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A kinematic analysis of ladies figure skating jump technique throughout the last four decades

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Abstract

The goal of this study is to estimate the longitudinal progression of jumping technique performing a kinematic analysis of six major jumps from the 1980s to the present in women's figure skating. Fifteen female figure skaters chosen as top performers from four decades – from 1980s to the present, were studied. For all female athletes, three kinematic jump characteristics were quantified: preparation and flight phase time durations (PFT, FFT), average body angular velocity in flight phase (AVF). Several conclusions were drawn from the results; the comparative analysis by decade demonstrated that technique performance and thus the kinematic profile of the jumps changed over time; double Axel showed a trend towards increasing duration of the PFT and AVF; triple Salchow - clear decrease in the PFT and FFT and a significant increase in the AVT at 2020s; triple Lutz - constant duration of the FFT and significant increase in AVT; triple Toe Loop - relative invariance of all three parameters from the 1980s to the 2010s and a significant change in the 2020s.; the highest AVT was measured on A. Trusova (2020) at quadruple Lutz - 5,22 rpm. A suggestions in order to improve jumping technique were synthesized: the female figure skaters need to work thoroughly on improving the functional performance of their lower limbs by improving their individual jumping strength/speed profile; there is also a need to improve the dynamic properties of the lower limbs, such as maximum force at takeoff, initial speed of the flight phase, and elasticity index at takeoff; in order to meet the need to increase the jump difficulty and attractiveness, it is necessary to improve the movement of the upper body segments during rotation in the flight phase, including the head. Efforts should be focused on reducing the body's moment of inertia, which accelerates rotation in the flight phase.

Keywords: Figure skating, skating jump phases, kinematic analysis

1. Introduction

Jumping is the most important technical and aesthetic element in figure skating routine performance. Jumping technique is constantly evolving over time. This, combined with the athletes' increased strength qualities, results in the performance of jumps with more than three body revolutions [1].

The kinematic structure of jumps is divided into three subsystems: spatial, temporal, and spatiotemporal. We have optimal kinematic structure when the implementation is realized with as close to perfect kinematic characteristics as possible, forming the three subsystems. This optimal kinematic structure of the jump is strictly individual for different athletes and is determined by the performers' efficient movement on the ice, allowing more energy to be used for the specific movements in different types of jumps [2]. This means that the kinematic structure is directly related to the athletes' strength training.

Recreational figure skaters' kinematic skating structure differs significantly from that of elite or professional skaters [3]. Elite skaters are more efficient kinematically than non-professional skaters. They are flexible, graceful but strong and have good coordination.

Multiple research teams have found that jump height changes very little when a figure skater upgrades from a double to a triple and then to a quadruple jump [4 -7]. It is becoming clear that the increase in revolutions is achieved primarily by increasing the angular rotational velocity in air, which results from increasing angular momentum at takeoff and decreasing total body moment of inertia during the flight phase of the jump [8].

For coaches and analysts in figure skating, quantifying all kinematic characteristics in the jumps that form the kinematics of the performance is critical [9 - 12]. Their detailed knowledge is required for accurate analyses and thorough insight into each athlete's individual kinematic profile.

The aim of the study is to perform a kinematic analysis of the six basic jumps performed by some of the best figure skaters in women's figure skating from the 1980s to the present day. The focus is on the connection between the two main phases of the jumps, the preparation phase and the flight phase, with the angular velocity of the body during the rotations. This allows improving each athlete's individual kinematic profile and helps eliminate some technical issues in performance.

2. Methods

To conduct this research the video file analysis software, Kinovea 0.9.4, was used to analyze the different jump types - duble Axel, triple Lutz, triple Flip, triple Salchow, triple Loop and triple Toe loop. This software has options to slow down, compare, select and measure various kinematic, biomechanical parameters of the movements in the videos. For the research, the most effective, top 15 female figure skaters were selected from the following four decades: the 1980s, 1990s, 2000s, 2010s and 2020s.

Table 1
Study participants by decades

1980s	1990s	2000	2010	2020
Kira Ivanova [13]	Yuka Sato [17]	Carolina Kostner [20]	Mao Asada	Kamila Valieva [24]
Midori Ito [14]	Chen Lu [18]	Shizuka Arakawa [21]	Elizaveta Tuktamysheva [22]	Anna Shcherbakova [25]
Claudia Leistner [15]	Michelle Kwan [19]		Yuna Kim [23]	Alexandra Trusova [26]
Elaine Zayak [16]				

The video files with the performances were selected by Youtube according to several important criteria:

- From each decade with with the earliest appearances dating back to the 1980s and the newest dating to the 2020s has been chosen elite figure skaters
- The video must have maximum maximum quality guaranteed by good resolution and high frame rate, necessary for excellent visual control and observation of the jump performance;
- The selected videos were chosen as examples of the best skating technique and execution of the different types of jumps and their phases;
- Video files by the years of some of the best figure skaters that have performed in their skating program the following jumps- double Axel, triple Lutz, triple Flip, triple Salchow, triple Loop, triple Toe loop.

Each jump in figure skating is divided into four main phases - entry, preparation phase, flight phase and landing. Using the program Kinovea 0.9.4. these video files were processed through the stages:

- Cutting and saving the two phases, preparation and flight phase of the 6 jumps;
- Determining the marked points in time, time initial and time final of preparation and flight phase;
- Calculating the duration of the two listed phases by the difference of the two specified limiting time instants;
- Determination of the average angular velocity of body rotation at the shoulders during the flight phase - from the moment of separation of the body from the ice to the moment of the first contact of the skate with the ice. For this purpose, body rotations at the shoulders were counted during the flight time. The angular velocity at each jump of all skaters during the flight phase was quantified by the ratio of revolutions/time of the flight phase;

At the end of all the operations described above, three kinematic characteristics of all jumps were quantified for all athletes: preparation time (Δt_p) and flight phase (Δt_f), mean angular velocity of the body during flight phase (ω). Their means and standard deviations were then determined along the listed decades. Statistical analysis was performed with SigmaPlot10.

3. Results and Discussion

The obtained results are presented graphically in Figs. 1 - 7.

3.1. Double Axel

There is an increase in the duration of the preparation phase. Axel jump is the most difficult to perform. It takes greater force than the rest of the jumps due to jumping off forward without the assistance of a toe-pick and an extra 90 degree turn. This jump requires a skater to jump off the ice in an explosive way.

The flight phase tends to be consistent at all times. It is clear that the more revolutions the skater performs, the more time it takes to complete them. As the revolutions increase a coach develops an individual training program for each skater that focuses on greater height as well as faster rotation. The higher the skater jumps the more time it gives the skater to complete the required revolutions.

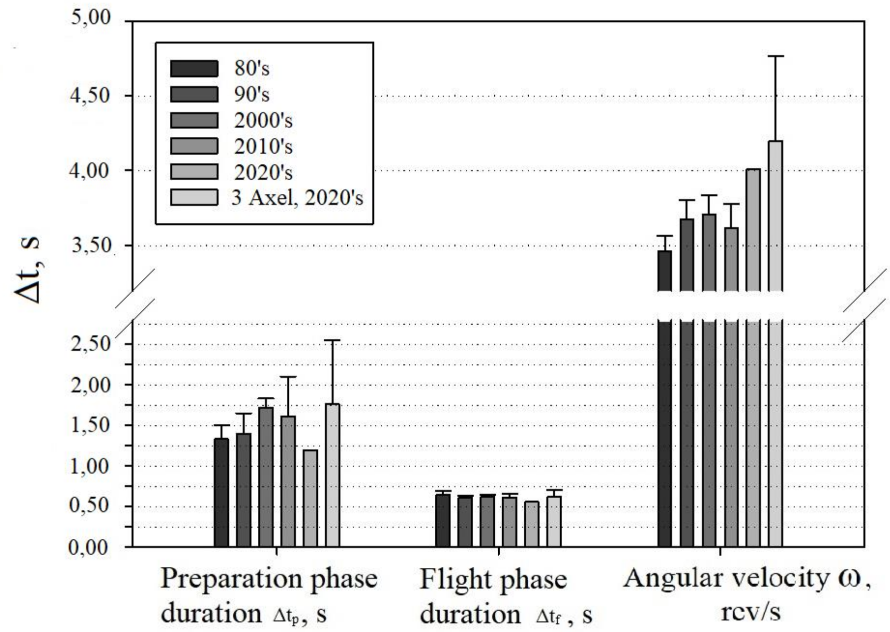

Fig. 1. Kinematic analysis of a jump technique “double axel” in ladies’ figure skating

The angular velocity has increased dramatically over the years. This increase ranges from less than 3.5 rpm for skaters in the 1980s to more than 4.2 rpm for skaters in the 1920s. Considering that the flying times are almost identical, it is concluded that one of the reasons for the faster rotation is optimization in body posture. The posture of the flying body is determined by its moment of inertia. Less moment of inertia means less drag on the body during rotation and hence higher angular velocity.

3.2. Triple Loop

The kinematic structure of the 3 Loop jump is shown in Fig. 2. This jump together with the triple flip (Fig. 3) as shown in the graph shows that all three parameters examined remain almost unchanged over the decades. That is because the entry into the jump has a much easier preparation phase then some of the other jumps, which makes it easier to start the turn. With this jump, it's easier to wind up your body before the takeoff. This creates a strong momentum of the body and makes it easier to rotate in the flight phase. Too much winding up can lead to pre-rotation.

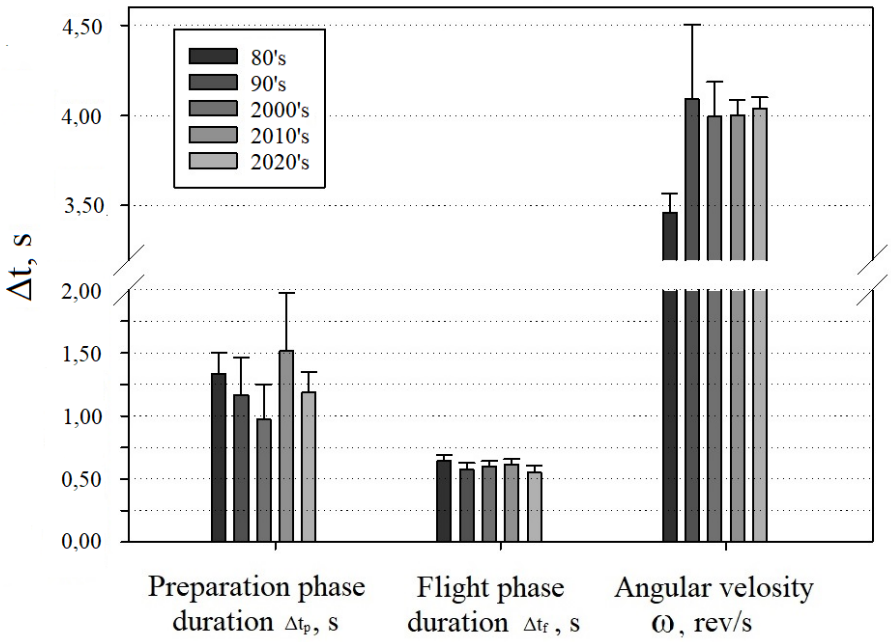

Fig. 2. Kinematic analysis of a jump technique "triple loop" in ladies' figure skating

3.3. Triple Flip

Almost the same conclusions from the analysis are observed for the triple flip jump as for the triple Loop. The results show an interesting temporal stability of these two jumps. The similarities lie in the preparation phase and body angular velocity, which increases upon toe-pick impacts the ice with the right free leg and swing motion of the left free leg as in the triple Loop.

3.4. Triple Salcow

From Fig. 4 it can be seen in the triple Salchow an unchanged duration of the two phases examined, preparation and flight, from the 1980s to the 2010s. However, a significant decrease in the duration of both parameters can be observed for the 2020s. That means less preparation and less flight time. The angular velocity in the 2020s is higher than in previous decades. This is because the overall physical and technical preparation of skaters on and the ice is greatly improved. This leads to an increased rotational speed in all elements of the jumps performed with rotational movement.

Physical and age limit requirements have also been significantly changed. Female competitors are now much lighter and younger. The duration of the connections between the jump phases has been shortened. Body compactness (crossing the arms and legs) has been maximized, resulting in an increase in angular velocity by reducing the body moment of inertia.

In quadruple Salchow all movements must be as accelerated and dynamic as possible in order to reach the goal. The posture of the body in the various phases should be changed as quickly as possible, which determines the speed of movement of all body segments. The muscular impulse transmitted to the body during the preparation phase in the takeoff should be maximized in order to achieve a longer flight phase in which there is sufficient time for the 4th rotation.

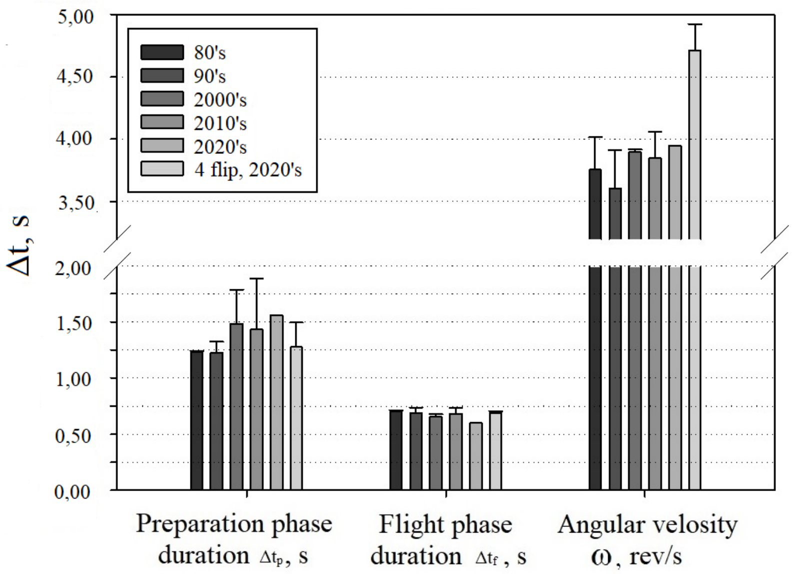

Fig. 3. Kinematic analysis of a jump technique "triple flip" in ladies' figure skating

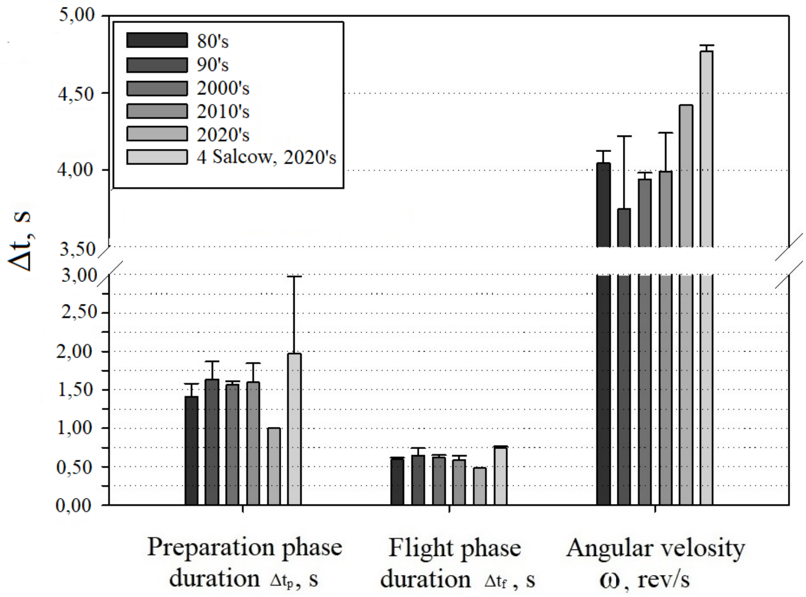

Fig. 4 Kinematic analysis of a jump technique "triple salchow" in ladies' figure skating.

3.5. Triple Lutz

In triple lutz, the preparation and flight phases are almost identical in the decades. There is a tendency for the angular velocity to increase, from about 3.5 rpm (revolutions per second) to over 3.8 rpm. A characteristic of this jump is the importance in working out the right moment or timing of the takeoff from the right edge. If this does not happen in time, the skater instead automatically goes to the wrong edge. This jump is very specific for each skater. It is the most difficult jump to perform technique wise. Not all skaters are capable of performing it properly and it mostly has to do with skaters getting the habit during the training process of taking off the wrong edge.

To be able to perform the quad Lutz, the skater must first need to be able to perfect the triple lutz. Then the skaters need to increase the takeoff speed, the force of the toe-pick stabbing the ice, depth of bending the knee and speed of propelling the arms. The edge also needs to be done quicker and the angle of the edge needs to be smaller.

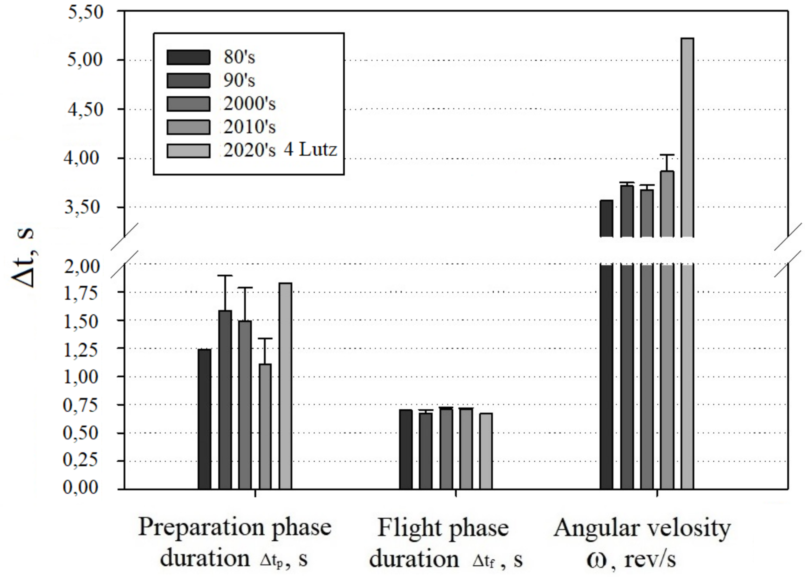

Fig. 5 Kinematic analysis of a jump technique "triple lutz" in ladies' figure skating.

For the 2020 quad Lutz, it is evident that there is a trend of increasing preparation phase duration, no change in flight phase duration, and a significant increase in angular velocity of the body.

3.6. Triple Toe loop

The Triple Toe loop data show interesting trends. The preparation phase is increasing, averaging from the 1980s to the 2000s. The flight phase is almost constant from the 1980s to the 2010s, with a sharp decrease in the 2020s, from about 0.7 to 0.5 s. The rotational velocity remains relatively constant, from the 1980s to the 2010s, increasing at 2020 relative to the 1980s from about 3.8 rev/s to 4.2 rev/s. The quad Toe loop is furthest to the right of the graph and has the longest flight phase and highest angular velocity, of about 4.7 rev/s.

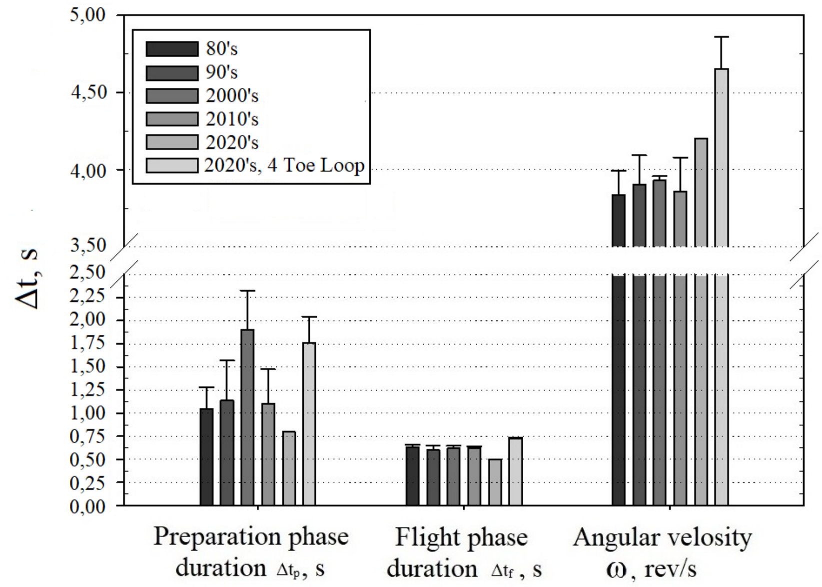

Fig. 6 Kinematic analysis of a jump technique "triple loop" in ladies' figure skating.

3.7. Statistics

The quantitative data obtained for the duration of the preparation and flight phases as well as the angular velocity of body rotation, suggest that these elements of the jumps must be interdependent at individual decades. A good preparation phase implies a longer flight phase and sufficient angular velocity of the body in flight. To verify these assumed correlations of the measured angular velocities ω with the two estimated phases, - preparation and flight- , a linear correlation analysis was performed and the parameters R, R^2 и adjR^2 were quantified. These actually showed to what extent the angular velocity of the revolution is determined by the performance of the previous two jump phases at different decades.

Double Axel. Statistical correlation analysis showed a very strong correlation (adjR^2=0.918) between flight phase and angular velocity in double Axel. This logically means that sufficient flight phase time provides the required number of rotations.

Triple Loop. The preparation phase did not show a good correlation with angular velocity (adjR^2=0). While borderline significance of statistical relationship (adjR^2=0.496) was obtained between the flight phase and angular velocity.

Triple Flip. Interestingly, for the triple Flip jump, the preparatory phase showed an excellent correlation with angular velocity (adjR^2=0.815). While a weak correlation (adjR^2=0.403) was obtained between the flying phase and angular velocity.

Triple Salchow. Importantly for the triple Salchow jump, again the preparatory phase showed an excellent correlation with angular velocity (adjR^2=0.879). Just as an excellent correlation relationship (adjR^2=0.966) was obtained between flight phase and angular velocity.

Triple Lutz. For the triple Lutz jump, the preparation phase showed no statistically significant correlation with angular velocity (adjR^2=0.321). Similarly, no correlation relationship (adjR^2=0.213) was obtained between flight phase and angular velocity.

Triple Toe loop. In the triple Toe loop, the preparation phase showed no statistically significant correlation with angular velocity (Radj^2=0). However, an excellent correlation relationship (Radj^2=0.949) was obtained between flight phase and angular velocity.

Table 2
Data the resulting linear correlation coefficients between angular body velocity ω and the two preparation phase times Δt_p and the flight phase time Δt_f.

Linear correlation coefficients	R ω-Δt_p	R^2 ω - Δt_p	adjR^2 ω-Δt_p	R ω - Δt_f	R^2 ω - Δt_f Δt_f	adjR^2 ω - Δt_f
Double Axel	0,354	0,126	0,000	**0,969**	**0,939**	**0,918**
Triple Loop	0,281	0,078	0,000	0,788	0,622	0,496
Triple Flip	**0,928**	**0,861**	**0,815**	0,743	0,552	0,403
Triple Salchow	**0,954**	**0,910**	**0,879**	**0,987**	**0,974**	**0,966**
Triple Lutz	0,701	0,491	0,321	0,640	0,410	0,213
Triple Toe loop	0,342	0,117	0,000	**0,981**	**0,962**	**0,949**

The most interesting result for a significant correlation, as shown in Table 2, was obtained for the triple Salchow (Fig. 7). Here, both time characteristics show a statistically significant correlation with angular speed. Furthermore, it is observed that a larger duration of the two phases determines a lower angular velocity of body rotation. This result requires further analysis and probably indicates the strong technical specification of triple Salchow performance.

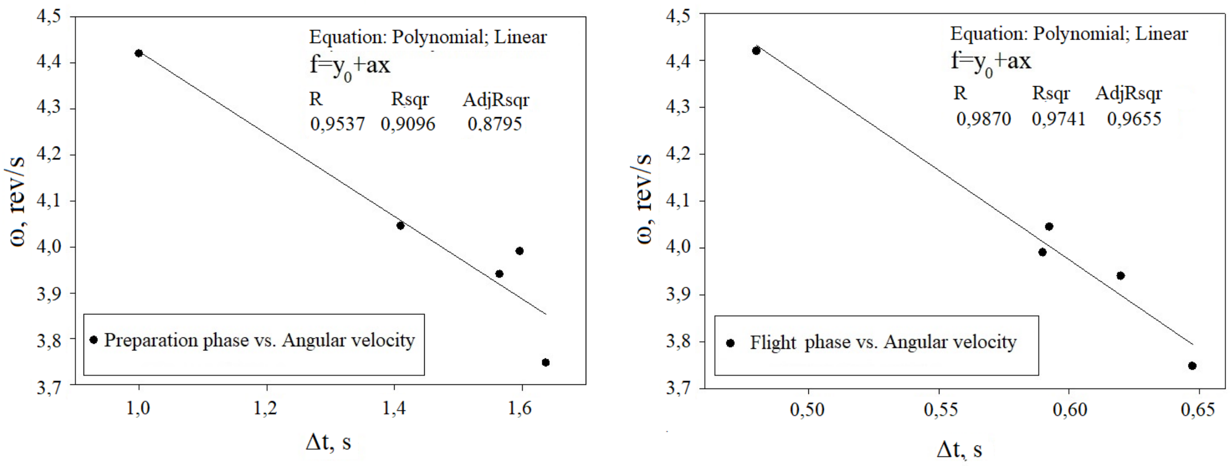

Fig. 7. Correlation relation between angular body velocity ω and the two durations of the preparation phase Δt_p and the flight phase $\Delta t_f \Delta t_f$.

4. Conclusions

After the kinematic analysis, three kinematic characteristics of the six basic jumps in figure skating were measured, graphed and analyzed. The first and second are time characteristics, i.e. preparation and flight phase durations, the third is the angular velocity of the body rotation during the flight phase.

Based on the presented results, several main conclusions were formulated:

1. The values of the measured three biomechanical parameters showed a strong dependence on the individual anthropometric, physical, technical and psychological characteristics of each athlete.
2. The comparative analysis after decades - 80s, 90s, 2000s, 2010s and 2020s - proved that the technique of execution and thus the kinematic profile of the jumps changes over time.
3. Double Axel - showed a trend towards increasing duration of the preparation phase, increasing angular velocity of rotation and no change in the duration of the flight phase.
4. Triple Loop and Flip - the duration of the preparation and flight phases and the angular velocity of the rotation did not change over time.
5. Triple Salchow - there is an unchanged duration in time from decades 80s - 2010s duration in the preparation and flight phases as well as in the angular velocity of the body in the flight phase, but a clear decrease in the first two and a significant increase in the last characteristic at 2020s.
6. Triple Lutz - constant duration of the flight phase and significant increase in angular velocity over the years.
7. Triple Toe Loop - relative invariance of all three parameters from the 1980s to the 2010s and a significant change in the 2020s.
8. The highest angular velocity was measured on Alexandra Trusova (2020) at quadruple Lutz - 5,22 rpm.

Considering the essence of the formulated conclusions, the following recommendations were made:

A. The female figure skaters need to work thoroughly on improving the functional performance of their lower limbs by improving their individual jumping strength/speed jump/speed profile.

B. There is also a need to improve the dynamic properties of the lower limbs, such as maximum force at takeoff, initial speed of the flight phase, and elasticity index at takeoff.

C. In order to meet the need to increase the difficulty and attractiveness of the jumps over time, it is necessary to improve the movement of the upper body segments during rotation in the flight phase, including the head. Efforts should be focused on reducing the body's moment of inertia, which accelerates rotation in the flight phase.

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