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The Quintuple Axel: What Are the Risks?

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Abstract
Before the International Skating Union (ISU) can consider giving quintuple jumps base values and grades of execution, they should consider the physical risks to their athletes that these jump elements can have. Using approximate heights and weights for a skater, the limits of the most difficult jump, the quintuple axel, will be modelled to determine some of the injuries that could occur from training, landing, and mis-landing it. This paper will use the data from the previous associated paper, [1], for these models, to attempt to determine the severity of the risks, which the ISU should take into consideration before assigning scores which could encourage or discourage skaters to chase the new "impossible" jump.

Keywords: *Sports; Biology; Physics; Mechanics; Figure Skating; Sports Injuries*

Introduction
As all the quadruple jumps have been landed at least once in figure skating competitions, it would be logical for the ISU to next assign base values and grades of execution (GOE) to the quintuple jumps, from the toeloop to the axel. However, as the rule change in 2018 was initially to allow the quality of elements to be rewarded over the quantity of more difficult jumping passes [2, 3], it is questionable whether quintuple jumps need to be given points. Furthermore, with more rotations, the risk of injury becomes greater [4] and this paper will explore some of those injury risks, particularly focusing on those associated with the quintuple axel jump.

Injuries have a multitude of mechanisms of action and different sources. The impact, overload, overuse, structural vulnerability, inflexibility, muscle imbalance, and rapid growth [5] are all factors that could lead to injuries in figure skating, and are especially relevant to injuries related to jump landings.

Knee Injuries
Knee injuries are most commonly found within synchronised skaters and adult skaters, and anterior knee pain occurs through constant use during gliding and acceleration that is required for skating skills [4]. While the knee pain is generally low level, a more severe knee injury that can occur is the anterior cruciate ligament (ACL) injury, which can occur both from drop jumps [6], or spin positions like the Biellmann spin [7]. ACL injuries also usually occur during unilateral loading in sports like handball [6] which figure skating jumps are, as they land on a single leg. Injuries occur with movement of the frontal plane of the knee [6].

Newton's Second Law for Rotation defines torque, τ, as:

$$\tau = I\alpha = I\frac{\Delta\omega}{\Delta t}. \qquad (1)$$

In the case of a quintuple axel, the average angular velocity required was calculated to be 49.8 rad s^{-1} from the previous paper [1]. After rotating in the air during the jump, a torque then is produced by the ground on the skater upon landing – meaning the final angular velocity of the skater is zero. Assuming that the skate boot is rigid with respect to the rest of the ankle and lower leg, the first point that will experience said reaction torque will be the knee ligaments of the skater. Therefore, the lever arm, L, will be the length of the skater's lower leg, and will be taken to be 0.39 m [8]. This torque is further exacerbated in jumps that have a poor knee bend, which also leads to a lack of exit speed after the jump. The tensile strength of the ACL, the maximum force that can be applied before the ligament fails, will be taken to be F_{max} = 626 N [9].

$$I = \frac{1}{2}MR^2 \qquad (2)$$

As in the previous paper [1] the skater will be modelled as a cylinder when in the air with their arms tucked in [10]. The moment of inertia is therefore described in Equation 2, where M is the mass of the skater, assumed to be 55 kg, and the radius of the cylinder, R , 0.1 m. Through a frame-by-frame analysis of the landing of an axel jump [11], it is estimated that the time interval, Δt, is 0.067 s.

$$F = \frac{\tau}{L} = \frac{743\ Nm}{0.39\ m} = 414N \qquad (3)$$

Therefore, it is safe for the skater to perform the jump. However, in the case of poor technique where the skater does not bend their knees sufficiently, damage to the ligaments can occur in both their knees and other joints or muscles.

Ankle Injuries

Ankle joint movements are influenced by multiple forces: the muscle activity, moments acting on the bony interfaces within the joint, ligamentous structures, and soft tissue structures [12]. Movements are also influenced by factors that influence the dorsiflexion range of movement, the forwards and backwards movement of the ankle: both internal and external factors. The dorsiflexion range of motion is important to achieve a stable position of the ankle joint during functional movements, and limiting this can have a negative impact on jump landings at the initial contact [13].

Ankle sprains are the most common skating injuries, with a prevalence of greater than 50%, and they occur the most commonly in male and female singles skaters [4]. Practicing jumps with multiple rotations places them at a higher risk of ankle injuries than synchronised skaters and those practicing jumps with fewer rotations, particularly if the landing occurs before the rotations are completed in the air [4]; underrotating jumps can lead to an increased risk of injury, which leads to a large inversion torque on the ligaments of the ankle.

As compiled in the supplementary data of *Quintuple Axel Rotation Speed* [1], the average male skater reaches a peak height of 0.59 m. The skater's foot will be accelerated by gravity, landing on their medial forefoot. Since the reaction force is caused by the ground, the radius, r, from the axis of rotation is the distance between the ankle and the ground, and this will be taken to be 0.13 m; as the height of the blade is approximately 44 mm [14], and the distance from the bottom of the foot to the ankle is approximately 90 mm. When underrotating a jump or landing poorly, there is likely to be a degree of supination of the ankle, and this damage begins to occur at the angle of 41.4° [15].

$$\tau = Fr\sin\theta = Mgr\sin\theta = 46.4\ Nm \qquad (4)$$

Equation 4 shows the torque on the ankle when landing on it incorrectly by landing on the outside edge of the blade as normal, and the ankle rolls too far. This is greater than the failure torque of the ankle, 45.3 Nm [15] and emphasises the increased risk of injury posed by more challenging jumps.

Conclusion

Multiple injuries can occur from any figure skating jump, and the quintuple axel is likely to cause some of the most severe injuries considered thus far, with a single poor landing potentially leading to an ankle sprain. With the dorsiflexion of the ankle limited by the skating boot, this can have a significant negative impact during the jump landings on the ankle. Furthermore, when one part of the landing system is limited, jumpers and skaters can try to compensate with other parts of their bodies, and can put their hips, backs, knees, and shoulders at additional risk of injury to chase multi-rotational jumps [4, 13]. Additionally, overuse injuries are becoming more common in figure skating, particularly in singles skaters, and they are the most common injuries in junior female skaters [4].

With multi-rotation jumps requiring additional training to rotate and land, these overuse injuries would be likely to increase. Finally, multiple injuries within the foot, ankle, back, and knees can also be caused due to problems with the skating boot and both its fit and rigidity [4]. The boot limits the knee and ankle motion that the skater can have, which prevents them from absorbing forces adequately on their jump landings [4], which can lead to them compensating with other parts of their bodies [13]. Until the technology for figure skating boots improves, it would be unwise to provide base values for quintuple jumps, as this would encourage skaters to risk more severe injuries chasing the points.

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