The Biomechanics of Cranial Forces During Figure Skating Spinning Elements

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ABSTRACT — Several facets of figure skating, such as the forces associated with jumping and landing, have been evaluated, but a comprehensive biomechanical understanding of the cranial forces associated with spinning has yet to be explored. The purpose of this case study was to quantify the cranial rotational acceleration forces generated during spinning elements. This case report was an observational, biomechanical analysis of a healthy, senior-level, female figure skating athlete who is part of an on-going study. A triaxial accelerometer recorded the gravitational forces (G) during seven different spinning elements. Our results found that the layback spin generated significant cranial force and these forces were greater than any of the other spin elements recorded. These forces led to physical findings of ruptured capillaries, dizziness, and headaches in our participant.

Keywords: **Figure skating, acceleration forces, spinning.**

Background

There are nearly 180,000 members of United States Figure Skating Association[1] the majority of whom are adolescents. Youth athletes have often been studied to identify techniques in decreasing sport-specific injuries, such as basketball and soccer with knee injuries.[2,3] As in any sport, there are certain injuries specific to figure skating[4] and an improved understanding of these injuries has provided the ability for enhanced athletic performances. On-ice biomechanical analyses of complex jumps have lead to customized dry-land training programs to enhance the athlete's ability to create appropriate vertical and rotational velocities needed to execute these jumps.[5-7] A proper understanding of jump landing forces to the lower extremity has encouraged boot modifications and increased off-ice training of jumps.[8]

Spinning is an essential element in figure skating, but it has not yet been examined to the same extent as jumping. Senior level skaters are required to complete three separate spin sequences during a program. These spin sequences are a combination of several different spinning positions, and can vary between 10 - 30 seconds in duration. Within the skating community there are reports of dizziness, headaches, vision disturbances, and rarely sudden loss of consciousness while practicing spinning elements.

Summary Box

The cranial forces in the spinning elements of figure skating are significant enough to result in superficial vascular damage.

These cranial forces are also significant enough to lead to symptoms of headache, nausea, and dizziness lasting hours after figure skating spinning.

Spins with the head near the axis of rotation are subjected to less force compared to spins where the head is further from the axis of rotation.

The vestibular system, specifically the vestibulo-ocular reflex, is challenged during these spinning elements, since the head is moving in a direction opposite of the eyes' gaze.[9] Repetitive rotations can cause insult to the vestibular system and may result in symptoms similar

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to motion sickness.[9] Given the duration of the spin and the magnitude of the resultant linear forces caused by the skater's acceleration into these elements, it may be possible to elicit a vascular response within the body known as a "red out" or a "black out." A "red out" takes place when negative G-forces are imposed on the body. Blood is forced towards the head causing capillaries to rupture and the person may have the visual experience of seeing red. The body's tolerance is not as developed for handling negative G-forces and will experience a red out more rapidly starting at negative 2G.[10] Conversely, a "black out" occurs with a positive G-force, and results in blood being drained from the head and extremities towards the body's core. In this situation a person's peripheral vision will begin to fail starting at 2-3G with the decreased arterial pressure in the eyes.[11] If arterial pressure is not restored a visual experience of seeing black will take place before loss of consciousness, which occurs at approximately positive 4G.[10]

Figure 1. Accelerometer placement.

Understanding the cranial forces experienced by figure skaters during different spins and the symptoms that follow these spins may aid athletes and coaches in establishing injury prevention measures. To date, no investigations have been conducted to study the forces that are generated around the head of figure skaters during the spinning elements. The purpose of this case report is to describe the resultant linear forces that impacted a single figure skater's head during selected spinning elements. This single case is part of an on-going study to quantify the accelerative forces generated around the head during on-ice figure skating spinning elements and document the physical reactions that ensue after completion of such elements.

Methods

Study design and participant information: This case report is an observational, biomechanical analysis of a healthy, female, senior-level figure skater who is currently part of a larger study. This study was approved by the institutional review board at Connecticut Children's Medical Center, and the participant was consented prior to data collection. The participant was asked to complete a questionnaire describing her current US Figure Skating level, years of experience in competitive skating, hours per week spent training, and injury history.

Data collection: The participant was asked to perform seven different spinning elements that she was experienced and comfortable performing for this study. The participant chose to perform: a back scratch spin, a layback spin, a hair-cutter spin, a camel into a donut spin, a forward scratch spin, a sit spin, and finally a broken-leg spin. After completing each spin the participant was asked if the spin she had just completed was representative of her mastery of the spin. If she felt, that the spin was representative then she would move on to the next spin, otherwise she would repeat the spin.

Acceleration data, at the participants' head, was collected, for each spin, using a single triaxial 1,000G accelerometer (Biometrics LTD, Gwent, United Kingdom). The accelerometer was attached to the center of the participant's forehead using a custom made headband. The headband was lined with a silicone strip to prevent movement of the accelerometer during the test. The accelerometer was connected via a small cable running down the participant's back, to a wireless transmitter that was secured to the participant's waist using a belt (Figure 1). This configuration allowed the participant to spin freely without significant interference from the instrumentation.

The accelerometer was programmed for a 10G range (+5G to -5G) with an excitation voltage of 5mv and a channel sensitivity of 10mV. Acceleration data were collected at 100Hz using DataLog software (Biometrics, LTD, Gwent, United Kingdom). Video data was also collected for each spin using a Cannon 7D camera (1920x1080 at 30 fps). Once collected the acceleration data about each of the axes were imported into Matlab (Mathworks, Natick, MA) for postprocessing. In Matlab, custom code was used to smooth the raw data using a 4th-order, zero-lag, low-pass Butterworth filter with a cutoff frequency of 10Hz. Once smoothed, the data were corrected as needed to account for DC drift during data collection. Although the force data were collected as component forces about the X, Y, and Z axes, it was felt that the most accurate means of presenting the force data was as the resultant force acting on the participants head. The resultant force was calculated using the following equation,

$$Fr = \sqrt{F_x^2 + F_y^2 + F_z^2}$$

where Fr is the resultant force, Fx, Fy, and Fz are the component forces about the X, Y, and Z axes respectively.

Table 1. Participant Demographics

Age	23 years
Height	170 cm
Weight	47.7 kg
Years of Competitive Skating	18 years
Current Level of Competition	Senior
Days/Week Devoted to Spinning	4 days
Hours/Week Devoted to Spinning	4 hours
Injury History	Two Concussions

Figure 2. Layback spin.

The total force was then plotted over time for each of the spins to determine if the G-force thresholds for a red out (-2G) and black out (4G) were exceeded. If it was determined that the thresholds were exceeded the total time the participant spent above the threshold was calculated for each spin. The total numbers of revolutions completed per second were calculated by counting the number of revolutions the skater performed using the video data.

Results

The results presented in this case study are based on a single female figure skater (Table 1).

The results indicate that none of the spins reach the black-out threshold of 4G, and with the exception of the layback spin none of the spins crossed the red-out threshold of -2G (Table 2).

The layback spin (Figure 2), produced a sustained -2.2G upon entry into the spin, and then produced a 1.8G force upon exit of the spin (Figure 3). Therefore the participant experienced a possible red-out condition for a total of 0.07 seconds while performing a single layback spin.

Discussion

The current study describes the cranial forces a single skater was subjected to during multiple spinning elements. The genesis of this biomechanical evaluation comes from personal observations of vascular and vestibular findings that have been reported in figure skaters. Following extended bouts of spinning, figure skaters have complained of headaches, visual disturbances, and dizziness in addition to broken capillaries in their fingers, arms, and around their eyes. These symptoms are

Table 2. Summary of Spinning Results

Spin	*Maximum Negative G Force (G)*	*Maximum Positive G Force (G)*	*Time Over G Force Threshold (s)*	*% of Spin Over Threshold*	*Revolutions Per Second (rev/s)*
Back Scratch	-0.7	0.9	0	0	4
Broken Leg	-0.5	0.5	0	0	2
Camel Donut	-1.3	1	0	0	1.5
Forward Scratch	-0.4	0.5	0	0	4.25
Hair Cutter	-0.7	1.2	0	0	2.25
Layback	-2.2	1.8	0.07	0.2	2.5
Sit	-0.5	0.7	0	0	1.5

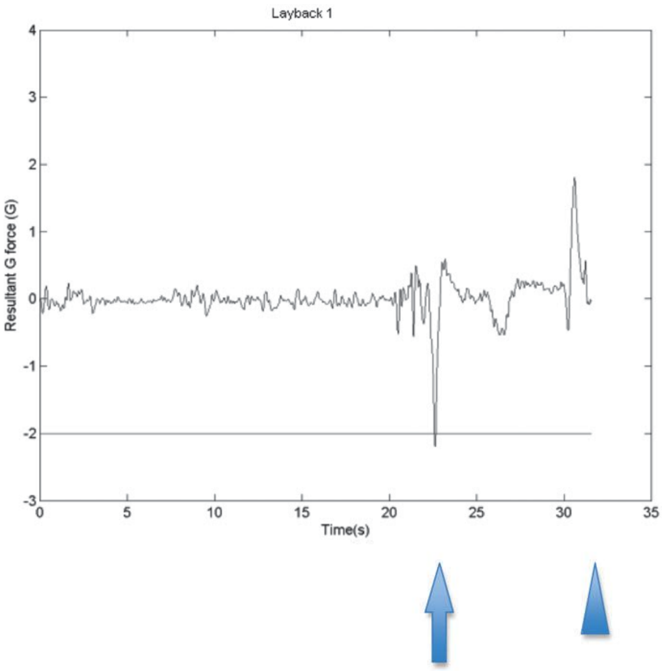

Figure 3. **Force plot for layback spin.**

understood enough that programs often have recovery time built in to protect the athlete from jumping while still symptomatic from the spin. The participant in this study had expressed a similar history of capillary hemorrhage, headaches, and visual disturbances throughout her career while completing layback and scratch spins. While participating in this study, our skater had the greatest forces produced during her layback spin with -2.2G recorded during the entry into the spin and 1.8G recorded during the exit. She suffered periorbital and forehead petechiae as well as subconjunctival hemorrhages in her right eye (Figure 4). She also reported a headache, nausea, and malaise for several hours after the study. Although our participant only exceeded the red-out threshold for 0.07 seconds during her layback spin, it is not uncommon for figure skaters to practice a single spin upwards of 30 times in a given practice session. Given this information, our participant could possibly spend a total of 2.1 seconds over the vascular threshold while practicing a layback spin.

The participant completed several types of spins. It was observed that when the participant's head was closer to the axis of rotation the recorded forces were lower, which was expected. This fact was demonstrated with the scratch spins, broken leg, and sit spins. The camel, hair-cutter, and layback spins required the head position to extend away from the axis of rotation. Increased cranial forces were seen with the layback spin. The recorded forces increased as the participant extended backwards into the layback spin. It is also important to note that the position of the head and not the speed of the spin is the greatest contribution to cranial forces measured. This can be demonstrated by noting that the forward scratch spin, in which the head was in line with the axis of rotation, was nearly double the speed of the layback spin (4.25 rev/s *vs* 2.5 rev/s respectively) and had less than a third of the total measured cranial force.

Cranial forces that have the potential to cause injury have been studied in cohorts of adolescent athletes participating in contact sports such as football and ice hockey. In these studies the resultant linear acceleration can exceed 25G and 22G respectively during contact to an athlete's head.[10, 11] The forces produced in this case study were negligible in comparison, however the time of exposure to these forces for the figure skater could be substantially greater. Relating these findings to the findings reported for high school football players, the average duration of impact lasted 10.2 + 3.6 ms,[10] while the figure skater in this case study exceeded the red-out threshold for 70 ms. In this case the body's ability to compensate for these increased cranial forces had been exceeded. This was evidenced by the physical findings of ruptured capillaries and petechiae. The etiology of the symptoms of dizziness, headache, and nausea is not clear. It is likely that these symptoms are secondary to an overtaxing of the vestibular system. In this situation one would expect a fairly rapid recovery of the symptoms. It has been reported that there are cases of prolonged vestibular dysfunction following excessive spinning. This fact brings up the possibility that repeated bouts of elevated cranial forces could also lead to direct vestibular dysfunction or central neurologic changes similar to those seen in concussion. It is then plausible that younger, more neurologically immature skaters may have an increased risk of complications following repeated bouts of spinning that result in increased cranial forces.

This study does present with limitations. First, our participant's past medical history does include two diagnosed concussions throughout her skating career. Second, our participant was a senior-level skater who devoted countless hours of practice to perfect her spinning capabilities. Although her spinning ability may be extrapolated to other skaters competing at a senior level, it cannot be compared to lower-level skaters. In addition our calculations of spin revolutions were estimates based off video analysis.

Figure 4. **Photograph depicting participant's periorbital petechiae and subconjunctival hemorrhage.**

Conclusion

This report presents data collected from a single, senior-level, female figure skater, who is part of a larger study examining the cranial forces measured in figure skaters at different levels of skating ability. The results of this report showed the significance of sustained negative G-forces on the skater's head as she performed her spinning elements. These forces were significant enough to lead to physical findings such as ruptured capillaries, headache, and nausea consistent with exceeding the red-out threshold. These symptoms however are also consistent with vestibular dysfunction. Further research needs to examine the threshold of spinning that can lead to symptoms, the cumulative effects of spinning, as well as a understanding of how entry-level spinners handle the forces generated by spins compared to senior-level spinners. Head positions closer to the axis of rotation in the spin mitigate some of the cranial forces and may be useful in spinning technique. In the future we will need to differentiate symptoms from vascular injury and vestibular dysfunctions. Understanding spins and the problems associated with spinning can better aid in creating sport-specific injury prevention measures for young skaters.

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