Forces and Time Delay due to Impact with Gates in Ski Racing

by

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Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Mechanical Engineering

at the
Massachusetts Institute of Technology

June 2016

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ABSTRACT

In an effort to better understand impacts with gates during ski racing competition, on-snow measurements and observations were made of both standard gates and inflatable gates. These observations highlighted the importance of impact force and time. Two additional experiments were done to analyze these factors and compare their values for standard gates and inflatable gates. Gates were hit with a controlled weighted pendulum and force sensor to measure the impact force. To measure time, slow motion footage was taken of the gates clamped in a baseball pitching machine. The baseball’s velocity was scaled to model the skier using conservation of energy principles. The footage was analyzed with position tracker software.

Inflatable gates were found to have a lower mean impact force of 28.55 ± 5.89 N compared to the standard gate impact force of 44.55 ± 7.12 N. Although they exhibited lower impact force, the inflatable gates had a longer time to clear out of the skier travel path due to isolated bending in the small area of impact. The time for the tip of the inflatable gate to clear was 0.63 ± 0.1s compared to the 0.43 ± 0.03s it took for the tip of the standard gate to clear. From these results, it can be concluded that inflatable gates have a softer impact force, but require a modification in racing form in order to increase the impact area and thus decrease momentum and balance losses due to gate bending around extremities.

Thesis Supervisor: Anette Hosoi

Title: Professor of Mechanical Engineering
ACKNOWLEDGEMENTS

Firstly, I would like to extend thanks to the many people who contributed equipment, information, time, and energy to this project:

To Stefan Dag from Airkipp, for his expertise and history in gate design and for contributing inflatable gates and associated materials for this project.

To Brad Williams from World Cup Supply and Giovanni Berutti from SPM, for contributing knowledge on the current standards and testing practices for gates as well as for contributing several new hinges to be tested.

To Jay Cummings and the rest of the Jay Peak Ski Team for their time and for allowing us to use their hill space for testing purposes.

To the MIT ski team for allowing me to borrow gates and equipment, Coach Jason Christopher for his setting knowledge, and especially to Katy Kem for assisting in on-snow data collecting on a cold wet day.

Special thanks goes to Bob Rich from Reebok for allowing me to come to Reebok Headquarters multiple times to use their baseball pitching machine, as well as to Ben Knapton who operated the machine and assisted with setup.

Secondly I would like to thank my thesis advisor Peko Hosoi for her expert advice in all things physics or sports related and for her constant enthusiasm and support. This project would not have been completed without her positive outlook and technical advice.

Last, but definitely not least, thanks to my friends and family who have supported me through not only this project but also every other aspect of MIT.
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1. INTRODUCTION

1.1 Overview of Ski Racing

Alpine ski racing is an extreme sport with a long history. Advancements in technology as well as trends in serious injuries have largely dictated changes in the sport over time along with overall athlete performance. Due to the nature of the sport, equipment plays an integral part in performance; and new technologies are released every year pertaining to pushing skiers to their limits.

In ski racing, athletes must correctly navigate obstacles called gates or poles, meaning both feet must cross a plane drawn from one gate to the next, see Figure 1.

![Figure 1-1: Correct navigation around ski racing gates.]

There are four main types of alpine ski racing competition: slalom, giant slalom (GS), super giant slalom (super-G), and downhill. The differences in these events are based on the distances set between gates, the amount of gates, and the length of the course. Slalom and GS are technical events with overall shorter courses, tighter turns, and lower speeds; whereas super-G and downhill are speed events with much longer courses and a focus on maintaining...

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1 Image credit to USSA Gate Judge Duties & Responsibilities Document.
momentum and speed. Due to the long course length and dangerous speeds, super-G and downhill competitions are less common. Slalom and GS are the main competitions for most college level and younger athletes.

**Figure 1-2a:** Standards for setting GS course.²

**Figure 1-2b:** Standards for setting slalom course.²

² Images credit to Slalom and Giant Slalom Guidelines for Basic Course Setting.
This paper focuses specifically on gate impact in slalom style racing. Although the gates used in all events are the same, the way in which the skier impacts the gate and the force of the impact varies greatly based on the event. Due to the short distances between gates in slalom, racers need to ski very close to the gates in order to maintain a fast line. A style called cross-blocking is often employed for this purpose, where the skier impacts the gates with their shins while driving forward with their outside arm to prevent it from hitting their face.

![Image](image.jpg)

**Figure 1-3:** The figure above shows a skier impacting a gate using the standard cross-blocking technique. The majority of the body is on the inside of the gate while the skis go around. The outside arm is used to drive the gate away from the face.

For the three other events, skiers avoid intentionally hitting the gates as their speeds are much higher, in the range of 30-90mph\(^4\), and the turns are large enough that it is possible to maintain the fastest line without impacting the gate. Additionally, this thesis focuses specifically on slalom because it is a more common event for recreational or non-competitive ski racers. The types of injuries sustained in high speed events are more critical compared to those of slalom and thus the athlete competing in high speed events is typically a professional who is more concerned with injuries not related to gate impact; whereas slalom courses are skied by a larger variety of non-professional racers with higher safety expectations.

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\(^3\) Image credit to Wikipedia: Slalom Skiing page.

\(^4\) “Ski Racing Disciplines and How They Differ”
1.2 History of Slalom Gates

Gates have always been an integral part of slalom racing and as the sport progresses over time, so does their design. The original slalom gate consisted of two pieces of bamboo held in the snow and connected by a colored flag. These gates were problematic because they had minimal flexibility and racers could become injured or bruised by brushing into them. Additionally, due to the flexibility threshold of bamboo, the gates would often break upon impact. This meant most of the gates might need replacing after a particularly aggressive skier. In extreme cases, such as at Val d’Isère in France, a skier could be pierced by a gate that was not completely vertical in the snow.\(^5\)

![Figure 1-4: Patent images of the original hinged gate concept.\(^5\)](image)

In 1969, the bamboo pole was replaced by a flexible plastic pole and in the 1970s the modern hinged gate was invented, see Figure 4. The gate works by using a spring hinge located at the base where the gate is mounted in the snow. It allows the gate to snap back as the skier hits it and dissipates a large portion of the impact energy. The gates were adopted into higher level competitions in the 1980s, and in the late 80s the screw base was developed to better hold the gates in the snow. These plastic hinged gates with screw base are the standard style of gates used in competitive racing today. Many adaptations of this design

\(^5\) The Story of Modern Skiing
\(^6\) Image taken from US Patent No. US4270873A
now exist, including variations in diameter, hinge mechanism, and snow-hold base design; but the overall structure remains similar to the original concept.

The advent of the hinged gate brought about differences in racing form. Due to the reduction in impact force and injury, skiers were less concerned about hitting the gates. In fact, the cross-blocking style was invented in slalom to purposefully impact the gate and create a tighter line. Although the new gates allowed for more impact, there was still injury associated with hitting them at speed; and so new protective equipment such as shin guards, pole guards, and helmet bar were created to act as a shield to protect the skier from the impact with the gate across their body.

![Figure 1-5a: Previous slalom racing form prior to hinged gate.](image7)

![Figure 1-5b: Modern slalom racing form post hinged gate, note addition of protective equipment.](image8)

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7 Image credit to Vail Daily News  
8 Image credit to Buying Guide for Race Accessories.
1.3 Current FIS Gate Specifications

Currently, the Fédération Internationale de Ski (FIS) maintains specifications for the gates, termed flex poles, allowable for use in races. The specifications mandate a design consisting of upright pole, hinge mechanism, and anchoring base. There may only be one hinge in the gate. Specifications such as outer geometry are regulated strictly whereas other areas such as hinge mechanism and materials are more open to variation as long as they behave consistently with the testing standards.

![Diagram of ski racing flex pole as defined by FIS Specifications](image)

**Figure 1-6**: Aspects of ski racing flex pole as defined by FIS Specifications.

Regulations on gates are necessary in order to maintain consistency and fairness across races because gates have an enormous impact on the racer’s performance. Although necessary for standardization across competitions, the specifications are not necessarily highlighting the best design for the gates. They are grounded more in historical expertise of what has worked in the past, rather than mechanical theory. They even state that “the fact that these requirements are satisfied or that these specifications are applied does not

---

guarantee against the poles breaking or skiers being injured by them” and also, “In principle, however, there is room for further development.”

1.4 Drawbacks to Current Gate Design

Although the history of gates from rigid bamboo to flex poles shows major improvement, there are still issues with the current design. Ultimately there are two major users influencing gate design: racer and course setter/coach.

1.4.1 Racer Interaction

The racer’s interaction with the gate consists of speed maintenance, injury prevention and associated psychological factors. Depending on the type of gate and the mass and form of the skier, a substantial amount of momentum can be lost due to impact with the gate.\textsuperscript{10} Forearm and shin bruises due to this impact are also very common in the ski racing community. So common in fact, that they are rarely reported and considered simply an aspect of the sport and possibly a matter of pride, see Figure 7.

\textbf{Figure 1-7:} Bruises on arm, a common injury in slalom racing.\textsuperscript{11}

\textsuperscript{10} Reid et al.

\textsuperscript{11} Image credit to Elli Terwiel
Although bruising is a minor injury, there are also psychological factors associated with repetitive pain from impact, especially for younger or inexperienced racers. According to a recent study, young athletes exhibited greater speeds and confidence when training on whisker or stubby gates\textsuperscript{12} as opposed to standard sized gates.\textsuperscript{13}

Studies such as this show drawbacks to marking turns with gates, and there are less physical designs such as lasers or snow level markers which could work as well as the gates; however, there is importance in maintain the integrity and tradition of the sport. Drastic changes to the gates could hugely alter the sport by decreasing or eliminating risks and challenges. Maintaining a level of challenge is an aspect that must always be considered when designing sports equipment. Because of this, it is important to research the impact forces in the current gates and evaluate whether the injuries a racer could receive from these impacts are drastic enough to prompt a redesign of the gate. Additionally, identifying and mitigating momentum losses due to impact would contribute to the sport without drastically altering the tradition.

1.4.2 Course Setter/Coach Interaction

Coaches are another important user critical to the gate design. Coaches are typically responsible for setting courses during practices or competitions. Gates are bulky and awkward to carry especially on chairlifts and while skiing, see Figure 8. A typical bundle of gates can weigh between 45 - 60lbs, and one course may require multiple bundles to have enough gates for the entire length.\textsuperscript{14} Additionally, setting requires a large drill and measuring tape. Due to the amount of equipment and weight it can require multiple people and a great deal of time to set a training course. The aspects of setting ease, while more difficult to measure qualitatively than force impacts, are critical to the overall design of the gate. Any modifications made in this area which could maintain the traditional gate impact while alleviating setting difficulties would be huge improvements to the current gate design.

\textsuperscript{12} Whiskers: brushes marking turns. Stubbies: short pieces of rubber. Alternatives to gates for training purposes.
\textsuperscript{13} Kipp et al. study
\textsuperscript{14} From SPM website: gates weigh roughly 3lbs. Meaning 45-60lbs when bundled in sets of 15-20 gates.
1.5 Objective of this Thesis

Due to the drawbacks with the current gate design, there is an opportunity for redesign; however, advances cannot be pursued without first understanding more about the current gates. Very few studies have been done on the actual impact forces between the skier and the gates. In this paper, I will be testing current gates to measure the impact force and analyzing these impacts to better understand the features critical for performance. In addition, these impacts will be studied in comparison with a new inflatable gate which is currently used in some recreational racing leagues. These gates consist of a tube of ballistic nylon placed in the snow and then inflated. They are low weight and are advertised as a softer impact for the skier. Using these as a comparison for impact should highlight features of the current hinged gate which may otherwise be overlooked.

Section 2 describes three experiments performed to understand the gate impact. The first, described in Section 2.1 measured impact of a racer hitting gates on-snow. Force sensors and video were used to better evaluate the impact. The second experiment, described in Section 2.2, used information gained from studying the on-snow experiment to model the impacts of different gates in a more controlled environment. The final testing, described in Section 2.3, used high speed video to study repetitive impacts in a controlled environment. Analyzing the video provided insight on the motion of the gates due to a high speed impact.

Overall, Section 2 describes the setups of the three experiments and the corresponding parts of Section 3 summarize the results. Section 4 draws conclusions on the key qualities of gate performance as well as highlights areas for future research.
2. EXPERIMENTAL SETUPS

2.1 On-Snow Data Collection Setup

In order to model the gates in a controlled environment, physical on-snow testing had to be performed to better understand the factors at work. The ultimate goal of this testing was to find approximate values for the force by a skier impacting both traditional and inflatable gates.

A course was set consisting of 15 gates. There were twelve standard FIS regulated gates* and three inflatable Airkipp gates set for the course. The course was set as a traditional hero course with even spacing throughout on a gradual slope. Gates were set roughly 11m down the hill and 2m across. The course was divided into three sections: the first being six standard gates, followed by three inflatable gates, finishing with six more standard gates, see Figure 2-1.

Force sensors were used to measure the impact of the gates. As most skiers use the cross-blocking technique to knock gates out of the way, the sensors were mounted on the ski poles right below the pole guard as shown in Figure 2-2. After two runs, the right hand force sensor was removed as it was too restrictive of the skier’s movement.

Figure 2-1: Setup of course. X’s mark standard plastic gates and O’s mark inflatable gates. * marks the camera location
After several practice runs, four runs were performed where force sensors collected data and video was taken. A novice college level skier performed all the runs for consistency.

Figure 2-2: Shows location of sensors on ski poles, directly below the pole guards.

2.2 Controlled Impact Force Setup

The second experiment more rigorously studied the gate impact. Specifically, the goal was to study the differences in impact force between the inflatable and standard gates. Several different types of standard gates were used in order to create a better comparison.

Using impact force information gained from the on-snow experiments, a testing apparatus was prepared to study the impacts in a more controlled and repeatable environment. A large weighted pendulum was used in order to create a controlled impact. Gates were clamped horizontally and the pendulum was rigged to swing and hit the gates, mimicking the way in which a skier would hit a gate in the course. The pendulum was fitted with a force sensor in the area where it would strike the gate. The length and weight of the pendulum were altered in order to obtain force values deemed comparable with the on-snow testing. This experimental setup is shown in Figure 2-4.
The advantage of this controlled impact was that multiple types of gates could be tested in the same setting. There are two diameters of upright pole commonly used in adult racing: 27mm and 32mm. Additionally, SPM, one of the lead manufacturers in traditional racing gates, makes two different types of hinges: a poly cord hinge and a metal hinge. The poly cord hinge is simpler and lighter, whereas the metal hinge is more durable, heavier, and easily repairable.

![Figure 2-3: The hinges on the left are poly cord hinges. The image on the right is an exploded view of the components of a metal hinge.](image)

Using all possible combinations, there were four different types of standard gates that might be used in a competition and one type of inflatable gate:

1. 27mm Upright and Metal Hinge
2. 27mm Upright and Poly Cord Hinge
3. 30mm Upright and Metal Hinge
4. 30mm Upright and Poly Cord Hinge
5. Airkipp/iGate (Inflatable Gate)

For each of the different gates, a minimum of five trials were performed. For each of the trials, the pendulum was dropped from the same height and the impact force was determined as the peak readout upon impact. The gates were all impacted the same distance from the base/snow mounting zone.
2.3 Controlled Impact Time Setup

From the initial on-snow test, it was clear that impact force was not the only critical factor. The amount of time it took the gate to clear out of the skier’s path seemed slower for the inflatable gates. Because of this, another experiment was performed to determine the differences in time to clear the skier for the inflatable versus hinged gates. Time taken to clear from the skier’s path, or critical time, is defined here as the amount of time it takes for a gate to go from vertical to 90 degrees upon impact.

Analysis on time was taken using the help of several people at the Reebok Headquarters in Canton, MA. Reebok granted the use of their baseball hitting machine, shown in Figure 2-5, which normally shoots baseballs at a clamped bat to allow for cyclic testing. For this testing, the gate was clamped where the baseball bats normally are held and the machine was used to launch baseballs at the gate at controllable speeds. Figure 2-6 shows how the gates were clamped in the machine.
Figure 2-5: Reebok baseball bat testing machine. Balls are fed hydraulically from the left into a chamber on the right where bats are clamped. Computer software controls the air pressure launching the balls and records the initial ball velocity.

Figure 2-6: Clamping of gates in baseball bat holder.
In order for this testing apparatus to model an actual skiing impact, the velocity of the ball had to be manipulated to a reasonable value. Conservation of energy principles were used to calculate an approximate value for the ball to match that of the skier.

Using conservation of energy:

\[
\frac{1}{2} m_b v_b^2 = \frac{1}{2} m_{s,\text{eff}} v_s^2
\]

Where \( m_b \) is the mass of the ball, \( v_b \) is the velocity of the ball, \( m_{s,\text{eff}} \) is the effective mass of the skier, and \( v_s \) is the velocity of the skier.

Solving for \( v_b \):

\[
v_b = \sqrt{\frac{m_{s,\text{eff}} v_s^2}{m_b}}
\]

Substituting appropriate values yields \( v_b = 85 \text{mph} \). The pitching machine was capable of shooting from 50-130mph, so this ball velocity was within the capabilities.

The standard gates had to be cut in order to fit into the machine, and the inflatable gates had to be folded slightly at the end with the clamp in order to fit, see Figure 2-6. For the standard gate, the ball impact was set a distance of 20in. from the base. For the inflatable gate, the ball impact was set a distance of 27in. from the base. An important note for this experimental setup is that the clamp at the top was designed to spin with the baseball bat after an impact. There was no way to restrain this, so in the tests some of the impact is absorbed by the machine hinge here rather than the gate hinge. The tests were performed in the same way however, so the measurements should still be usable in a comparative context.

A high speed video camera was arranged in front of the machine to collect slow motion footage. Table 2-1 summarizes the trials performed on both the standard gate and the inflatable gate, with the exception of the 60 PSI hit which was only done on the inflatable gate as the standard gate fractured at the 55 PSI hit.

\[ m_b = 0.145 \text{kg}, \quad m_{s,\text{eff}} = 2.62 \text{kg}, \quad \text{and} \quad v_s \approx 20 \text{mp} \text{h} \text{ for advanced slalom racers.} \]

Note: \( m_{s,\text{eff}} \) was approximated based off Lenetsky et al. work studying effective mass due to hits in Kung Fu. As this is a hit made by the arm at high speeds it is an appropriate comparative value.
<table>
<thead>
<tr>
<th>Pressure [PSI]</th>
<th>Avg. Ball Velocity [mph]</th>
<th>Number of Hits</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>55</td>
<td>25</td>
</tr>
<tr>
<td>35</td>
<td>70</td>
<td>25</td>
</tr>
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<td>115</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>120</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2-1: Pressure settings and associated ball velocity for cyclic testing of gates.
3. RESULTS

3.1 On-Snow Data Collection Results

The motivation for collecting on-snow data was to gain approximate values for impact force which could be recreated in a controlled environment. There are many difficulties with collecting physical data in an uncontrolled environment. In this case, issues specific to skiing such as limited time\textsuperscript{16}, snow surface quality\textsuperscript{17}, temperature, and associated equipment malfunction created large amounts of uncertainty in measurements. Of the four runs performed on the course, two yielded data reasonable to use for evaluation\textsuperscript{18}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{force_graph.png}
\caption{Force results from on-snow data collection.}
\end{figure}

Figure 3-1 shows the two runs that yielded effective hitting of the gates. The solid line is run six and the dotted line is run eight. The red zones are standard gates and the white is the inflatable section. Video of the runs was used to match the sensor impact with the appropriate gate type. As is clear from this graph, the time between gates decreases and force increases with time. This is because the skier accelerated through the course as they

\textsuperscript{16} Each run took \textasciitilde20min including chair lift time. Course setup took \textasciitilde30min. Additionally, due to fresh snow the course needed to be slipped several times in order to be skiable.

\textsuperscript{17} Snow Conditions for testing day (Jay Peak Ski Area, Jay, VT 4/9/16): \textasciitilde30-40°F, 11am-2pm, icy spring surface with 3-4in. of fresh powder covering, lightly snowing during testing

\textsuperscript{18} Other runs showed no peak forces, due to missing the sensor when hitting the gates.
progressed. Additionally, for run six there are three gates hit in a row because the skier used an inside hand clear.\textsuperscript{19}

Feedback from running the course introduced a new factor for evaluating gate performance. There was a noticeable “grab” previously not predicted from the inflatable gates. They tended to pull the arm into an unbalanced position when they impacted the arm. Although felt while skiing the course, this was even clearer post experiment by studying video of the runs.

As shown in Figure 3-2, the inflatable gate hinges wherever it is hit by the racer. By impacting the inflatable gate with the small surface area of the ski pole, the gate bends around the pole. The aftermath of this affect is shown in the image to the right where the sudden drag of the hand causes the skier to momentarily lose balance.

![Figure 3-2: “Grab effect” of hitting inflatable gate.](image)

Because of this added factor, impact duration was analyzed from the sensor data as well as force. Figure 3-3 shows how the force peaks in Figure 3-1 were used to approximate maximum impact force and impact time duration, Max. Force, and Delta T respectively.

\textsuperscript{19} Inside Hand Clear: Rather than cross-blocking, skier uses inside hand to block gate from hitting face. Usually used when gates are closer or when there is less time time between gates.
A plot of these results for all impact peaks in the trials for both the standard and inflatable gates is shown in Figure 3-4.

**Figure 3-3:** Method for analyzing on-snow data collection.

**Figure 3-4:** Force plotted against impact duration time, clustering of data points.
<table>
<thead>
<tr>
<th></th>
<th>Mean Max. Force [N]</th>
<th>Mean Delta T [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Gate</td>
<td>35.1 ± 24.1</td>
<td>0.045 ± 0.015</td>
</tr>
<tr>
<td>Inflatable Gate</td>
<td>56.2 ± 22.5</td>
<td>0.10 ± 0.019</td>
</tr>
</tbody>
</table>

Table 3-1: Mean values for both the standard and inflatable gates.

It is important to note the incredible amount of uncertainty in these values, ranging from 18-69%, due to the uncontrolled nature of the experiment. Although not enough to strongly prove anything, these results and clustering of data points prompt further investigation. Sections 2.2 and 2.3 describe the setups for two experiments that go into further detail and perform more rigorous experimentation on the factors of force and time highlighted by this experiment. The results are presented in Sections 3.2 and 3.3.

3.2 Controlled Impact Force Results

As detailed in Section 2.2, four different types of gates were impacted the same way with a pendulum and force sensor. Figure 3-5 shows the results from the experiment.

**Impact Force by Gate Type**

<table>
<thead>
<tr>
<th>Gate Type</th>
<th>Force [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30mm Diameter with Poly Cord Hinge</td>
<td></td>
</tr>
<tr>
<td>30mm Diameter with Metal Hinge</td>
<td></td>
</tr>
<tr>
<td>27mm Diameter with Poly Cord Hinge</td>
<td></td>
</tr>
<tr>
<td>27mm Diameter with Metal Hinge</td>
<td></td>
</tr>
<tr>
<td>Inflatable Gate</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3-5: Max. Impact force by gate type.
The results showed variation among the different standard gate configurations; however, there was no common factor influencing the differences. The 30mm diameter gates displayed greater impact force than the 27mm diameter with metal hinge, but less than that of 27mm diameter poly cord hinge. Grouping all the standard variations together and comparing with the inflatable gate is shown in Figure 3-6.

![Impact Force by Gate Type](image)

**Figure 3-6:** Impact force by gate type, clustering standard gates.

The mean impact force for the inflatable gates was $28.55 \pm 5.89$ N and the mean impact force across all standard gates was $44.55 \pm 7.12$ N. The impact force on the inflatable gates was lower when all other factors were controlled.

Future research in this area should explore the variation in impact forces for the different configurations of standard gates. By testing many more combinations with more trials, an optimal low force combination might be found. This could be compared with the inflatable gate to see if it is possible to achieve comparable low impact forces within the design of the standard gate.
3.3 Controlled Impact Time Results

To quantify the "grab" factor discovered in on-snow testing, slow motion videos taken using the setup described in Section 2.3 were analyzed. The footage allowed for more controlled study of the grabbing phenomenon with the inflatable gates.

Figure 3-7: Max. Standard gate during impact on the left, inflatable gate on the right. Note how the inflatable gate acts like a double hinge, bending around the impact point as well as at the base.

As described in Section 2.3, the critical value to quantify was the time to clear the skier's path. This was measured by analyzing the video with tracker software. The impact point and the tip of the gate were treated as point masses and tracked through time as shown in Figure 3-8.
Figure 3-8: Gate motion following impact being tracked in high speed video.

The y-values of the tracked points, with zero being the hinge point of the base, were output and used to calculate time to clear\textsuperscript{20}. This process was repeated for runs with both the inflatable and standard gates at different ball velocities. Table 3-2 summarizes the runs and velocities analyzed with this technique.

<table>
<thead>
<tr>
<th>Pressure [PSI]</th>
<th>Ball velocity [mph] - Standard Gate</th>
<th>Ball Velocity [mph] - Inflatable Gate</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>89</td>
<td>88</td>
</tr>
<tr>
<td>45</td>
<td>97</td>
<td>98</td>
</tr>
<tr>
<td>50</td>
<td>108</td>
<td>105</td>
</tr>
<tr>
<td>55</td>
<td>118</td>
<td>112</td>
</tr>
</tbody>
</table>

Table 3-2: Summarizes runs and velocities analyzed.

The y-positions over time for the impact point and the gate tip were plotted. A spline interpolation was used to estimate the amount of time from maximum distance from zero\textsuperscript{21} to zero. An example showing this on both the standard gate and the inflatable gate is shown in Figure 3-9 and Figure 3-10 respectively\textsuperscript{22}.

\textsuperscript{20} Gate swinging from 0-90° is equivalent to y-position going from max to zero.
\textsuperscript{21} Here this is maximum negative value due to way initial zero position was defined.
\textsuperscript{22} Note: a linear interpolation could have been used for the standard gates, but it was not an appropriate fit for the inflatable gates. Because of this a spline interpolation was used for all graphs for consistency.
Figure 3-9: Y-position over time for impact point and gate tip of standard gate, 97mph ball.

Figure 3-10: Y-position over time for impact point and gate tip of inflatable gate, 105mph ball.
These graphs are interesting because they show the more linear nature of the standard gates as opposed to the inflatable gates. The lag in the tip of the inflatable gate is clearer than that of the standard gate. The results from doing this analysis on all trials are shown in Figure 3-11.

**Times for Gate to Clear Skier Path**

<table>
<thead>
<tr>
<th></th>
<th>Inflatable Gate</th>
<th>Regular Gate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Point</td>
<td>Blue</td>
<td>Red</td>
</tr>
<tr>
<td>Gate Tip</td>
<td>Red</td>
<td>Red</td>
</tr>
</tbody>
</table>

0 0.2 0.4 0.6 0.8

Time to Clear Skier [s]

**Figure 3-11**: Results of measuring time to clear skier path.

The uncertainty for the regular gate is very large here because at 118mph the gate fractured. This meant that the time to clear was very fast. Removing this outlier yields the graph shown in Figure 3-12.

**Times for Gate to Clear Skier Path (With Outlier Removed)**

<table>
<thead>
<tr>
<th></th>
<th>Inflatable Gate</th>
<th>Regular Gate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impact Point</td>
<td>Blue</td>
<td>Red</td>
</tr>
<tr>
<td>Gate Tip</td>
<td>Red</td>
<td>Red</td>
</tr>
</tbody>
</table>

0 0.2 0.4 0.6 0.8

Time to Clear Skier

**Figure 3-12**: Results of measuring time to clear skier path with outlier removed.
The average time for the inflatable gate to clear the path, middle: 0.50 ± 0.09s tip: 0.63 ± 0.1s, was larger than the average time for the standard gate, middle: 0.47± 0.03s, tip: 0.43 ± 0.03s. The differences in the impact point time to clear were not statistically significant, but the differences in tip time were. This quantifies why the inflatable gates felt “grabbier” while skiing. The tip of the gate lagging in the skier’s path meant it was wrapping significantly around the arm.

More tests would need to be done to better quantify this time difference; specifically, multiple trials at the same velocity and with a range of impact sizes. The small area of impact creates a localized bending point. If hit with a larger area, such as the skier’s body rather than hand, then the gate may not wrap around as much. The sample set of data shown here gives reason to believe that the inflatable gates have a longer contact time with the skier, and a longer time to clear their path, both critical factors as change in momentum to the skier should be avoided. Change in momentum is also related to impact force and time. Even though the gates may have a lower force, if the time delay is longer then they will have a similar and possibly greater affect on the skier’s momentum.
4. CONCLUSION

Although gate design has improved over time, there are still issues and risks with the current models. Weight and general bulkiness are huge issues for setting courses in a timely manner, and the impact forces on slalom racers are fairly high, especially for beginner racers still mastering proper form. Because of this, a redesign such as inflatable gates could be an option that would lessen the forces and lighten the total weight of the gate. However, the current state of these inflatable gates has a few drawbacks. When hit with a small area, such as the ski pole or hand, they can bend locally and wrap around that area. This issue could be resolved by an adaptation in form in which the skier would ski through the gates with their chest or waist instead of using their hand. The impact is less for the inflatable gates, so there is low risk to injury, and the larger area would prevent the gate from bending too sharply.

Because changes in athlete form have a much larger impact on the tradition and authenticity of the sport, a design change to the inflatable gate may be a more practical option. If the inflatable gates were built with thin, semi-flexible, structural beams down their length, the sharp bend that grabs the skier could potentially be avoided and the gate would still have a relatively low impact force compared to the standard plastic flex poles.

Overall, more studies on ski gate design and impact is important. Little research exists for this aspect of ski racing, which is significant because skiing is a sport that relies so heavily on advances in equipment technology. Advances in race gate technology could do a great deal in making training more feasible and cheaper and thus potentially opening the sport to a larger range of participants.
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