

SPINNING IN CONTROL

Physics of Triple Axel Jumps in Figure Skating

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13/12/2013



Image.1: *Composite photography of a professional figure skater executing the triple Axel jump combo with a double spin*
[13]

Figure skating is a unique winter sport that involves speed and power while still maintaining elegance and subtly in the movement on ice. The skaters charge across the silvery stage of ice with great agility then suddenly, the skater leaps into the air while spinning so fast that one cannot count how many times they have rotated before landing gracefully onto the ice continuing their majestic glide.

While watching these performances of incredible speed and precision, one will wonder, how it is humanly possible to jump and spin that fast, never mind on a plane rough surface but, on a slippery *ice*. At first sight the entire idea of jumping from an icy surface and rotating one's body in the air seems very unstable and dangerous, yet these professional figure skaters seem to do it with such stability and subtlety, we are left but to be mesmerized and amazed.

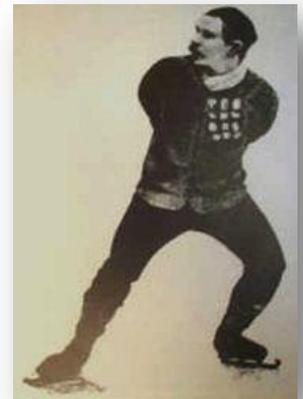
The first question the ones with scientific mind will have is: What is the underlying physics behind these leaps and multiple rotations? Indeed there are underlying physics which can, at least theoretically, give the explanations; however, we must also investigate further by looking into what the skater is actually doing during the jump spin.

After identifying the physical laws and gaining some practical knowledge we could pose another question: Can we look to improve the jump spins? And furthermore, what is the limit for the number of rotations one can complete during a jump spin?

To answer these series of questions we will focus on one of the jump spin techniques of figure skating that has the most rotations in the air and often dubbed as the *most difficult* element in figure skating – Triple Axel.

What is an Axel Jump?

The term *Axel Jump* is coined after the Norwegian figure skater Axel Paulsen (1855-1938), who was the first skater to perform such jump in 1882. The Axel jump is unique from other jump spins in the sense that it has an extra half rotation in the air due rotation of the orientation of the skater's body before and after the jump (body facing forward while take-off, then facing backward when landing). This means that a triple Axel jump actually requires $3\frac{1}{2}$ rotations in the air. This is the reason for triple axel being considered as one of the most difficult elements in figure skating. ^[1]



Axel Paulsen: 'The fastest human on skates' ^[14]

Historically, triple axel has been more prominent element for the male skaters while only a handful of female skaters were successful in execution during competitions. Triple axel is currently the maximum rotations to be executed in the professional figure skating scene. Although a quadruple axel ($4\frac{1}{2}$ rotations in the air) does exist, no skater, male or female, has yet accomplished this jump in competitions. ^[2]

Physics behind the Jump Spin

The physics behind the jump spin is not very complex. In fact, the whole process of jump spin can be more or so, accurately explained using the laws of classical mechanics.

Conservations of Energy

Conservation of energy in its simplest description is that the energy cannot be created nor destroyed, meaning that in order to gain one type of energy, one must seek to convert another type of energy into the desired one. ^[3]

This principle is the same in jump spin. In order to gain height and rotation, one requires kinetic energy, vertically, and rotational kinetic energy. These energies are achieved through conversion of linear kinetic energy which is gained from the skater accelerating across the ice. The fact that ice has little to no surface friction allows the skater to gain velocity very fast (and this is why jump spins are possible on ice in the first place!) and gain a large amount of linear kinetic energy. The internal energies of the skater such as chemical potential energy and elastic potential energy of the muscles at the point of take-off also contribute to the conversion to the desired energies.

The conservation of energy is evident again while landing, after the spin, when the skater continues to glide across the ice. The rotational kinetic energy and the gravitational potential energy, due to the height gained while jumping, are now converted into linear kinetic energy.

Of course, during different stages of the jump, the conversions between the energies are not 100% efficient meaning that there will be some conversions into undesired energies such as sound and heat.

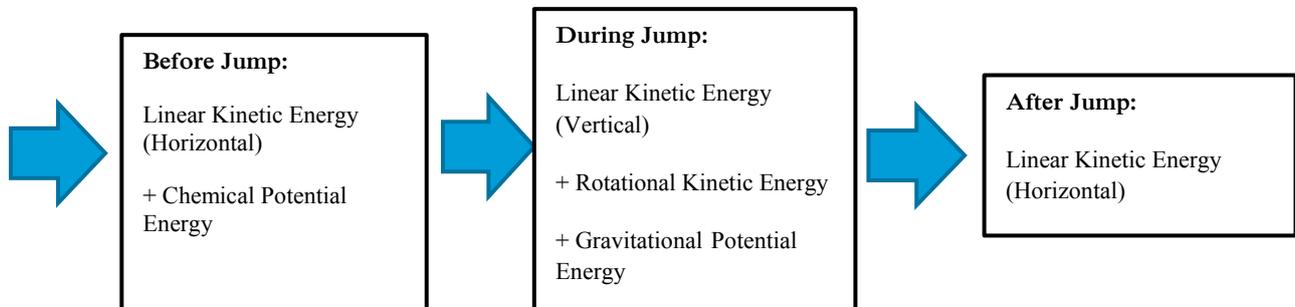


Figure.1: Energy diagram of useful energies involved before, during and after the jump. Note that the Gravitational Potential Energy has been gained due to the gain in height (by James Lee 2013)

Conservation of Momentum

Conservation of linear momentum and angular momentum are also one of the principle laws of physics along with the conservation of energy. In the same sense as the aforementioned conservation law, the conservation of linear momentum and angular momentum states that for a moving body, both linearly and rotationally, the respective momentum before and after must be the same as long as there are no external forces acting on it. ^[4]

Conservation of angular momentum is especially important in explaining the skater during rotation. While in the air, there are no external *rotational forces, torque*, acting on the skater, and hence the conservation of angular momentum should hold at this moment. The following expression describes the conservation of angular momentum:

$$I_i \omega_i = I_f \omega_f$$

Figure.2 : Equation showing the conservation of angular momentum. Where I is the moment of inertia and w is the angular velocity. i and f denote initial and final respectively.

The above equation shows that angular momentum depends on the moment of inertia and angular velocity. From this relationship, it can be easily seen that varying the moment of inertia will also vary the angular velocity in order to maintain the initial angular momentum. This means that the angular velocity of a rotating body can effectively be increased by decreasing the moment of inertia.

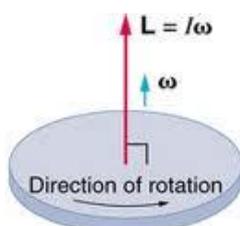


Figure.3 Diagram showing the direction of the angular velocity and the angular momentum ^[5]

Newton's Third Law

The ever famous Newton's law also plays a part in our explanation of the jump spin. Newton's third law of motion can be summarized to: for every force there is an opposing force of the same magnitude [6]. As we can already see, this is very important in the take-off stage of the jump spin. Following the Newton's law one can 'push' against the ground and the ground will 'push' back with the same magnitude giving propulsion for the jump. However, it is trickier for our skater who must do this on ice where the simple action of 'pushing' against the surface is difficult due to the frictionless nature of its surface. We will tackle this problem later on.

Triple Axel: Analysed

Now that we have introduced ourselves with the underlying physics, let us now look at the actual triple axel jump itself. We will look into more details of each part of the jump spin element and describe some of the features using the physics we have previously identifies as the female skater of the below figure attempts the triple Axel jump.

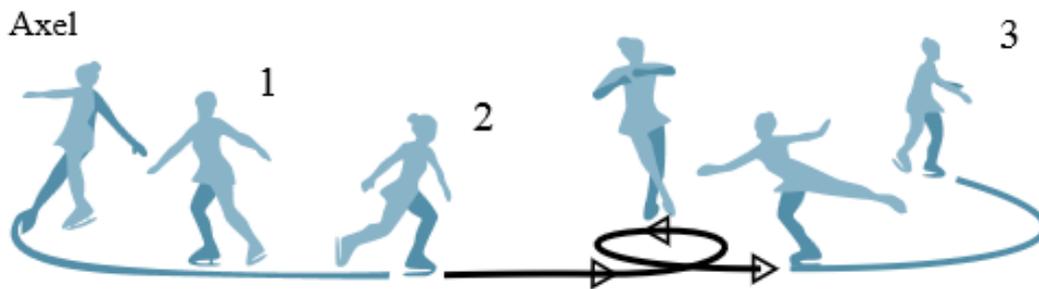


Figure.4: Simple diagram of a female skater executing Axel jump. Triple Axel will involve three (and a half) rotations in the air. [7]

Take-off

Before the take-off, our female skater of *figure 4* is seen to glide across the ice preparing for the jump spin. As the skater glide across the ice, she will be accelerating and hence gaining more speed. The reason for this is to gain as much linear kinetic energy as possible before the take-off. As mentioned in the conservation of energy section of the article, the more linear kinetic energy the skater has the more vertical kinetic energy she will gain meaning that she will jump higher getting more 'air-time' for the spin. In addition to this, rotational kinetic energy will also be gained from this allowing her to spin faster in the air.

At the point of take-off, in addition to the external kinetic energy of the skater, there will be some internal chemical energy from the muscles of the skater as she pivots and pushes off the ice with her supporting leg. In actuality, this energy is what differentiates between the skaters and how high they can jump as it depends on their body structure and muscle mass.

This is one of the reasons why jump spins such as triple axel, which requires longer air time and faster rotation in the air, are more prominent amongst male skaters and are rarely executed by female skaters. The power required to accelerate before the jump and to take-off will be significantly greater for the male skaters due the masculine body structure. [8]

Finally, in order to take-off with stability on ice, there must be sufficient friction between the blade of the skate and the surface of the ice. This is solved by the unique design of the figure skating skate. The skates worn by the figure skaters are different to other skates in a sense that at the front edge of the skate there is something called the 'toe pick'. It is a group of saw-like teeth which allows a better 'grip' on the surface of the ice with its sharp edges at the point of take-off.



Image 2: Toe picks allow the skater to obtain better purchase in the ice when doing a jump. ^[15]

It is important to note, however, that it is not only the toe pick which allows the stable take-off. Since, as the skater is taking off, the rotation must also be initiated which means that the skater's body has also started to rotate while jumping from pivot of the toe pick. If the skater does not maintain a good posture by stabilizing her limbs and centre of mass, she will lose her balance and will lead to the failure of the jump. This, similar to the energy required to jump, depends largely on the ability of the skater.

In air

Now that our skater have successfully managed to take-off, she must now rotate at a high speed while her time in the air. Although it will differ depending on how high a skater jump, but the average time a skater has while in air is less than a second!^[9] This means that to execute the triple axel, our skater must complete three and a half turn in under a second.



Image 3: Skater assumes the tight body position for maximum spin ^[16]

In order to rotate fast in a very short time, the skaters will use the consequences of conservation of angular momentum to its fullest extent. On *figure.4*, just before the take-off, our female skater has her arms and her non-pivoting leg spread out. This will increase her moment of inertia and since torque is directly proportional to the moment of inertia, this will allow her to apply more torque to her body when initiating the spin upon take-off.^[10]

While in the air, the skater assumes a 'tight body' position in which she quickly resumes her initially spread out arms towards her body while crossing her legs to minimise her moment of inertia. Since the skater is not subjected to any external torque at this point, in order to conserve angular momentum, her angular velocity will increase allowing her to rotate very fast.

During the tight body position, it is also important that the skater maintains her core, abdomen and torso, straight to maintain a stable spinning position and for a stable landing.

Landing

Assuming that our female skater has now successfully completed the three and a half term in the air, she must now land safely. In reality, the landing part of the jump spin is actually the most important part as most mistakes and failures arise at this point. If the skater does not maintain her stable posture on landing she will lose her balance and fall which can lead to a large deduction of points, and even worse, lead to injuries. ^[11]

Let us consider what is going on between the in-air phase and the landing phase. While still in air the skater has a large amount of rotational kinetic energy as well as gravitational potential energy due to the gain in height when jumping. In order to slow herself down, it can be seen on figure.4 that upon landing she spreads her arms and her non-pivot leg wide. This is to, of course, to maintain her balance but also to increase her moment of inertia in order to will decrease the angular velocity she initially had hence slowing down her rotation.

Once landing stably back onto the ice, she will continue to glide across the ice with the linear kinetic energy gained from the conversion of rotational kinetic energy and gravitational potential energy.

It is also interesting to note that throughout the entire Axel jump, the skater also had a linear motion even while in the air – her path being a projectile motion – this is due to the conservation of linear momentum.

Now our female skater has successfully executed her triple Axel and can gliding through the ice preparing for her next element of the program. It is also interesting to consider that the whole process only takes about a second or two in real life!

Quadruple Axle and even more?

We have now analysed the triple Axel jump in detail and identified several factors and underlying physics behind each phase of the jump. Now, we can ask the question: can we take it further than this?

As mentioned previously, more rotations than triple Axel, namely quadruple axel, does exist and there have been reports of successful execution of such jump, however, it is yet to be accomplished in official competitions due to its difficulty. Despite this, quadruples of other jumps have been successfully, although rarely, achieved in official competitions^[12]. If this is the case and the only difference between the quadruple axel and the other jumps is the extra half-turn, is this *extra half-turn* the current limit for the sport?

Using the information we have acquired earlier, we know that in order to achieve more rotations in the air, we require longer in-air time and faster spin during this time. Theoretically this can be achieved by increasing the speed of the skater before take-off (hence more kinetic energy) and having a stronger lower body for higher jumps.

The research showed that the maximum rotation speed is around 2000 degrees per seconds, which is approximately five and a half turn if the skater is allowed to spend a second in the air. However, the current record for longest air time to be achieved is only 0.9 seconds.^[13]

Although not quite close enough yet, this still hints the possibility of not only the quadruple axel but even quintuple axel! Of course, in practice this will be very difficult for the skater to achieve and it will not be a consistent feat.

However, there is a possibility of technological aid in enhancing the rotations. As with any other sports which the performance depends on a fraction of a second, the figure skating equipment also has the potential to be technologically improved to reduce factors which currently constraints the possibility of quintuple axles.



Image 4. *Will quintuple jumps be possible one day?*^[17]

And most importantly, we must not overlook the fact that every year after year, new and better skaters are introduced to the sport and more effective and efficient strategies and training methods are being developed. Therefore, in my personal opinion, in the near future, quadruple and even quintuple Axels will be a common scene in figure skating.

After all, the physics is there, we just have to put into practice.

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