10 world class skaters with an age from 16 to 25 years were selected for further analyses.

A minimum of two cameras was applied to record the jumps in DV-format with 50 Hz. The cameras were fixed and could be tilted or zoomed. The positions of the cameras and markers in the background image and the control points were geodetically measured. The cameras were gen-locked. As measurement systems were used the electronic Tachymeter (TOPCON 213) and since 2007 the TRIMBLE Total-station 5503DR with non reflected measurement of the distance (Figure 2).

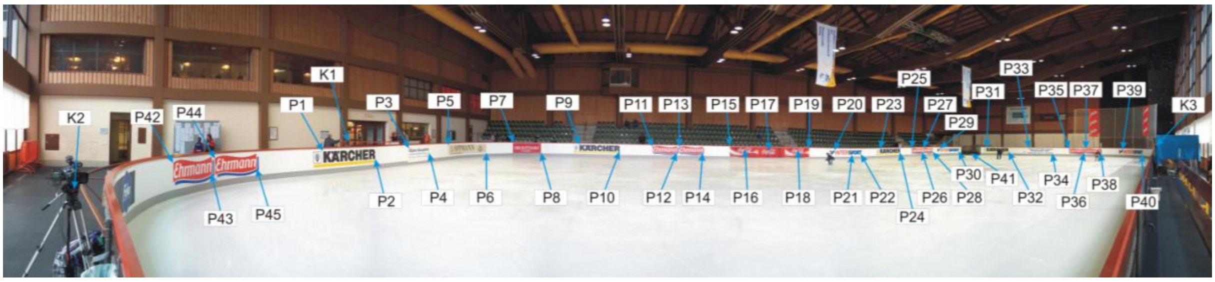

Figure 2: The ice ring 60 x 30m with measurement points and camera positions (K1-K3).

The marker positions in the inertial reference frame were defined by videometric analysis of the real motion with the system "Simmess" of the IAT (Drenk, 1994).

With respect to an exterior coordinate frame, the inertia tensor I, is computed as

$$I_{11} = \int_V (y^2 + z^2) dm, \quad I_{12} = -\int_V xy\, dm, \qquad I_{13} = -\int_V xz\, dm.$$

The formula for I_{21}, I_{yy}, I_{yz}, I_{zx}, I_{zy}, I_{zz} are analogous. Using eigendecomposition of I the three principal moments of inertia I_{xx}, I_{yy}, and I_{zz} could be identified. The smallest one I_{zz} corresponds to the direction of the longitudinal axis.

Based on Hildebrand (1997), a mathematical algorithm for computing biomechanical parameters in figure skating has been developed. The explicit computation of the total inertia tensor (I_{xx}, I_{yy}, I_{zz}) uses all inertia tensors of body segments as well as the skates. In the analysis of the moment of inertia (MOI) during flight phase one frame before last contact to the ice to one frame after the first contact to the ice has been applied.

To answer the question, if landing with AR is the preferred landing solution strategy, we furthermore analyzed if AR is applied in landing when only 0,08 s or less were available for the last 180° rotation. Therefore we have applied visual criteria for the movement of the shoulder and hip axis which resulted in an answer "yes" or "no". The first contact on ice after the flight was assessed as the reference point. The time frame of 0,08 s for the last 180° rotation is empirical, based on real time determined.

For the correlation between the different MOI and flight time the correlation coefficient Pearson r was calculated. For the correlation between the execution with or without AR in relation to the time for the last half rotation with more or less than 0,08 s the Phi-coefficient ϕ was statistically calculated as a measure for the power of the association between these two dichotomous characteristics.

RESULTS: Within the three groups of jumps skaters (S) with the smallest flight time in the QJ (S3, S8) or in the 3A (S9) have the smallest MOI during the flight (Table 1). They also have the smallest MOI at the last contact on ice. Otherwise the skaters with the longest flight time in QJ (S2, S5) have bigger MOI in preparation of landing (Figure 3) and perform on average.

Table 1
Flight time (t_{FL}), moment of inertia (MOI) at the last contact on ice, during the flight and in preparation of landing of 12 jumps

	Parameter	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
4S	Flight time t_{FL} [s]	0,68	0,72	0,66									
	MOI last contact [kgm^2]	1,90	1,68	1,11									
	MOI flight [kgm^2]	0,82	0,83	0,46									
	MOI landing [kgm^2]	0,96	1,56	0,74									
4T	Flight time t_{FL} [s]				0,72	0,76	0,74	0,72	0,68				
	MOI last contact [kgm^2]				1,56	1,67	1,56	1,40	1,28				
	MOI flight [kgm^2]				0,67	0,81	0,85	0,60	0,59				
	MOI landing [kgm^2]				0,73	2,03	0,99	0,83	1,01				
3A	Flight time t_{FL} [s]									0,62	0,72	0,72	0,72
	MOI last contact [kgm^2]									2,09	3,69	2,75	2,82
	MOI flight [kgm^2]									0,73	1,14	0,94	0,93
	MOI landing [kgm^2]									0,60	0,97	1,34	1,23

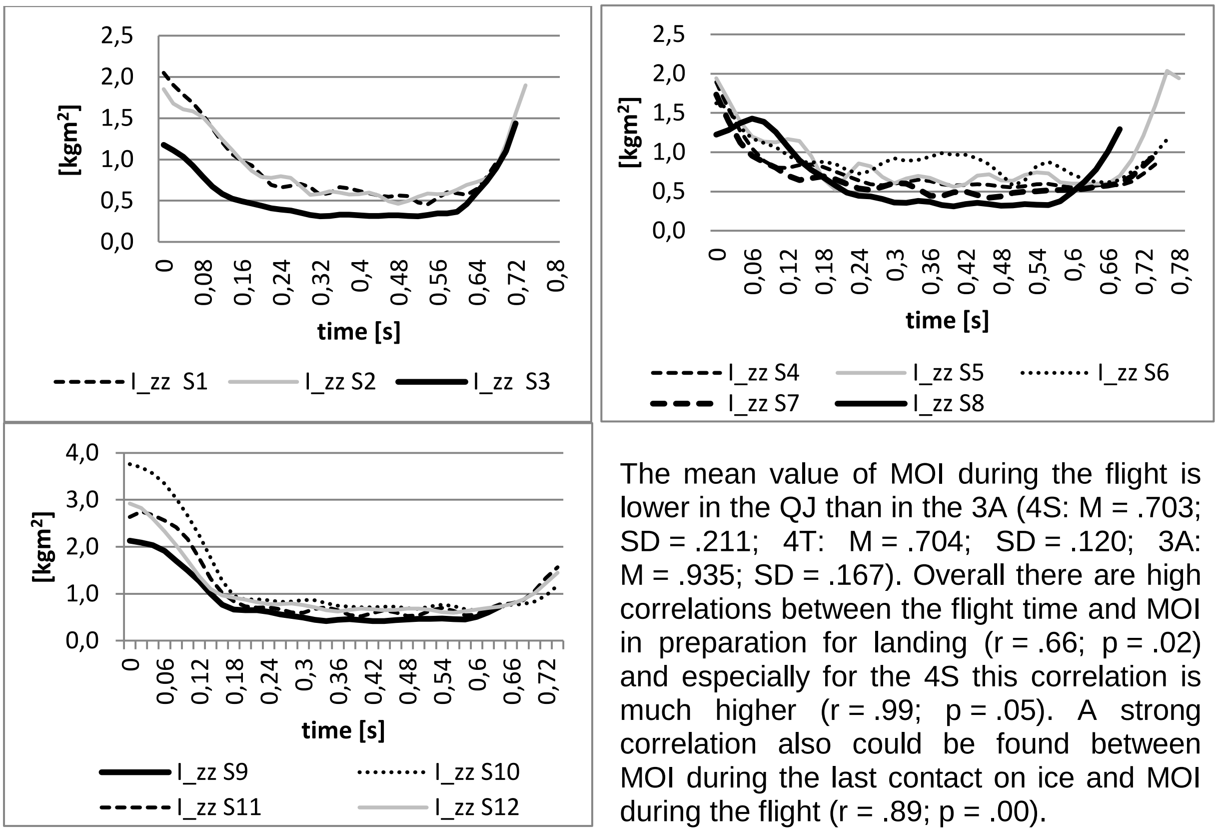

Figure 3: MOI during flight in the 4S, 4T and 3A

The mean value of MOI during the flight is lower in the QJ than in the 3A (4S: M = .703; SD = .211; 4T: M = .704; SD = .120; 3A: M = .935; SD = .167). Overall there are high correlations between the flight time and MOI in preparation for landing (r = .66; p = .02) and especially for the 4S this correlation is much higher (r = .99; p = .05). A strong correlation also could be found between MOI during the last contact on ice and MOI during the flight (r = .89; p = .00).

Interestingly there is low and no significant correlation between MOI during the flight and MOI in preparation for landing in general (r = .36; p = .25) but with a higher correlation in the 4S compared to 4T and 3A (r_{4S} = .72; p = .49; r_{4T} = .53; p = .36; r_{3A} = .46; p = .54). 11 of the 12 skaters performed an active rotation of the upper body against the lower body while preparing for landing (AR) (Table 2). The only skater who did not execute the AR had a longer flight time (> 0,08 s) in the last rotation. Consequently, there is a high correlation (ϕ = 0.68) between the execution of AR in relation to the flight time available for the last 180° of rotation.

Table 2
Four fields table for jumps with/without against rotation (AR)
in relation to the flight time (t_{FL}) ≤ 0.08 s or ≤ 0.08 s

	AR	
	yes	no
$t_{FL} \le 0.08$ s	11	0
$t_{FL} \ge 0.08$ s	0	1

DISCUSSION: Worldwide the total number of excellent QJ is limited. Because the final target in our scientific support is to create conditions and solutions for a perfect jump for the individual skater we included QJ with a high quality of execution. For this reason a small sample of 12 elite skaters was analyzed. To identify successful strategies or solutions of execution the study was very helpful to identify correlations between different aspects of the execution of jumps with more than three rotations and differences between skaters. With this approach we could develop individual solutions for perfect QJ for German skaters. For optimum individual solutions in QJ the interrelation between the flight time, MOI during the flight and MOI at the last contact on ice is very important.

CONCLUSION: Effective flight phases can contribute to high GOEs for QJ. They are characterized by very small values of MOI at the last contact on ice, to reach very quickly the closed position and to keep this position as long as necessary. To enable the skater to perform a very good QJ even in the second half of the short as well as of the free program the skater needs an optimum individual solution for these jumps, e. g. with the shortest possible flight time. In our study the shortest flight times were performed by skaters with the smallest moment of inertia and by skaters who turned into this favourable position very quickly and who kept it as long as necessary.

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