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BIOMECHANICS OF ROTATIONAL MOVEMENT IN OFF-ICE FIGURE SKATING JUMPS: APPLICATIONS TO TRAINING

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Abstract

Introduction. The aim of this study was to characterize kinematic parameters of the rotational body movement during the off-ice figure skating multi-revolution jumping exercise and to propose applications to training. ***Material and Methods.*** Six elite Polish female junior singles figure skaters were examined performing single and their respective maximum total rotation vertical jumps in off-ice conditions. Measurements of the ground reaction force were performed with a KISTLER (500 Hz) piezoelectric sensor platform with BioWare Software, synchronized with the cinematographic analysis using the Vicon T-Series motion capture system. ***Results.*** The analysis revealed positive linear relations between selected jump parameters of the pre-take-off phase and after the landing. Two moments of countering torque were also noticed: the first in the landing phase, and the second before reaching the stabilized position. ***Conclusions.*** Applications of the findings for off-ice training were discussed.

Key words: figure skating, biomechanics, rotation, training, jumps, forces

Introduction

During last decades, figure skating has seemed to be one of the sports that has considerably evolved, especially in the case of jumps in singles skating categories. Since 2018 Winter Olympics, senior men competition medals have been won by skaters who performed more than two different kinds of quadruple jumps [1]. It is important to mention that jumps are one of the highest scoring elements at high level skating performances. Skaters collect points for each element. The more revolutions the skater performs in one type of a jump, the higher scoring value is received [2]. The ability of performing multiple revolutions around the longitudinal axis of the body is essential in the figure skater's performance. Attempting those maneuvers requires not only technical excellence, but also an ability to overcome enormous forces.

Results of the previous studies indicate that performing jumps with one rotation may impact the ankle joint with the force of 3-8 bodyweight (BW). The forces increase with each additional turn [3, 4, 5]. Further investigations showed that stiffness of skating boots negatively affects the range of motion of the ankle joint. This results in changing the natural distribution of the shock wave pattern through the limb, which negatively affects flexion from distal to proximal joints, which normally occurs as a result of landing [4, 6].

Smaller overloads and more natural ranges of motion during jumps performed in figure skating techniques were obtained in the off-ice conditions [6, 7]. This indicates the necessity to conduct research on the technique of figure skating jumping elements not only on ice, but also in off-ice conditions. Previous research analyzing rotational abilities of skaters shows that the decisive parameters of jumps were height and angular velocity of rotation [8, 6].

3D cinematographic comparison of figure skating jump performed in the on-ice and off-ice conditions showed some differences and similarities in the examined technical elements. Research revealed that the off-ice jumps performed on the ground in typical gym conditions wearing sports shoes can be used as a training tool in figure skating. This kind of training results in improving the dynamics of the take-off and achieving the proper pre-take-off position [6]. When performing the off-ice jump, a skater can decrease natural fear caused by high vertical velocity and the difficulties in maintaining required balance when performing the techniques on the ice. That is why the off-ice jumps appear to be more repeatable than the on-ice ones [6]. This fact can be helpful in training specific movement habits. It indicates that biomechanical investigation on the off-ice jumps can provide some valid insights into feasibility of this type of training. Characterizing the kinetic and kinematic parameters that can influence the number of revolutions during the flight phase of the jump is important for figure skaters as well as any other discipline where this type of movement is performed. Previous research demonstrated that some specific elements of the on-ice jumps can be simulated in the off-ice conditions, resulting in an improvement in the athlete's technique [6]. This type of training is already common in the figure skating coaching system. One of the most used exercises is the rotational jump (RJ). It is similar to the countermovement jump (CMJ), but with rotations along the longitudinal axis of the body and a single leg landing in a position similar to the one performed on the ice. Improving RJ in the off-ice conditions would reduce the training load and stress factor while maintaining the positive effect of the training. The aim of the study was to characterize kinematic and kinetic parameters of the rotational body movement during the off-ice figure skating multi-revolution jumping exercise and to propose application to training.

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Material and Methods

The study included 6 elite Polish figure skaters competing in the junior female singles skating category. The athletes had 8.5 ± 2 years of training experience. The number of their training hours exceeded 15 hours a week. The subjects represented similar skills levels. All of the skaters could perform each type of the double jumps and a couple of the triple jumps on the ice. The subjects' mean (± SD) age, weight, and height measures were 14.3 ± 2.3 years, 50.3 ± 12.2 kg, and 160.3 ± 8.6 cm, respectively. The skaters were free from any lower extremity injuries that would prevent normal training. The subjects performed two types of rotational jumps (RJ) which can be described as CMJ with spinning movement. The subjects were performing the jumps wearing similar sports shoes, which are typically used to perform off-ice jumps and enabled the use of the full range of motion in the ankle joint.

First, they performed one revolution around the longitudinal axis of the body during the flight phase (SRJ). Second, they performed the maximum possible number of revolutions (MRJ). In both cases, the participants landed on one leg with the other limb extended to the back, mimicking the ice skating technique requirements. The direction of rotation was the same as normally performed by the skaters during competitions. All the participants were rotating to the left side, which required landing on the right leg.

Measurements of the ground reaction force were performed with the use of a KISTLER (500 Hz) piezoelectric sensor platform with BioWare Software, synchronized with cinematographic analysis using the Vicon T-Series motion capture system. Markers were attached to track and record movement of the shoulders, C7 and Sl vertebrae, pelvis, toes on both feet and heel, but just on the right limb (RSHO, LSHO, C7, RASI, LASI, SACR, LTOE, RHEE, RTOE) (Vicon Nexus 1.8.5). Marking the foot with an additional marker allowed for the determination of the landing leg in the process of data analysis. On the basis of displacement of RASI and LASI markers, the angle of rotation during the flight phase (AOR) was obtained. It was calculated using the function α = arccos and the definition of dot vectors: $\vec{a} \cdot \vec{b} = |\vec{a}| \cdot |\vec{b}| \cdot \cos < (\vec{a}; \vec{b})$ [9], where 'a' was the LASI to RASI vector and 'b' was the vector of the horizontal axis of the absolute reference frame. The parameters were analyzed using the Microsoft Excel spreadsheet.

Data analysis was divided into two stages. The first one was the comparison between results of the single rotation and the maximum rotation jumps. The second part was the insightful characterization of the best MRJ performances.

On the basis of the vertical ground reaction force (Fz max [N]) and vertical torque (Tz [Nm]) time courses, the following parameters were determined: P max – maximum jump power [W], h max – maximum jump height [m], CM – swing depth [m], t – time of flight. Simplified Vicon motion capture analysis was used to identify the following key parameters: the angle of rotation [º], and ω – angular velocity [number of revolutions/s].

Results

The comparison of SRJ and MRJ (Tab. 1) shows changes for each of the analyzed parameters. The mean value of the rotation angle in SRJ was 355.5º ± 46.24 [deg], or 0.99 rotations in the flight phase. In an attempt to make the maximum number of revolutions, the subjects achieved an average of 714º ± 38.7 [deg], or 1.983 turns. Increasing the number of revolutions is primarily related to the increase in angular velocity and vertical torque. Performing a multi-revolution jump required significant increases in jump height, time of the flight, and the depth of the countermovement during the pre-take-off phase. Smaller (6-14%), but still significant, differences appeared in the vertical force and the power factor. The curve of the ground reaction force changes revealed one substantial pattern of the MRJ which applied to all the subjects (Fig. 1). The graph demonstrates that, during the pre-take-off phase, the highest value of the torque was always recorded before the peak of Fz. Additionally, the magnitude of the relative force (Fz rel = Fz max/mass) and Tz max had the highest influence on each other (Fig. 2). As Fig. 2 shows, the relation of those parameters is characterized by the linear negative regression. Force magnitude increased with a decrease in Tz. It is worth mentioning that neither of those parameters revealed any significant effect on the rotation angle or on the velocity of turning. The results show that the skater whose AOR was considerably better than others (6-14% of difference) did not achieve the best result in any other examined area (Tab. 2). The athlete with the best velocity of rotation (5-20% of the difference) differed considerably from the others (65-89% of difference). The varying parameter was a very short time (0.02 s) from obtaining the maximum value of Tz max to ob-

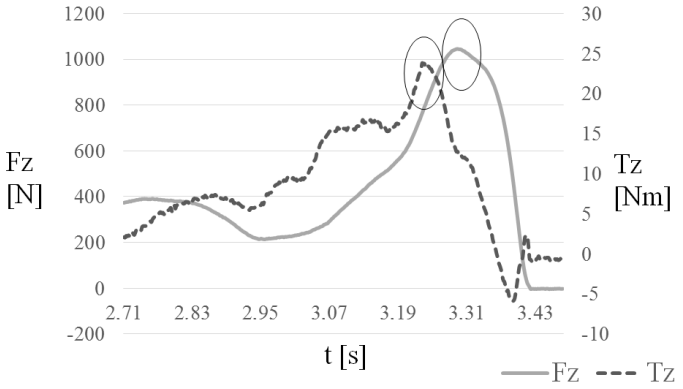


Figure 1. The course of the vertical component of the ground reaction force (Fz) (left axis) and the vertical torque (Tz) (right axis) during the pre-take-off phase of the MRJ jump for one of the subjects. Maximum parameter values marked with an oval

Table 1. Average values of the vertical jump parameters with one and the maximum number of revolutions and differences between them.

	Tz max [Nm]	ω [rev/s]	h max [m]	tf [s]	CM [m]	Fz max N]	Fz rel [N/kg]	P max [W]	P rel [W/kg]
One	29.74	2.70	0.23	0.37	0.17	1171.99	22.15	1225.42	23.42
MAX	38.81	4.39	0.28	0.45	0.22	1319.041	25.82	1303.29	25.30
Diff [%]	30.5	62.6	21.7	21.6	29.4	11	14	6.4	7

Tz max – maximum vertical torque, ω – angular velocity (number of revolutions per second), h max – maximum height, tf – time of flight, CM – depth of countermovement, Fz max – maximum vertical ground reaction force, Fz rel – relative vertical force (divided by body weight), P max – maximum power, P rel – relative power (divided by body weight).

Table 2. Chosen parameters of MRJ of each skater.

	AOR [º]	ω [rev/s]	h max [m]	Tz max [Nm]	Fz rel [N/kg]	P rel [W/kg]	t_{TzTO} [s]	t_{TzFz} [s]
1.	**780**	4.6	0.31	36	25	26	0.23	0.08
2.	734	**4.8**	0.22	28	26	22	0.21	**0.02**
3.	704	4.4	0.27	24	**28**	27	**0.19**	0.06
4.	701	4.4	0.27	32	**28**	**29**	0.20	0.10
5.	698	4.4	0.29	**63**	24	23	0.32	0.20
6.	667	3.8	**0.32**	50	23	25	0.33	0.13

(AOR – angle of rotation in the flight phase); ω – angular velocity (number of revolutions per second); h max – maximum height of the flight phase; Fz rel – maximum vertical force during the take-off phase divided by mass; P rel – maximum power during the take-off phase divided by mass; t_{TzTO} – time from the maximum Tz to the moment of the take--off; t_{TzFz} – time from the maximum Tz to max Fz. The best (grey colored cell and bolded number), and the worst (fair gray cell) results of each parameter are marked in the table.

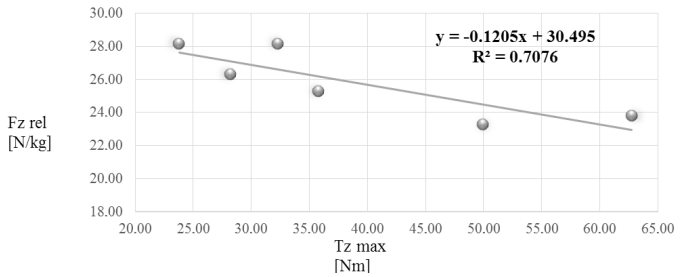


Figure 2. Relation between Fz rel [N/kg] and Tz max [Nm]. Trend line, formula and R^2 value are shown on the chart

taining Fz max in the pre-take-off phase (t_{TzFz}). The skater with the lowest AOR had the greatest height of the jump and the second best result in Tz max. At the same time, she engaged the lowest relative vertical Force (Fz rel [N/kg]) and achieved the longest time from obtaining Tz max to the moment of the take-off (t_{TzTO}) and the second lowest t_{TzFz}.

Further analysis showed the linear positive relation between t_{TzFz} in the pre-take-off phase and Tz max after the landing (Fig. 3). This means that the well-timed upper and lower body rotational movement in the pre-take-off phase can result in a lower value of vertical torque during landing. Additionally, the analysis of the curve of Fz and Tz in the landing phase shows that reduction in the rotational motion also occurs before the moment of the maximum force value (Fig. 4). Two moments of countering torque were also noticed: the first in the landing phase, and the second before reaching the stabilized position.

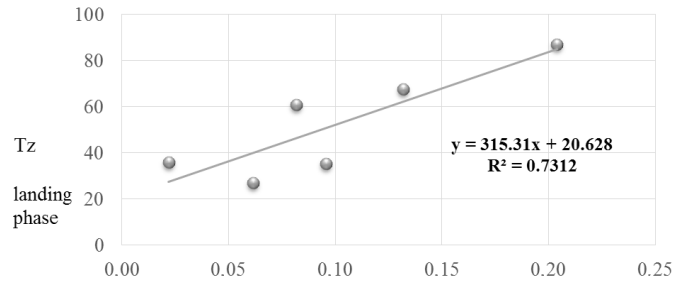


Figure 3. Relation between Tz max in the landing phase and t_{TzFz} in the pre-take-off phase. Trend line with its formula and R^2 plotted on the graph

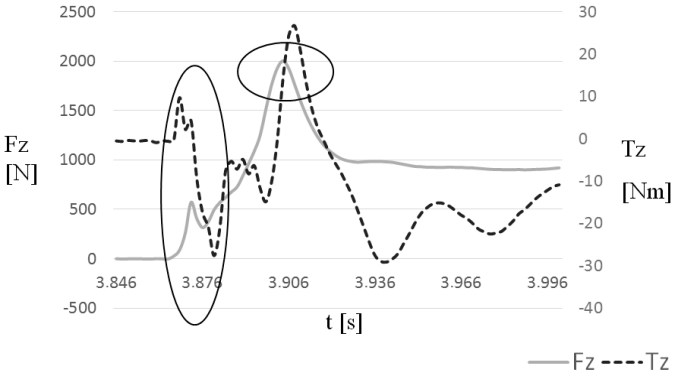


Figure 4. The course of the component of the vertical ground reaction force (Fz) (left axis) and the vertical torque (Tz) (right axis) during the MRJ landing phase of one of the subjects. Marked with horizontal oval – the highest value of the Fz parameter. Marked with vertical oval – the first recorded values of the Tz parameter

Discussion

The present study was a unique approach to the analysis of jumps with rotation around the vertical axis of the body in the figure skating techniques. At the same time, it was a continuation of the research on the feasibility of figure skating off-ice exercises in the training of the multi-rotational figure skating jumps [6]. One of the limitations of the study was the unknown influence of the various types of gym shoes that the subjects were wearing on the results of Tz in off-ice RJ. Nevertheless, the use of the unified type of shoes could have had an impact on the natural way of movement of the skaters. Created conditions and the equipment used were similar to the environment that commonly appears during athletes' training sessions. That gave them the comfort that was necessary for them to perform their natural mechanics of movement, which made the measurements ecologically valid. The results of the study confirmed previous reports: increasing the number of spins in both on-ice and off-ice conditions is achieved by increasing the speed of rotation in the flight phase and/or increasing the height of the jumps [6, 8].

Additionally, the present study demonstrated a significant influence of maximal vertical torque, maximal and relative vertical force, and power on increasing the number of rotations. A further analysis of the MRJ of the skater who performed significantly better than the others in the velocity of rotations showed that obtaining a higher speed of spinning is not directly related to the maximization of Tz in the pre-take-off phase. The time from maximum Tz to Fz max turned out to be the sig-

nificant one in this matter. In the technique of movement, it is associated with the coordinated action of the upper and lower body in the pre-take-off phase, which in rotational movement can be called 'timing'. The significant role of this element of the movement technique was observed when evaluating results of the subject who was able to achieve the best Tz max. The skater was, at the same time, the slowest in t_{TzFz}. Those results indicate that, without a dynamic and well timed pre-take-off phase, an athlete is unable to use the vertical torque and convert it into a better AOR result. With regard to training, this implies the possibility of achieving a greater AOR effect through a dynamic approach to rotations, while maintaining a synchronized movement of shoulders and hips and vertical rebound. An approach that is based primarily on increasing the range of motion and strength may be less effective (though further detailed investigations would be appreciated). The results revealed no significant relation between results in AOR and magnitude of Tz max. The skater with the best result of AOR in the jump did not obtain the best results in any other parameter. The skater's performance was based on proper proportions of the height of jump and the velocity of rotational movement. Therefore, on the basis of the present study, it can be concluded that better performance in MRJ can be achieved by combining good timing at the pre-take-off with maximizing the vertical force and vertical velocity, which results in higher jumps. Further cinematographic research, extended to full body analysis, seems to be justified. Previous studies raised the issue of the impact of the stiffness of the skating shoe blocking the full range of motion of the ankle joint and its impact on the height of the jump [11]. It was concluded that plantar flexion could theoretically contribute to up to 22% of the take-off velocity in maximal squat jump [10]. Moreover, the reduction in the range of motion of the ankle joint negatively affects the jump height [11]. Previous investigations determined that stiffness of skating boots influences the habitual movement pattern of skaters. This often results in an inability to use the full range of movement in the joint [3, 5, 6]. Taking into account that the present study confirms that the height of the jump increases the chance of achieving a higher AOR score, it should be emphasized that training performed in the off-ice conditions should include exercises that emphasize the full range of motion in the joints (especially the ankle joint). This can have positive effects on increasing the height of a jump. As already mentioned, dynamic training of both the lower limbs and the upper body may be more effective.

Investigation of the landing phase indicated a couple of important aspects. First, analysis of Tz max and Fz max curve showed that subjects had two possibilities of reducing the vertical torque: the first was before, and the second after the Fz max. Given that, skaters were stopping the rotational movement before entering the final landing position. This indicates the advantage of a counter-rotated position during the flight phase [12], which can be useful in entering the landing phase smoothly. Figure skating landing technique requires immediate stopping of rotational movement, so lowering the torque at this phase can also be crucial in the training itself. The present study showed the significant influence of the t_{TzFz} in the pre-take-off phase on the maximum torque during the landing. This relation reveals that the better timing (explained earlier) can cause lower Tz during the landing, making this element easier to attempt by a skater. However, it has no significant influence on the F max. Reducing vertical forces during the landing can be achieved by training the landing amortization.

Conclusions

This study revealed which kinematic parameters of the rotational motion in the multi-revolutions figure skating off-ice jumps seem to be the most significant. Improvement in the angle of rotation in the flight phase is primarily influenced by increasing the angular velocity and the height of a jump. Results of the study show a relation between velocity of spinning and the time that elapsed from the moment of achieving maximum torque and the moment when the maximum force was registered in the pre-take-off phase of the jump. With regard to training, this shows the possibility of achieving a greater effect in the number of revolutions through a dynamic approach to rotations while maintaining coordinated movement of upper and lower body. On the basis of the present study, it can be concluded that better performance in multi-revolution jumps can be achieved by combining good timing in the pre-take-off phase with maximizing the vertical force and vertical velocity, which results in higher jumps. Moreover, timing in the pre-take-off phase can lower the torque during the landing. Analysis of the curve of changes of the vertical torque and the forces during the landing revealed that the subjects had two moments of reducing the vertical torque: the first was before and the second after the maximum magnitude of the force. This implies that skaters were stopping the rotational movement before entering the final landing position. It indicates the advantage of the counter-rotated position during the flight phase to improve the ability to reduce the vertical torque.

Furthermore, it appears justified to extend the research on the off-ice jump techniques to increasing the number of subjects and including a wider spectrum of biomechanical and kinematic parameters. The use of full-body cinematographic analysis would be especially justified.

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