A Thesis Presented to

The Faculty of Alfred University

The Physics of Skiing

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In Partial Fulfillment of

the Requirements for

The Alfred University Honors Program

May 14, 2014

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Abstract

The purposes of these three experiments were to predict and analyze the physics involved in ski racing. The first experiment was to test the effectiveness of an athlete wearing a speedsuit to reduce air resistance and increase acceleration. This was done by analyzing video data from three different scenarios to compute and compare their accelerations. The scenarios and their respective accelerations were: standing up, jacket on, - 5.973 ± 0.1409 $\frac{m}{s^2}$, tucking, jacket on, - 5.425 ± 0.1967 $\frac{m}{s^2}$, and tucking, jacket off, - 6.830 ± 0.2532 $\frac{m}{s^2}$. An effective value for the resistance coefficient was found with these values: $\mu_k = -0.358$. The second experiment was to calculate the tangential force on the ski of a racer making a carved turn and to show that a smaller angle between the skier's legs and the snow yields a larger force. Through freeze-framing a video, an image of the racer at the apex of the turn was analyzed along with the measured velocity of the skier. Two videos were analyzed, and one photo of a professional skier was analyzed for comparison. The first run by Rebecca Spitz was calculated to have a tangential force along the ski of 712.0 ± 2.4 N at an angle of 35°. The second run by the same athlete had a tangential force of 977.0 ± 1.09 N at 31°. The professional athlete chosen to compare to was Ted Ligety, and the tangential force along his ski was found to be 1890 ± 86 N at 22°. The third experiment was to calculate a pseudo spring constant for the ski that is representative of the stiffness of the core. The ski was allowed to oscillate, and the frequency was measured. The value for the stiffness was used to calculate the approximate restorative force of the bent ski. The value obtained for the stiffness constant s was $s = 5000\, kg/s^2$. The restoration force of the ski flexed to 0.04 m was $200 \pm 0.01N$.

Introduction

Physics governs everyone's life. From gravity to driving to the processing of food, we cannot escape physics. There is one activity, though, whose sole existence relies on the workings of gravity and water frozen into glide-on-able crystals. That activity is skiing. While all sports rely on physics, few come close to skiing in terms of their heavy dependence on its laws (e.g. luge, curling).

The research conducted and reported on in this paper intends to qualitatively predict and quantitatively measure the physics involved in ski racing. I chose to research this topic because I have been skiing my entire life, and ever since I took my first physics class in high school, I cannot separate physics from skiing. While I practice for my races, I often ponder the physical forces that affect every move I make. After taking a course in the subject of skiing and snowboarding in the spring of 2013 at Alfred University, I decided to pursue my own research into the physics of ski racing.

Associated with ski racing is a large range of terminology specific to the sport. I would like to introduce some of this vocabulary to make the interpretation of physics easier for non-skiers:

<u>Sidecut</u>: The depth of the curved edge measured at the waist of the ski (Lind, 2004). The extension of the sidecut into a circle determines the radius of the ski. There are different requirements for the sidecut of the ski for the different ski racing disciplines (i.e. slalom, giant slalom, etc.).

<u>Carving</u>: A ski is carving when the ski is (almost) 100% on its edge in the snow. Carving reduces the amount of snow sprayed during the turn.

Skidding: A ski is skidding when it is *not* 100% on edge. Part (or all) of the base is sliding on the snow, thereby increasing the amount of friction and spraying more snow.

Slalom: The event in ski racing that reaches the slowest maximum speed. It is characterized by short, quick turns and shorter skis.

Giant Slalom (GS): The even in ski racing that is a step faster than slalom. It is characterized by quick (but much larger) turns and longer skis.

Tucking: The body position assumed by a racer when they wish to maximize their speed (while sacrificing turning ability).

Angulation: The act of a skier creating an angle at their center of mass between their legs and torso that maximizes the edging of the ski and minimizes the angle their legs make with the snow. The angle with the snow, when known, can be used to calculate the force on the ski.

Small Angulation:

Figure 1 ***A recreational skier with almost no angulation***[4]

Large Angulation:

Figure 2 ***The professional skier Ted Ligety racing with a lot of angulation***[5]

<u>Fall line</u>: The line down the mountain that is the most direct path down the hill; the path of natural descent from one point on a slope to another.

<u>Speedsuit</u>: A one piece suit worn by ski racers to reduce drag. They are traditionally made entirely out of spandex.

<u>Apex</u>: The “peak” of the turn; the point on a carved turn that is the most circular. In racing the apex usually occurs just above the gate.

Before diving into the complex mechanics of the subject, I would like to first introduce an excellent diagram taken from a comprehensive text that is appropriately titled *The Physics of Skiing.* The image is of a skier going straight down the hill (or as Lind stated, “[d]irectly down the fall line”), with all of the forces acting on the skier labeled. In physics this is referred to as a “Free Body Diagram.” This image is a particularly useful introduction to this discussion because it lays the groundwork for all of the forces that will act on the skier once he/she strays from the fall line.

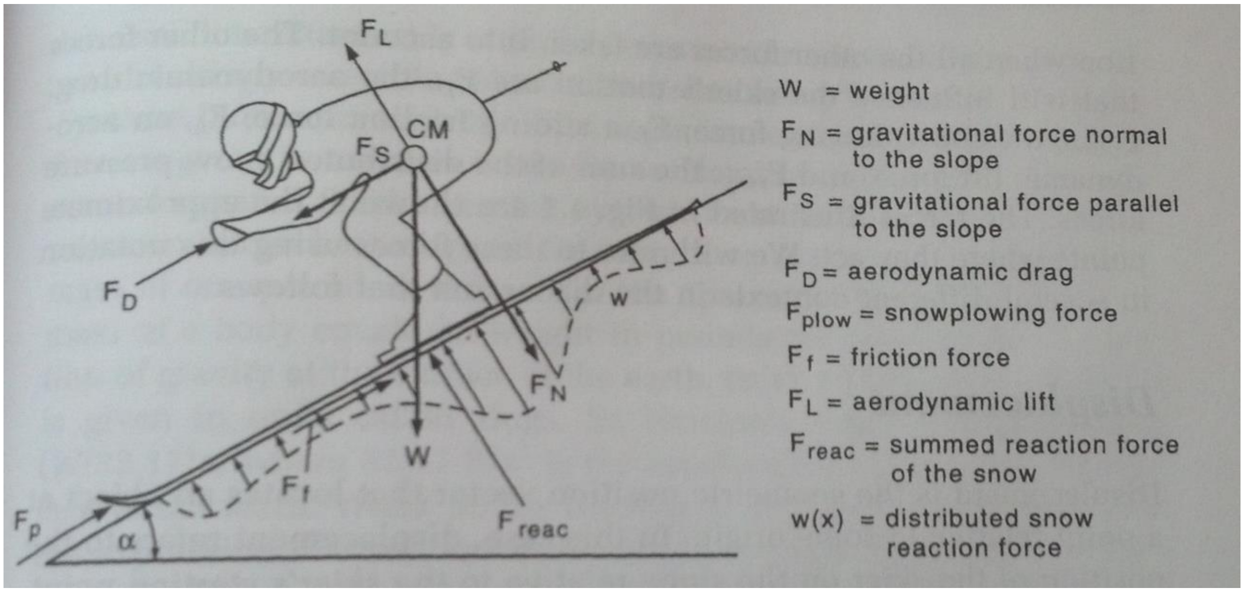


Figure 3 ***A skier descends down the fall line*** [7]

Figure 3 also illustrates a skiing body position known as the tuck, which is the very first dynamic of ski racing I would like to talk about. Tucking is an important tactic employed during GS, Super G and Downhill events. The racer attempts to position their body in a way that reduces drag while still being able to maneuver the ski. This greatly increases speed, which is vital for moving quickly on the less steep sections of the course. The figure also shows the forces associated with a tuck.

Besides the obvious affect of gravity pulling the racer down the hill, the aerodynamic drag force is one of the most important forces involved in the tuck. This force is one of the most influential in all of ski racing, and the design of much of the equipment can be attributed to overcoming its effect. Drag during a tuck is affected by a number of factors. The skier's arms create an "edge" that cuts through the air, thereby pushing the air away from the torso where it would produce drag. The skier also crouches low enough that their thighs do not increase the frontal surface area of the body.

The most important factor in reducing drag (while in or out of the tuck) is the clothing being worn by the racer. It is no surprise that a larger surface area of the object that is moving causes more drag (which is why F1 cars are low to the ground, or why sailing actually works). A racer wears a speedsuit to reduce their surface area as they descend. The speedsuit is skin tight, so there is no fabric available to catch the wind and cause the racer to slow down.

The other resistive force that racers have to overcome is the force of friction between the skis and the snow. Racers will use wax to reduce this force to a minimum, but it is ever present. Another free body diagram is shown in Figure 4:

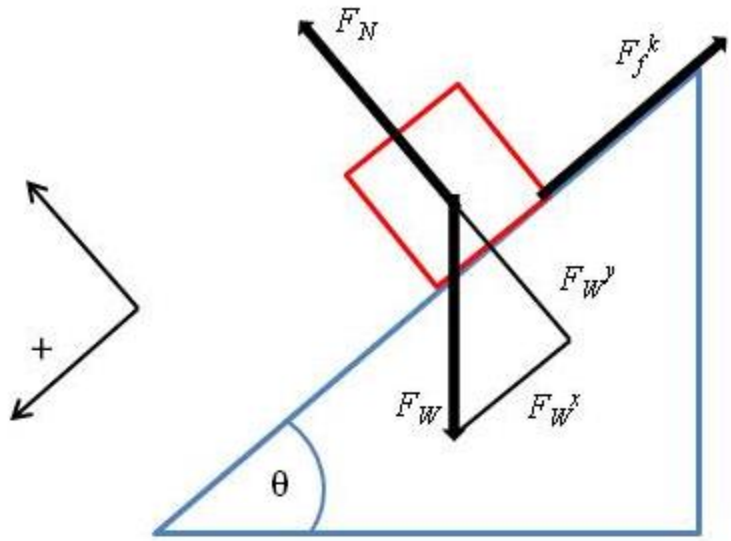


Figure 4

From basic principles, the coefficient of kinetic friction of a racer accelerating down the hill can be found:

$$F_{net} = ma_x$$

The net force in the x-direction is the force due to gravity on the skier and the negative force due to the effective friction on the snow:

$$F_W^x - F_f^x = ma_x$$

$$mg\sin(\theta) - F_f^x = ma_x$$

Theta here is the angle the slope makes with the horizontal (see Figure 4). Now we put in our equation for friction$F_f^x = \mu N$:

$$mg\sin(\theta) - \mu N = ma_x$$

Where *N* is the normal force and μ is the effective coefficient of kinetic friction. In this case, $N = mg\cos(\theta)$

$$mg\sin(\theta) - \mu mg\cos(\theta) = ma_x$$

Solving for μ we have

$$\mu = \tan(\theta) - \frac{a_x}{g}$$

One of the most noticeable differences between recreational skiing and ski racing is the type of turn that is made. Before explaining the effect of the position of the skier's body on the turn, it is easier to first look at the shape the ski makes during the turn (and consequently the track it leaves in the snow). The definitions of carving and skidding were briefly introduced earlier, but a more in-depth explanation is necessary.

When a recreational skier wishes to turn, they usually do not care about maximizing their speed. The skier is usually just having a good time, and isn't worried about the energy being wasted in the spray of snow. Perhaps they're even trying to control their speed on a steep slope.

The skidded turn, therefore, is common to most skiers. It is characterized by the ski *not* being in line with its velocity, so the angle the base (or bottom) of the ski makes with the snow is very small. This means that more of the base is in contact with the snow, hence the "skidding."

Snow, however, is not usually one frozen mass, so the surface of the slope reacts by spraying up snow. The spray is lost kinetic energy, causing the skier to slow down. Since racing is about optimizing speed, skidding is not advantageous to racers. Carving, then, is vital to ski racing success. Figure 5 shows a skidded turn and a carved turn placed side by side. It is also important to note that a skidded ski generally does not bend in the same way a carved ski does. This important concept will be discussed shortly.

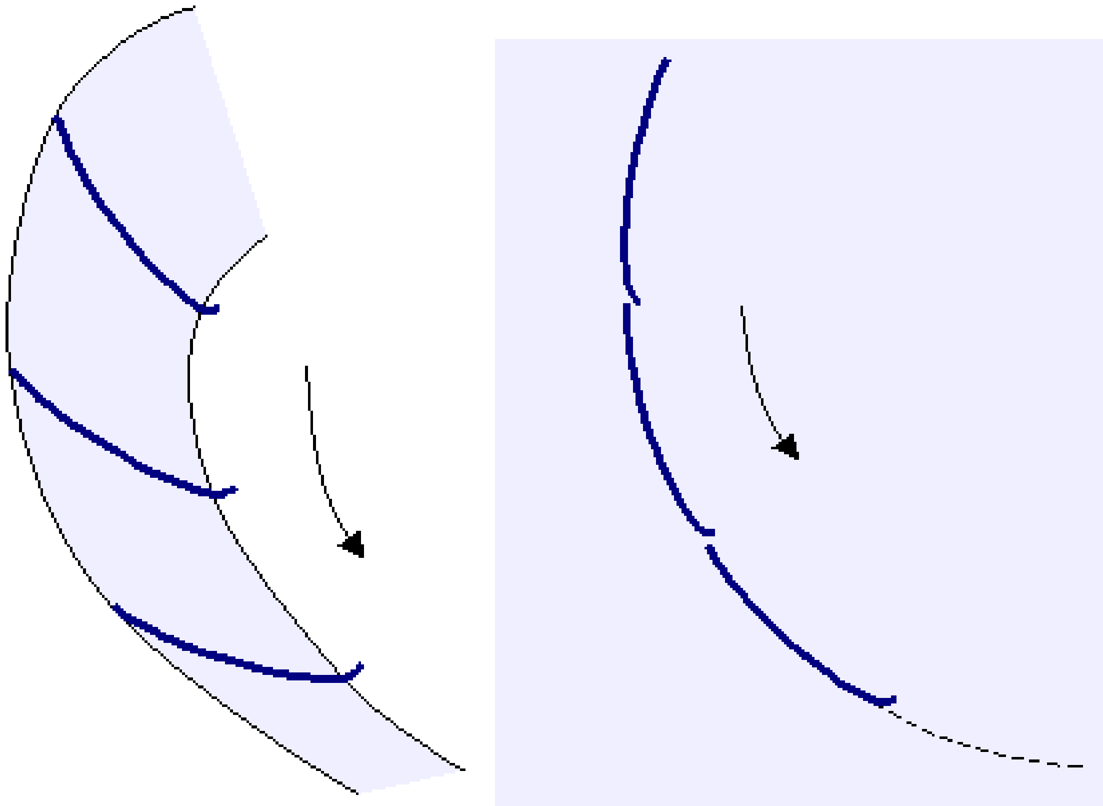


Figure 5 ***A ski (blue line) during a skidded turn (left) and a carved turn (right). In the image of the skidded turn, the light blue area is the snow that will be swept out of the way by the ski. The light blue in the carved turn does not indicate anything special; the ski will have minimal spray[1].***

Whereas the base of a ski in a skidded turn makes a small angle with the snow, the base of a ski in a well-carved turn makes a larger angle with the snow. This larger angle reduces the amount of contact the base has with the snow. The surface area affected by friction is greatly reduced. The edge, because it is so thin, does not spray nearly as much snow as the base of a skidding ski.

The mechanics of the carve are much more interesting than that of the skid and require a more in-depth discussion of the physics involved. A skidded turn is achievable through a variety of simple body positions, while the carved turn can only be achieved through the perfect balance of power and stability. It is helpful to start from the ground up with an analysis of the track of the carved turn in relation to the center of mass. A discussion on achieving the carve will come later.

A carved turn is ideally circular (as depicted in Figure 2). Since this is the case, there must be some other source of the shape besides the turn itself. A straight ski, when flexed (bent) into the hill, will only make a slight curved shape. However, if the ski were to be curved in some way, it would make a round imprint in the snow when it was flexed into the hill. The sidecut of a ski is the main proponent of carving.

From a geometrical point of view, the sidecut is classified in a way that makes it much easier to interpet. On a ski, the sidecut is actually the radius of the circle the ski could make. For example, the radius of my slalom skis is 12.5 m. This means that if I were to hold my ski on edge bending it as far as it would reasonably flex and let it make its own circle, the radius of this circle would be 12.5 meters. The sanctioning bodies for ski racing establish requirements for the radius of skis for the various ski racing disciplines.

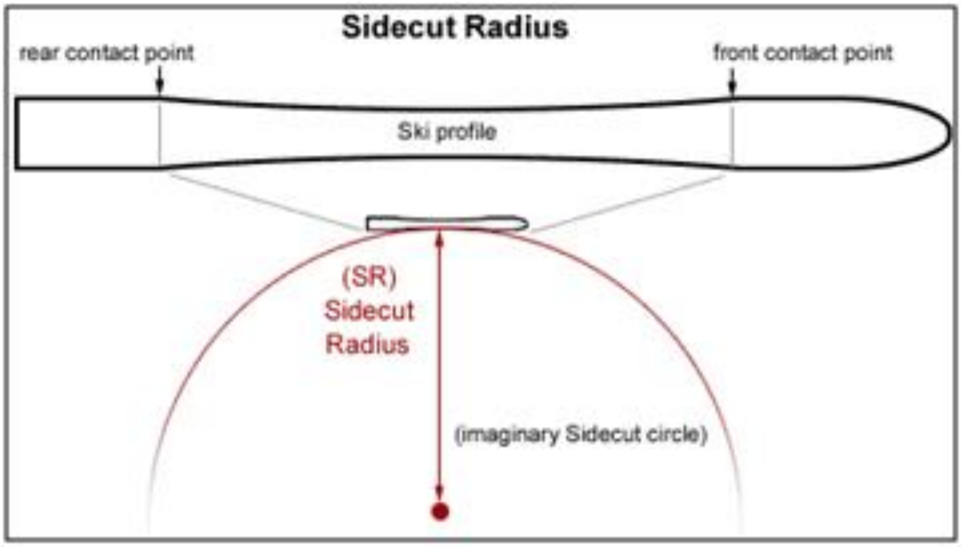


Figure 6 ***The sidecut of a ski and the projection of its "Imaginary Sidecut Circle[2]***

The body positioning required for near-perfect carving takes years to master. When watching a skier, a good indication of their ability to carve is their ability to angulate. Angulation is an all-encompassing term used to describe how small the angle is between the skier's legs and the snow. The smaller the angle (ironically this is called having "huge angles"), the larger the angle the ski makes with the snow, and the more it can flex. If the angle between the skier's legs and snow is too large, the ski cannot handle a lot of force. However, if a racer has extremely small angles, the ski can handle extreme forces. This is why the professionals are so low to the ground in their photos. They have the ability to reach extremely small angles, which helps compensate for their high speed and consequently high force on their ski.

Figure 7 ***Professional racer Didier Cuche at 15° during a downhill race***[3]

A skier making a carved turn can be modeled as a mass on a string. Therefore, I can use the same equations to calculate the force on the ski during the apex of the turn. This force is the tangential force. The derivation for the equation of the tangential force is presented below:

$$a_c = \frac{v^2}{r}$$

$$F_c = ma_c = \frac{mv^2}{r}$$

$$F_t = F_c \cos(\theta) = \frac{mv^2}{r} \cos(\theta)$$

Here, F_t is the tangential force, which is the force the skier exerts onto the skis. F_c is the centripetal force caused by the circular shape of the turn. As can be seen from the equation for force, an increase in the radius of the turn (r) causes a decrease in the force (F_t) on the ski. A decrease in the angle (θ) also causes an increase in the tangential force on the ski. Therefore a skier who is moving faster and is more angulated will have a larger force on the ski than a skier moving slower with little angulation.

How do the skis handle this force? Recreational skis are usually constructed with a softer wooden core. However, race skis usually are made with metal on the inside, increasing their stiffness. But what does this have to do with the force? The racer must be strong enough to bend the metal core race ski. If they cannot exert enough force, then they will not be able to properly carve the ski.

There is another implication to the bending of the ski. When watching slow motion shots of racers, one can observe that the ski wiggles up and down a bit, indicating it has the ability to oscillate. The ski can be (kind of) modeled as a mass on a spring. When the ski is flexed in the turn, it will have stored energy, just as a spring pulled past the equilibrium point does. As the skier exits the turn, the ski restores itself to a displacement of 0, and the stored energy is released. This force is the propelling force of the carved turn. In racing, this is known as the "pop." Controlling the pop can be difficult. If the ski restores itself and exerts a force that is stronger than the skier, or the skier does not have their center of mass in the right place, the ski can launch itself forward and leave the racer behind.

By calculating a pseudo-spring constant of the ski (which we will call the stiffness factor *s*), we can find the force the ski exerts on the racer. To find *s,* the oscillations of the ski are measured after being displaced a distance *x* by a mass *m.* Starting from basic principles,

$$k = s = \omega^2 m$$

$$F = -sx$$

$$F = -\omega^2 mx$$

where F is the restoration force of the ski.

Methodology

Before I begin to describe the methodology, I should go over the equipment and software that was employed during data collection. The majority of the data collected was done using an iPod Touch. An iPod Touch has an accelerometer inside. By using an app called Sensor Data[8], I was able to connect to the accelerometer and collect information from it. The application provides information on acceleration in all 3 directions, roll, pitch and yaw.

In addition to Sensor Data, I used a program called *Video Physics*[9]. This program has the capability of taking a video of a moving object and then later calculating its acceleration. The program requires the user to place an object of known length somewhere in the frame so that the program can scale properly. This will be explained in more detail below. A normal cell phone camera was used for various other experiments.

<u>Are speedsuits effective?</u>

Two people were needed for this experiment: one cameraman and one skier wearing a speedsuit underneath their jacket. A section of the hill was chosen that has a consistent slope angle for about 10 meters. The angle of the hill was measured at the point where it appeared to be most consistent.

Once both participants were ready, the Video Physics app was launched. Before recording a new video, the person with the camera chose a spot on the hill that is far enough away from the path the skier will take so that they can be sure to get the whole sequence in the frame without rotating their body. The skier being recorded placed a ski pole in the frame with a known length. This enabled the Video Physics app to scale the resulting video.

With the camera being held steady in position, the person with the camera instructed the skier to move so she was just out of the video frame. She should position the camera so that is perpendicular to the hill. In other words, the iPod body should be parallel to the movement of the skier, and should not be facing up or down the hill. The skier was recorded going down the hill until she completely exited the frame. This was done three times for three scenarios: standing up with jacket on, tucking with jacket on, and tucking with just a speedsuit. The same section of the hill was used each time to ensure the angle of the slope and snow conditions were consistent.

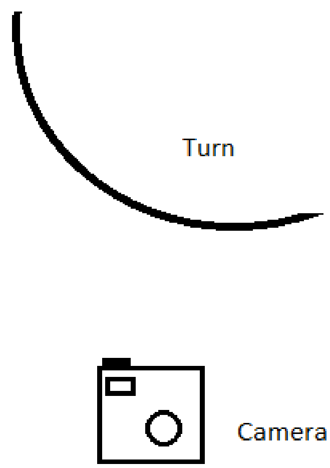
In-course and during-skiing accelerometer use

Using the Sensor Data program was quite easy. First I opened the program and made sure that it was ready to take data. Since the iPod must be placed under clothing, I had to start taking data before I was skiing. After the collection had started, I carefully placed the iPod as close to my center of mass as I could, making sure it was vertical. Immediately before I began my descent, I jumped quickly. This created a spike in the data to alert me of where the data actually starts. As soon as I was done skiing, I stopped and jumped again to create another spike.

The data is output in a .csv (comma separated value) file. The file must be retrieved through iTunes. Once this has been done, the data can be imported into a program like Microsoft Excel for analysis.

The Big Turn

This experiment required two people as well. A section of the hill was chosen that had a steep to medium pitch that transitions into a very flat section. The big turn will occur on the flat section. With the skier at the top of the pitch, the cameraman was positioned on the flat, looking up the hill, so that the skier has enough room to make one large turn. The cameraman began the video and signaled to the skier they were ready to film. The skier then began the iPod data collection with Sensor Data. The skier tried to get as much speed on the steep section of the hill by going straight down the fall line. They would then make one turn immediately in front of the camera. This turn should (as well as the skier can) be 100% carved, with maximum pressure on the ski and attempting to maximizing their angulation. A rudimentary diagram is presented below:



Once the turn had been completed, both the data collection and the video recording were stopped.

Measuring the Oscillations of the Ski

To measure the oscillations of the ski, I placed each end of my slalom ski on two tables that were spread apart. The distance they were apart from each other was such that only a small length of the ski was on the table. The ends of the skis were not clamped down for this experiment because a ski changes its length considerably when it is bent, and clamping it greatly hindered its ability to flex. To measure the displacement I attached a yardstick to a vertical stand behind the ski. Before measuring any displacement or oscillations, the initial displacement of the ski relative to the yardstick must be recorded.

Before measuring oscillations, I hung various weights off of the ski to see how much mass it takes to get it to flex to the point where it would in a turn. After this was done, I prepared to measure the oscillations. I first taped the iPod with Sensor Data onto the middle of the ski where the ski boot would be. I then put a metal rod through the loop that holds the hanging weight. The hanging weight was placed on the side of the loop closest to my hand. When the rod is dropped, the weight will slide off, allowing the ski to oscillate. To collect the oscillation data, I dropped the rod immediately after beginning data collection with Sensor Data, and only stop collection when the ski is not visibly oscillating anymore.

Results and Analysis

Are Speedsuits Effective?

For this experiment, three different videos were taken with Video Physics: skiing down with a jacket on and not tucking, skiing while wearing a jacket and tucking, and skiing without a jacking while tucking. The goal is to show that wearing a speedsuit does indeed decrease the amount of drag on the skier, thus increasing their overall acceleration.

The Video Physics files were uploaded to a computer and analyzed in Logger Pro. This program (designed by the same team that built Video Physics) can analyze the displacement, velocity and acceleration of a moving object in a video. The figure below is a screenshot of what the file window looks like during analysis:

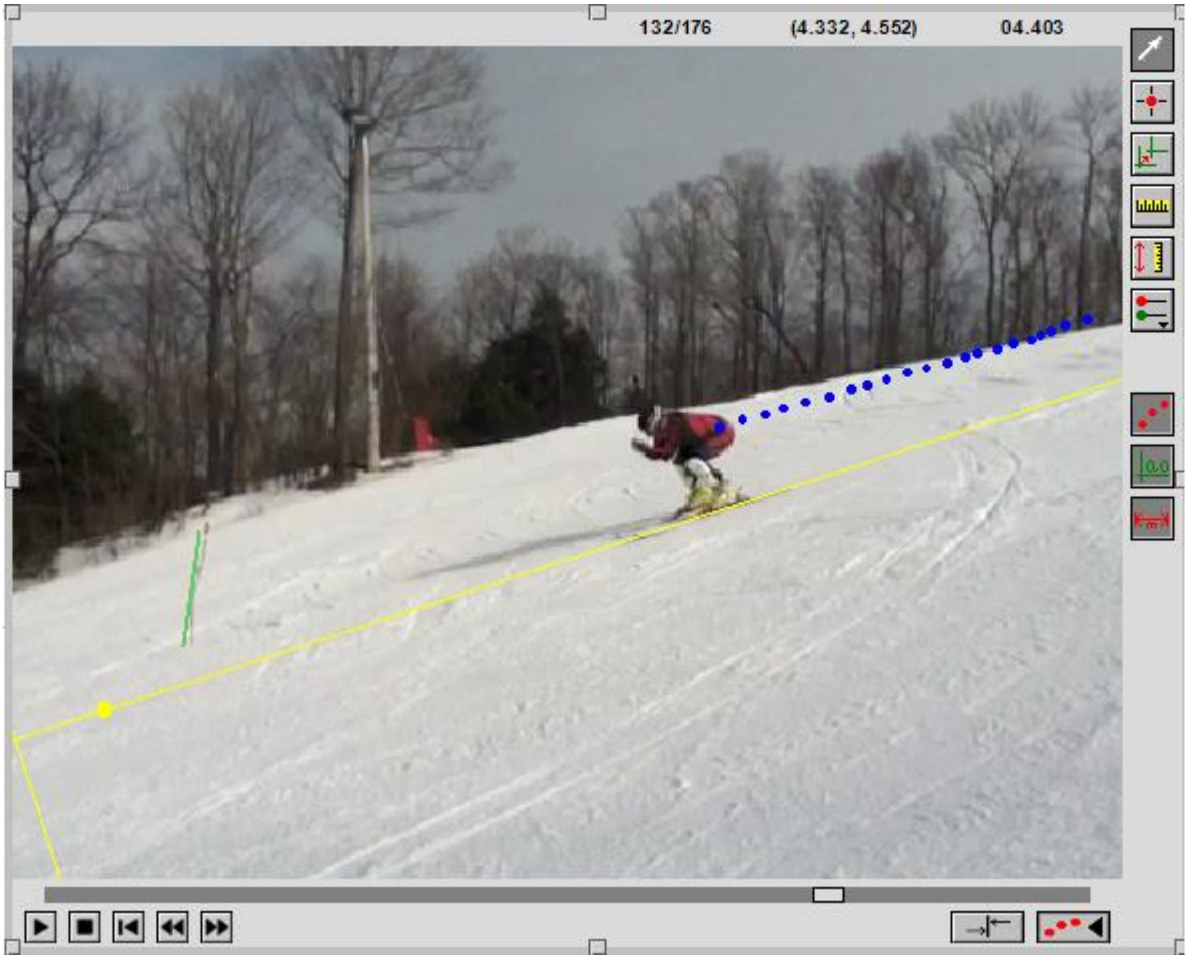


Figure 8 ***The video analysis window from Logger Pro. It is apparent here that the video camera was not perfectly aligned with hill because the skier's right foot appears to be in front of the left. The skier's right leg should appear to be completely blocked by the left.***

In this image, the yellow line is the coordinate axis defined by the user. It is rotated because we only want the acceleration in one direction. The green line is a line drawn to match the length of the pole. The user must input the actual length of the pole, which the program uses to scale the distances in the video. The blue dots are how the program tracks the movement in the video; they are put in manually, frame by frame, on the same spot of the skier each time.

The program produces a graph of the location of the skier versus the time passed by tracking the increasing distance between the dots. A linear equation of the form $y = mx + b$ is then fit to the graph. This equation is analogous to one of the kinematics equations for one dimensional motion: $v = v_0 + at$. By inspection, we see that the value of the slope m is the acceleration of the skier.

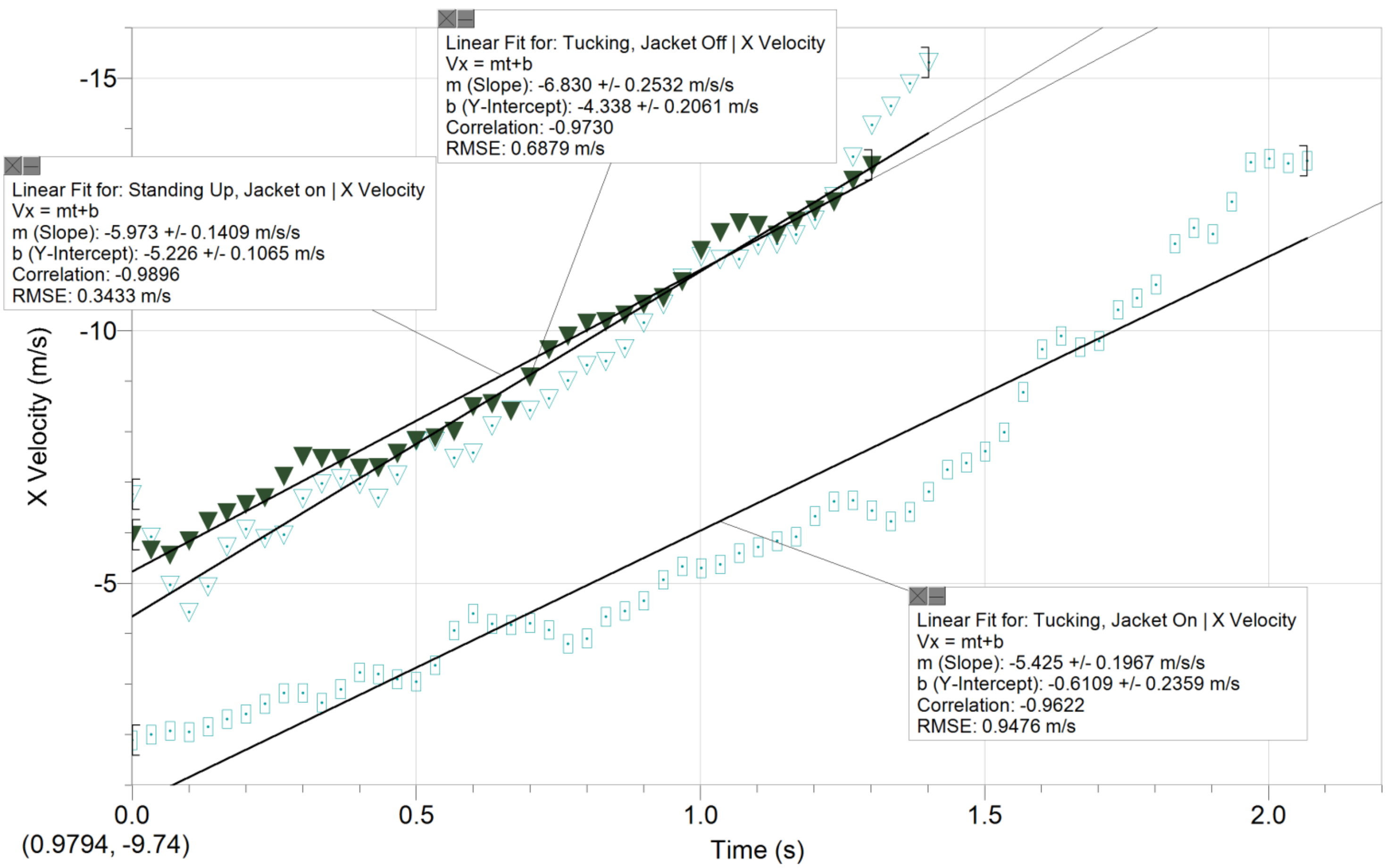


Figure 9

	Standing Up, Jacket On	Tucking, Jacket On	Tucking, Jacket Off
Acceleration	- 5.973 ± 0.1409 $\frac{m}{s^2}$	- 5.425 ± 0.1967 $\frac{m}{s^2}$	- 6.830 ± 0.2532 $\frac{m}{s^2}$

The values for the acceleration are negative because of the way the coordinate axes were defined. Although this is true, it does not change the fact that the acceleration of the skier tucking without a jacket is much larger than the accelerations of the other two scenarios. The implication is that a racer will ski significantly faster whilst wearing a speedsuit.

It is odd that the acceleration for the skier while tucking and wearing a jacket is smaller than that of the skier standing and wearing a jacket. The discrepancy with the values may be due to the fact that the "Standing, Jacket On" video was accidentally taken on a slightly different part of the hill.

Although this is true for these values, the accelerations found are actually impossible. The maximum value the acceleration could have been on this slope is given by:

$$a = g\sin(\theta) = (9.8\ m/s^2)\sin(21.5°) = 3.59\ m/s^2$$

So what went wrong? After further analyzing the video data, it was discovered that the camera was not oriented properly with respect to the skier. This would cause the scale of the video to change as the skier descended down the hill. This could have been prevented by placing markers at consistent intervals down the slope. The individual taking the video should also be sure that the lens is parallel to the path the skier will take down the hill.

Effective/Total Resistance

Using the acceleration calculated for the tucking skier wearing a speedsuit, we can calculate the effective coefficient of kinetic friction for the snow on this slope. This is not the true coefficient of kinetic friction because the value contains the air resistance. We will also be neglecting the surface area of the ski, which under these circumstances affects the frictional force on the ski.

Unfortunately the accelerations calculated are much larger than expected, which will cause the coefficient to be negative. For simplicity, we will flip the sign of the calculated acceleration so that is in the direction of movement. From basic principles, we have

$$\mu_k = \frac{\sin(\theta)}{\cos(\theta)} - \frac{a_x}{g\cos(\theta)}$$

Using our value for a_x, the angle of the hill θ = 21.5°, and g = 9.8 m/s^2, we have:

$$\mu_k = \frac{\sin(21.5°)}{\cos(21.5°)} - \frac{6.856\ m/s^2}{9.8\ m/s^2(\cos(21.5°))} = -0.358$$

Since this was caused by the definition of the coordinate axes, the negative sign can be ignored, and the coefficient is μ_k = 0.358. The typical values for wet snow (which were the conditions on the data of data collection) are between μ_k = 0.30 and μ_k = 0.60.

The Big Turn

Due to some technical difficulties with the iPod, I was not able to use the data I collected this season for this experiment. The iPod did not collect the velocity data necessary to calculate the tangential force along the ski. I will instead reference data collected in 2013 when I took "The Physics of Skiing" with Dr. David De Graff.

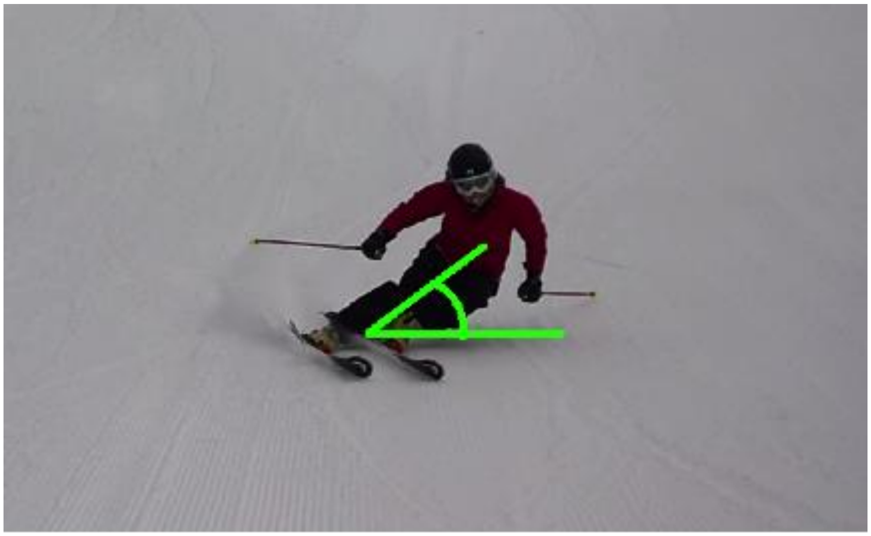


Figure 10 ***Rebecca Spitz, 35°. Angle measured with protractor held to screen***

Mass of Skier (Boots and Clothing Included)	Ski Radius	Max Speed (at apex of turn)	Angle Relative to Snow
77.482 kg	12.5 m	9.70 m/s	35°

To calculate the tangential force along the ski, we use the equation derived for tangential force:

$$F_t = \frac{mv^2}{r\cos(\theta)} = \frac{(77.482)(9.70)^2}{12.5\cos(35)} = 712.0\ \pm 2.4\text{ N}$$

To calculate the g-force here, we use:

$$\frac{a_c}{a_g} = \frac{v^2/r}{g} = \frac{(9.7)^2/12.5}{(9.8)} = 0.77\ \pm 0.1g$$

Figure 11 ***Rebecca Spitz, 31°. Angle measured with protractor held to screen***

Mass of Skier (Boots and Clothing Included)	Ski Radius	Max Speed (at apex of turn)	Angle Relative to Snow
77.482 kg	12.5 m	11.623 m/s	31°

$$F_t = \frac{mv^2}{r\cos(\theta)} = \frac{(77.482)(11.623)^2}{12.5\cos(31)} = 977.0 \pm 1.09 \text{ N}$$

$$\frac{a_c}{a_g} = \frac{v^2/r}{g} = \frac{(11.623)^2/12.5}{(9.8)} = 1.1 \pm 0.1g$$

Figure 12 ***Ted Ligety, 22°.***

Mass of Skier (Boots and Clothing Included)	Ski Radius	Max Speed (at apex of turn)	Angle Relative to Snow
91 kg	45 m	29.44 m/s	22°

$$F_t = \frac{mv^2}{r\cos(\theta)} = \frac{(91)(29.44)^2}{45\cos(22)} = 1890\ \pm 86\ \mathrm{N}$$

$$\frac{a_c}{a_g} = \frac{v^2/r}{g} = \frac{(29.44)^2/45}{(9.8)} = 1.97\ \pm 0.1\ g$$

Athlete	Tangential Force	g-force on the athlete
Rebecca, run 1	712.0 ± 2.4 N	$0.77 \pm 0.1\ g$
Rebecca, run 2	977.0 ± 1.09 N	$1.1 \pm 0.1\ g$
Ted Ligety	1890 ± 863	$1.97 \pm 0.1\ g$

As expected, the tangential force on the ski is higher for a racer traveling at a faster speed and angulating at a steeper angle. The professional racer Ted Ligety was used as a reference to show an extreme. The photo is of him skiing in the discipline known as downhill, which is characterized by extremely high speeds. The force he is exerting on his ski is double that of what I could accomplish. In the next section we will discuss the implication of being capable of exerting a large force on the race ski.

Finding a Value Related to the Stiffness of the Ski

The Sensor Data application collects data on the acceleration in three directions. When attached to the ski, the up and down movement of the ski is represented by the acceleration in the z-direction. For our purposes, the acceleration in the z-direction and the time were extracted from the data. Each peak is an oscillation of the ski, so counting the number of peaks per second yields the frequency of oscillation for the ski. The graph of the acceleration in the z-direction of the oscillating ski is presented in Figure 15.

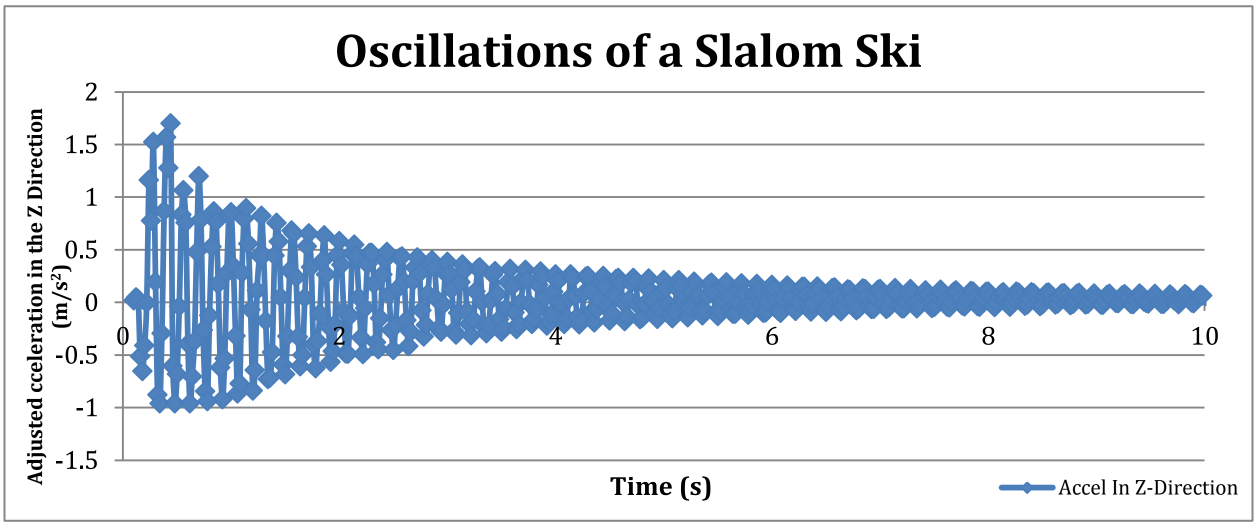


Figure 13 ***Note: The adjusted acceleration values on the y-axis are the true acceleration values divided by the value of g. The values have also been adjusted so that the oscillations are from zero.***

By inspection we see that the ski has some odd oscillations in the beginning. This was due to the ski bouncing a little bit on the table since it was not clamped down. After the bouncing ends, the ski behaves like a normal damped oscillator. The data collection was stopped before the ski finished oscillating. If it had not been stopped, I believe the ski would keep oscillating for a very long time.

The equation being used is that for calculating the spring constant, *k*. The value is not a true spring constant, though, so we will call it *s* (stiffness). The mass, then, is going to be 1/3 of the mass of the ski, which is the reduced mass[10].

The time between two and four seconds has the best sample of oscillations. This is where the peaks were counted. The frequency of oscillation of the ski was found to be 8 Hz. A race ski (with bindings) weights about 6 kg, so 1/3 of that is 2 kg. With this information, we have:

$$s = \omega^2 m = \left((8\,Hz)(2\pi)\right)^2 (2\,kg) = 5000\,kg/s^2$$

From this value, we can calculate the restoring force of the ski when it is bent during a carved turn. Increasing amounts of weight were hung off of the ski until it was approximately bent to where it would be during a carved turn. The deflection at that point is 0.04 *m*. Using our equation for the restoring force, $F = -kx$, and using our *s* instead of *k*, we get

$$F = \left(-5000\ {}^{kg}/_{s^2}\right)(0.04m) = 200\ \pm 0.01N$$

A skier with less strength can only bend the ski a certain amount. However, a strong skier can really bend (displace) the ski in the turn, which increases the restoring force of the ski. From the “big turn” data, we can easily see how Ted Ligety can put almost twice as much force on his skis as I can. Since he can displace his ski more than I can, the restoring force is much greater, and so he will accelerate faster at the end of the turn.

Discussion

There were a number of limitations with this experiment. I would like to discuss these, as well as offer advice for anyone who wishes to replicate these experiments in the future. I would also like to discuss other areas of research I am considering pursuing, and to discuss the implications of the data I have collected here and the data I will collect.

If these experiments were to be done again, there are a number of suggestions I have for the individual. All of the data should be taken on the same day, preferably a cloudy one. Because of the effect the sun has on the snow, the snow conditions could change throughout the day, thus changing the coefficient of kinetic friction. In addition, a slope should be used that has a more consistent pitch.

Ideally, a semi-professional racer should be used in these experiments. I am a good racer, but I cannot always carve perfectly. I did not have anyone who was significantly stronger than me to take data with. In addition, I think having a male racer to compare to would be interesting. The skis they must use during races have a different radius, so it would be interesting to see how different the calculations are when skiing on the same slope.

One of the most important aspects of ski racing that was not experimented on here was the use of wax. The wax on a ski makes the base glide better on snow of different temperatures. This is because the small amount of friction from the snow partially melts some of it. The wax improves how the ski interacts with this layer of water. It would be intriguing to test waxes on different snow conditions, as well as different waxes on the same snow.

An additional experiment could be to find the stiffness constant for a number of different skis. Since all skis are different, one could test a number of different brands of race skis. The values for *k* could also be found for Slalom, Giant Slalom, Super G, and Downhill skis. Recreational skis could be tested too to show how much stiffer race skis really are.

The stiffness constant experiment may have an application in the skiing world. Because the stiffness of skis really impacts how the skier performs, I think this test could be perfected so that business and athletes alike could have a standardized way to test the flexibility of their skis. Since skis become broken in over time, this could also be a test to see if the ski needs replacing.

I believe the experiments done here may be useful for coaches in analyzing their athletes further. For those individuals who learn quantitatively rather than qualitatively, these experiments could help show them how they have improved from the beginning to the end of the season. The Big Turn experiment could be used as a tool to promote fitness and test abilities. I plan on coaching ski racing in the future, and I look forward to discussing my experiments with my athletes. I am hoping to be able to implement them (and other experiments) into our training regime.

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