Analyzing the Mechanics of Women's Roller Derby
to Engage Introductory Physics Students

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Abstract

We describe some basic NYSED Regent's level physics examples taken from women's flat track roller derby. Women's roller derby is a relevant, fresh and appealing example for teaching introductory physics which we claim is particularly motivating for young women in which to situate the study of kinematics, circular motion and friction. Using data collected from an author's roller derby personal experiences we will show how topics from the NYSED Regents physics curriculum can be explored and illustrated. Sample questions for students are appended.

Introduction

Angell, Guttersrud and Henriksen (2004) found that female students, consider physics to be one of their most difficult subjects. They also report that physics students find developing a sound understanding of physics concepts to be both essential and difficult. This perceived complexity of physics topics by students is a good reason for physics educators to strive to showcase physics principles in new and interesting situations that can increase engagement for all students. Hatch and Smith (2004) report the use of (traditionally male) sports examples in physics showed positive student responses. Hence, we suggest women's flat-track roller derby as a fast paced, hard hitting, all-women's sport sometimes touted as being one of the fastest growing sports in America.

Since modern flat track roller derby reentered the public sports scene in 2001 there has been little physics literature written on the topic. However, Etkina (1998) reports using rollerblades to introduce basic kinematics to her students and then extending their practical kinesthetic knowledge into the more complicated areas of curvilinear and circular motion, inertia and centripetal force. Student interviews allowed her to record the positive effects the rollerblading activity had on her students. After Etkina's rollerblading unit, her students claimed to "see physics everywhere."

The NY State Education Department's Regents Physical Setting / Physics Core Curriculum (http://www.p12.nysed.gov/ciai/mst/pub/phycoresci.pdf) and the new New York State Science Learning Standards (http://www.nysed.gov/curriculum-instruction/2016-adoptedscience-learning-standards) require students to collect, represent, tabulate and interpret motion data, perform kinematics calculations determining velocity and acceleration, determine coefficients of friction, analyze interactions between objects, analyze forces via free body diagrams and use Newton's laws to determine motion. This topic is also interdisciplinary in that physical education, physiology (biology) and mathematics are also involved.

Methods Measuring Speeds and Distances

Introductory mechanics physics concepts can be illustrated by questions about women's roller derby behavior like **"How fast do we skate?" "How hard do we turn?"** and **"How fast can we stop?"** Determining typical measurements for derby phenomena forced the authors to conduct many experiments. To make measurements repeatable for students and teachers on a budget, almost all data were collected using stopwatches and the chart of the standard track with path lengths in Figure 1. According to WFTDA, the circumference of the inside line measures 148.5 ft (45.26m) and the circular crossover path is 178 ft (54.25m). Our stopwatch calculated speeds were verified using an inexpensive toy RADAR gun well known to the physics teaching community, the $69.99 Hot Wheels Radar Gun (http://service.mattel.com/instruction_sheets/j2358-0920.pdf) taking RADAR data at the end of straightaways, pointing the gun at the skater's chest.

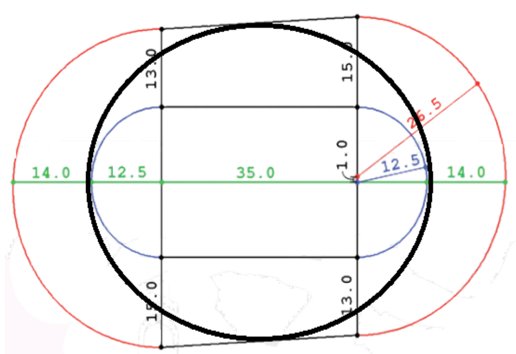


Figure 1. This image shows the dimensions of the Regulation track of the Women's Flat Track Roller Derby Association (wtdfa.com), all dimensions are in feet. The thick black line shows a circular path skated for speed measurements. Retrieved from *rules.wtdfa.com/* with author modifications.

How fast do they go? Determining typical speeds for two most common skating styles: Crossovers vs. Sculling

In roller derby, skaters are always accelerating or decelerating. Skaters generally accelerate by pushing against the floor with their skates, and the track pushes them back in their direction of acceleration. Skaters use a combination of crossovers and sculling to gain and maintain speed. Crossovers are when the skater picks up her outside foot to step over the inside foot to push herself toward the center of the track. Sculling is when the skater keeps all eight wheels on the track and uses a sideways pushing motion to propel herself forward (Figures 2, 3 & 4).

Figure 2. Stance. Toxin Dioxin skates low and centered. (Photo: Robert Krzaczek).

Figure 3. Crossovers. JoJo Thrasher using crossovers. (Photo: Robert Krzaczek).

Figure 4. Sculling. Karmalized sculling around the track. (Photo: Robert Krzaczek)

Using both the stopwatch and the radar gun, we first measured typical speeds of skater TaTa while sculling and crossing over (See Table 1).

	Crossovers	**Sculling**
Δt avg (sec)	10.6 sec	11.3sec

Table 1. Stopwatch Lap Times, same skater but two different paths and techniques. When using crossovers, TaTa naturally followed a circular path throughout (see Fig 2) and when sculling she followed the inside line of the track.

These data allow us to compare the two styles of skating. At first glance, the similarity in the times for each lap could lead one to believe that there is little difference between the two skating styles. However, TaTa naturally follows two different paths when using these two different skating styles. In the first trial, using constant crossovers, she naturally followed a circular path as she skated on the inside line at the turns and toward the outside line on the straightaways. In the second trial, TaTa was hugging the inside line as she sculled around the track (See Table 2).

	As Calculated from Stopwatch & Figure		**As Measured by Hot Wheels Radar Gun**	
	crossovers	**sculling**	**Crossovers**	**Sculling**
Average Speed	5.1 m/s	4 m/s	5.4 m/s	4.4 m/s

Table 2. When following the shorter path and sculling, TaTa's average speed was slower when using crossovers and following a longer path. The radar gun shows a similar comparison (though instantaneously higher due to faster than average velocity during the straightaway) between sculling and crossovers. ***5.4 m/s is about 12 mph.***

How hard do we turn? Finding Skaters' Centripetal Acceleration and the minimum associated frictional force

Knowing speed and turning radius, we can find the centripetal acceleration and the coefficient of friction for skaters. To find the centripetal acceleration and coefficient of friction for a skater using crossovers along a circular path we first draw a Free Body Diagram (FBD) for the skater.

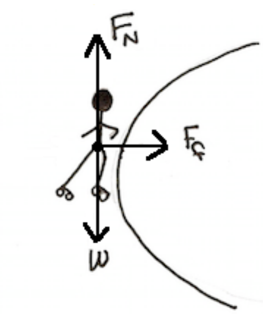


Figure 5. FBD with forces acting on a skater as she skates around the track.

To find the centripetal acceleration we must first find the radius of the circular path the skater was traversing. From Figure 1 we find the radius to be 30 feet or 9.14 meters. The velocity we use here was for the faster crossover skater.

$$a_c = \frac{v^2}{r}$$
$$a_c = \frac{(5.4m/s)^2}{9.14m}$$
$$a_c = 3.2m/s^2$$

3.2 m/s^2 is just under ***1/3g*** acceleration (compare to 0.75*g* – 0.95*g* cornering acceleration for most passenger cars and light trucks). Using the acceleration and the skater's mass, we can find the minimal radial (towards the center) force that friction must supply to provide this smooth centripetal acceleration around the curve.

$$\Sigma F_x = ma_c = F_f$$
$$F_f = ma_c$$
$$F_f = 77.1kg * 3.2m/s^2$$
$$F_f = 247N$$

To find the normal force provided by the surface of the track we also need the skater's weight, also determined from their mass of 77.1kg.

$$\Sigma F_y = ma = 0 = w * F_N$$
$$\therefore w = F_N$$
$$\therefore mg = F_N$$
$$77.1kg * 9.8m/s^2 = F_N$$
$$F_N = 755.58N$$

Finally, we can calculate the minimal (the skater could also be tangentially accelerating as well) coefficient of friction through a constant speed turn using the normal force and the force of friction. Also note that here we are simply providing reasonable figures for sample calculations via the Regent's Physics introductory model of friction; real world friction is quite more complex than the introductory Amontons-Coloumb model <https://en.wikipedia.org/wiki/Friction>.

$$F_f = \mu_f F_N$$
$$247N = \mu_f * 755.58N$$
$$\mu_f = 0.33$$

	Skater mass (m)	Normal force (F_N)	Average velocity (v)	Radius (r)	Centripetal acceleration (a_c)	Force of friction (F_f)	Coefficient of friction (μ_f)
Units	kg	N	m/s	m	m/s^2	N	
Crossovers	77.1	755.58	5.4	9.14	***3.2***	***247***	***0.33***
Sculling	77.1	755.58	4.4	9.14	***2.1***	***163***	***0.22***

Table 3. Data and calculations for skater centripetal acceleration and coefficient of friction for crossover and sculling. Passenger vehicle tires typically achieve $0.40 < \mu_f < 0.70$; Retrieved from *http://hyperphysics.phy-astr.gsu.edu*

These forces and accelerations are minimum values; we have modeled the path as a smooth circular path at unchanging speed and radius. Adding any nonzero tangential acceleration will increase these accelerations and frictional forces.

Inertia: Falling and the trajectories of skaters leaving circular motion

Falling skaters are standard fare at a derby 'bout and observing their paths provides a perfect opportunity to see inertia demonstrations. Since a fallen skater has insufficient friction to keep accelerating towards the center of the track, she will tangentially slide to the edge and even off the track. This is because she no longer generates sufficient centripetal force pushing her towards the center of the track to maintain her circular path. Since the direction of angular velocity is tangential to the circular trajectory the skater was traveling on, students can have fun predicting which spectators will get hit by a flying derby girl after she falls and slides into the crowd.

Figure 6. A fallen skater sliding off the track on both knees (the "rock star" fall) (Photo: Robert Krzaczek).

In Figure 6, the skater in red is at the mercy of her own inertia as she slides away from the track. However, the skater in blue, Wolf Blitzkreig, is still on her skates and can shift her center of mass and push hard enough to maintain enough angular acceleration to stay on or hold the track. This is similar to the traditional classroom physics demonstration horizontally whirling a ball tied to a string around a teacher's head and then cutting the string to watch the ball fly off tangentially. In the roller derby example, the ball is akin to the red skater and the force of friction provided by wheels is analogous to the string. Once a skater is no longer up and skating she flies off in the direction of her velocity just prior to her fall. This is a good place to compare the trajectories of the skater's slide after a fall when she falls on the curved portion of the track versus the straight portion of the track.

How fast do we stop? The Controlled fall: One knee vs. two knee (rock star) falls

Figure 7. Susan B. Agony, performing a one-knee fall (Photo: Robert Krzaczek).

Figure 8. Scarlett Bloodletter, performing a two-knee "rock star" fall (Photo: Amanda Dolan).

Studying controlled falls and stops in roller derby provide a good example of friction bringing an object in motion to a halt. By recording the stopping time and stopping distance and using basic kinematics we can compare the acceleration for various falls and intentional stops. Shockin' Audrey demonstrated two controlled falls (Figures 7 and 8) three times each with recorded stopping distance and time. A stopwatch was used to record the time it took her to slide to a complete stop after she hit the floor. The skate floor was constructed of one by one foot plastic tiles which were counted to find an approximate stopping distance once Shockin' had come to a complete stop.

	Time (seconds)		**Distance (meters)**	
	One-Knee Fall	Two-Knee Fall	One-Knee Fall	Two-Knee Fall
Average of 3 trials	7.7	2.6	4.2	1.6

Table 4. Observed distance and time for Shockin' Audrey to come to a complete stop while performing a one-knee and a two-knee fall as well as how far that skater slides after making contact with the floor.

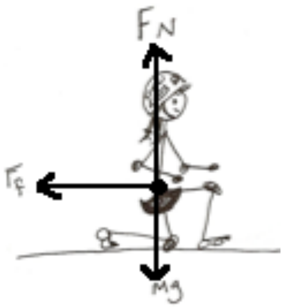


Figure 9. A traditional simplified Free Body Diagram (FBD) for a one knee fall, re-locating all forces at the CM of the skater.

Experienced physics teachers will note that given the above stopping distance and time data, taken together with final stopped velocities of 0 m/s and the (traditional introductory physics) ***approximation*** of constant acceleration, we can already model, formulate and calculate answers to the standard NYSED Regents physics one dimensional kinematics problems.

Here our simple one-dimensional solution model ***further assumes*** that the forces all act on a single point, setting all forces on the skater's center of mass, ***ignoring*** the fact the skater is an extended object whose center of mass is actually offset from the points of contact with the floor, where the normal force and frictional forces are actually applied. This simplified model is traditional and initially taught in this fashion with FBDs; later physics often extends the model offsetting the forces upon extended bodies to examine rotation, stability and tipping - sometimes later during rotational dynamics in Regents Physics, and certainly for more advanced AP or IB physics courses.

More Stopping Techniques –Controlled Stopping Without Falling: The Toe, T-, Plow and Tomahawk stops

Skaters also have (preferred) controlled methods for stopping at their disposal. We recorded and analyzed the stopping times and distance for four of these techniques illustrated in Figures 10-13. Shockin' Audrey and author Farrah Daze Rage collected sample data for these four different kinds of controlled stops, repeated three times each.

	Time (seconds)					Distance (meters)				
	Toe Stop Audrey	T-Stop Audrey	Plow Stop Audrey	Plow Stop Rage	Tomahawk Audrey	Toe Stop Audrey	T-Stop Audrey	Plow Stop Audrey	Plow Stop Rage	Tomahawk Audrey
Average of three repeated measures	3.77	2.48	2.87	1.62	1.16	9.65	5.89	7.62	4.62	2.95

Table 5. Comparing Four Methods of Stopping. Observation data show how long it takes for a skater to come to a complete stop as well as how far that skater slides after initiating the stop.

Figure 10. The Toe Stop. JoJo Thrasher (#800, center) drags her toe-stop, changing speed to dodge an incoming (left) blocker. (Photo: Robert Krzaczek).

Figure 11. T-Stop. Camraderay (#24 on the right), performs a T-stop. (Photo: Robert Krzaczek).

The phrase **"toe stop"** describes both the technique and the braking pad on the front of the roller skates. The basic method of performing a **toe stop** is to extend one skate behind the other, dragging the toe stop (breaking pad) of a skate on the floor (see Figure 10). The harder the skater pushes the toe stop into the ground, the quicker she will slow down. Toe stops (pads) are made from many different materials, and in different shapes. Sin City Skates, a popular site for buying roller derby equipment, sells fourteen different types (shapes and materials) of toe stops. Like a car brake pad, the toe stop material abrades away every time it is used; this wear and tear changes the toe stop shape and contact area and affects stopping ability. Finally, the skater's technique also influences the effectiveness of stopping.

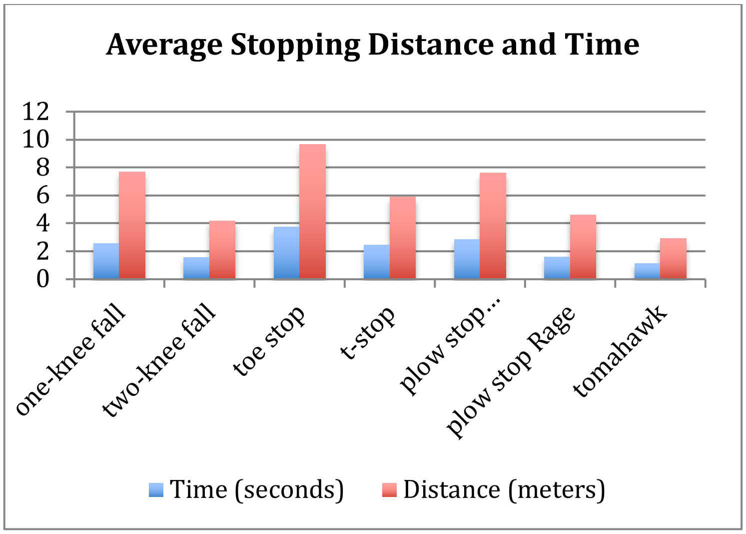
The **T-stop** (Figure 11) is a common method for stopping in crowded jams (confined spaces) since it allows the skater to keep her legs close together. To execute this stop, the skater must place one of her skates perpendicular to the rolling skate (usually direction of travel). The stopping power from the t-stop comes from the skater pushing the wheels of the perpendicular skate down on the floor (which will also abrade the wheels). The T-stop brings the skater to a stop about one second faster and in almost half the distance compared to using the toe stop. As with the toe stop, there is a materials aspect to the T-stop -- the wear condition and composition of the wheels are important. More than forty different types (shapes and materials) of wheels are available for sale.

Figure 12. Plow stops. Jacky Spades (#8, far right) and Poplockndropya (#32, center) are plow stopping to slow opposing jammer, GWAR (with gold helmet cover), (Photo: Robert Krzaczek).

Figure 13. A Tomahawk Stop by JoJo Thrasher (#800, on left). Both skaters are moving towards the left. (Photo: Robert Krzaczek).

The **plow stop** is more than just a method of stopping; it is also used for positionally blocking other skaters. To execute a plow stop the skater must skate with a wide, low stance, bending at her knees (similar to a skier's snow plow stance). She pushes the innermost wheels of each skate into the floor while turning her toes in. This causes her to slow down quickly and, depending on her stance, can also act as a barrier on the track, impeding skaters who hope to move past her. The low stance also helps with impacts with other players - think risky vehicle driving "brake check" behavior.

The **Tomahawk stop** is one of the fastest controlled stops on skates (and fastest in this paper). In contrast to the plow stop, the tomahawk does not require the skater to spread out on the track, so this stop can be executed in tight packs without fear of tripping other skaters. The tomahawk is also one of the most difficult stops for a skater to learn. To do a tomahawk stop the skater must first transition from skating forward to skating backwards. The skater will lean forward, in the direction opposite to her direction of motion, with her weight on her toes. Then she lifts up off her heels and rear wheels to stand on both of her toe stops (forming a Tomahawk shape with her body). Without any wheels rolling and only two toe stops dragging under her, the skater skids to a stop very quickly.



Graph 1. Comparing raw data: Average stopping distance and time for all falls and stops described in this paper.

Simple Mechanics of Initial Velocities, Accelerations and Friction Coefficients for Falling and Stopping

We here find the Normal force, initial velocity, average acceleration, force of friction and the coefficient of friction for each falling and stopping method described.

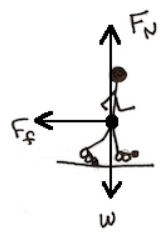


Figure 14. Free Body Diagram of Skater Stopping with a Toe Stop (she drags her toe stop to come to a halt).

For example, let's examine stopping by the toe stop. We have learned that a skater with a mass of 77.1kg comes to a full stop using her toe stop in 9.65m and 3.71s. Starting, we will draw a free body diagram of a skater coming to a halt (Figure 14). To find the skater's weight, we first need the skater's mass, which here is 77.1kg.

$$w = mg$$
$$w = 77.1kg * 9.8\frac{m}{s^2}$$
$$w = 756N$$

We know that the sum of the forces in the y-axis must be zero by applying Newton's second law: because while stopping the skater is not accelerating vertically in the y-direction (see FBD in Figure 14). Hence the Normal force and weight must vectorially sum to zero due to Newton's second law for the y-direction. Here the skaters' weight and Normal force are equal in magnitude but opposite in direction.

$$F_y = 0 = F_N + (-w)$$
$$F_N = w$$
$$w = 756N$$

Next, we will determine the skaters' initial velocity commencing the stop, then their average acceleration and finally the force of friction necessary to provide that constant acceleration. We have learned that a skater with a mass of 77.1kg comes to a full stop using her toe stop in 9.65m and 3.71s.

First, we will find the initial velocity. Since the final (stopped) velocity is 0m/s the initial velocity can be calculated in two steps. We can do that by first calculating the average velocity assuming constant acceleration (common in introductory mechanics) and using the definition of average velocity. Hence, initial velocity is just average velocity doubled:

$$\bar{v} = \frac{v_f + v_i}{2}$$
$$2.6\, m/s = \frac{0 + v_i}{2}$$
$$v_i = 5.2\, m/s$$

Once we have the initial velocity we can find the (again, assumed constant) acceleration (negative means opposite the displacement and initial velocity):

$$a = \frac{\Delta v}{t} = \frac{v_f - v_i}{t}$$
$$a = \frac{0m/s - 5.2m/s}{3.7s}$$
$$a = -1.4m/s^2$$

Using this acceleration we can find the force of friction that is causing the skater to slow to a stop (here negative means opposite in direction to total displacement and initial velocity):

$$\Sigma F_x = F_f = ma$$
$$F_f = ma$$
$$F_f = 77.1kg\ 8\ (-1.4m/s^2)$$
$$F_f = -106N$$

Finally, we can calculate the (standard Regents simplified Amontons-Coloumb model) coefficient of friction using the normal force and the force of friction:

$$F_f = \mu_f * F_N$$
$$106N = \mu_f * 755.58N$$
$$\mu_f = 0.14$$

For each calculation, we can check by comparison to reasonable figures discussed earlier in this paper, and verify correct units. Repeating the above calculations for an average of three attempts for each stopping time and distance, we can calculate all of the above values for each stopping and falling scenario described:

Kind of Roller Derby falls or stops	**Time (sec)**	**Distance (m)**	**Mass (kg)**	**Normal force (N)**	**Average Velocity (m/s)**	**Final velocity (m/s)**	**Initial Velocity (m/s)**	**Acceleration (m/s^2)**	**Force of friction (N)**	**Coefficient of friction**
One Knee (avg of 3)	**7.73**	**4.20**	**77.1**	**756**	**0.55**	**0.00**	**1.09**	**-0.143**	**11.0**	**0.015**
Two Knee (avg of 3)	**2.66**	**1.55**	**77.1**	**756**	**0.59**	**0.00**	**1.17**	**-0.442**	**34.1**	**0.045**
Toe Stop (avg of 3)	**3.77**	**9.55**	**77.1**	**756**	**2.54**	**0.00**	**5.07**	**-1.349**	**104.0**	**0.138**
T-Stop (avg of 3)	**2.48**	**5.90**	**77.1**	**756**	**2.39**	**0.00**	**4.77**	**-1.932**	**149.0**	**0.197**
Plow - Audrey (avg of 3)	**2.87**	**7.62**	**77.1**	**756**	**2.65**	**0.00**	**5.30**	**-1.848**	**142.5**	**0.189**
Plow - Rage (avg of 3)	**1.62**	**4.62**	**72.6**	**711**	**2.85**	**0.00**	**5.71**	**-3.549**	**257.7**	**0.362**
Tommie (avg of 3)	**1.16**	**2.94**	**77.1**	**756**	**2.56**	**0.00**	**5.12**	**-4.535**	**349.7**	**0.463**

Table 6: Using average of three measurements of time and distance for each fall and stop, plus skater's mass to calculate the Normal force, average and initial velocity, (assumed) constant acceleration, force of friction and coefficient of friction for each.

Conclusion

We believe that using real-world observed phenomena is a fun way to practice introductory physics, and using physics insight to re-interpret our marvelous world is also fun and empowering. Physical sports are broadly entertaining, and have been shown as appropriate for engaging our students, including some who are generally academically disinterested in physics.

Women's Flat Track Roller Derby provides an authentic, entertaining and whimsical way to practice often boring kinematics and mechanics conceptual reasoning and numeric problem solving using approximately valid physical numbers with simplified, approachable Regent's physics models and concepts in a uniquely female-centric and woman-friendly setting that can engage all of our students. Given Women's Derby is a fast-paced crowd-engaging sport, all physics students can enjoy a little adrenalin and spectacle, reinforce their newly learned physics content by applying it to a new context, and learn about a unique sport and community. Physics is the goal, empowerment and respect are the bonuses. And hopefully all will have a little fun.

About the Authors

Amanda Dolan, born and raised in Rochester, NY, graduated from the State University of NY at Buffalo with a B.A. in Physics in 2003. In 2009 Amanda joined Roc City Roller Derby and donned the pseudonym Farrah Daze Rage. Thinking about physics as she skated came so naturally she decided to focus on roller derby as her 2014 M.S.Ed. PHY690 masters project. Amanda currently runs a daycare out of her home while she works with a colleague to start a new public school in Rochester, NY. She would also like to thank Roc City Roller Derby and all its members for their assistance in this research.

Dan MacIsaac is an Associate Professor at Buffalo State Physics who coordinates the graduate physics teacher preparation programs. He has been inline skating only once while visiting Professor Eugenia Etkina of Rutgers University.

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Author Dolan, alias Farrah Daze Rage (sic. Faraday's Cage)
#49, Lead Jammer, doing what she loves (Photo: Robert Krzaczek).

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Appendix A. A Brief Introduction to Roller Derby

"Wayne Gretzky said: "Skate to where the puck is headed, not to where it's been"...except of course, in our case the "puck" is the opposing jammer, or a blocker we're trying to control...and it has a mind of its own. Roller derby is so much better than hockey." - Resident Eva (Roc City Roller Derby)

Author Dolan often speaks with people who are unaware of the recent resurgence of roller derby, yet many people remember roller derby's initial incarnation. With banked tracks, high speeds, minimal safety equipment and skaters with strong personae it is difficult to forget the roller derby created and promoted by Leo Seltzer in the 1930s. Barbee and Cohen's book, Down and Derby (2010) delves into roller derby's roots and how the 1970s gas crisis and the increased theatrical nature of the roller derby caused the sport's popularity to wane. Fortunately, in 2001 a group of people in Texas gathered to begin roller derby's meteoric comeback. Joulwan, founder of the Texas Rollergirls, chronicled the resurgence of roller derby in her book, Roller Girl (2007.)

These days the most common form of roller derby is played on a flat track and is regulated by the Women's Flat Track Derby Association (WFTDA.) Rules for the sport can be found at wftda.com/rules. Two thirty-minute halves are divided into an indeterminate number of "jams" which can last up to two minutes each. At the start of each jam eight blockers, four from each team, line up together forming "the pack." One jammer from each team starts behind the pack and earns one point for each opposing skater they pass legally and inbounds. Throughout the jam, the blockers are positioning themselves to help their jammer and stop the opposing team's jammer with a variety of hits, blocks and assists. After the jam ends, the skaters leave the track and each team has 30 seconds to get a fresh lineup of skaters out for the next jam.

Brenda "Skater Bater" Delano wrote a short and concise article for *American Fitness* (2010) explaining the basics of roller derby. A first time fan will most likely find roller derby very confusing, but with Delano's breakdown of the sport, any fan can get up to speed in just a few minutes. Delano describes the basic rules and game-play of the sport, as well as the intense effort skaters must put forth in training.

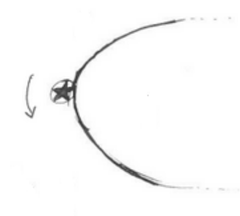
Appendix B. Sample Roller Derby Physics Questions

1. A 65-kilogram roller derby skater skates around the track in a horizontal circle with a radius of 9 meters. The skater maintains a constant speed of 5 meters per second.

A. Calculate the magnitude of the centripetal acceleration of the skater.

Answer: $a_c = 2.8\ m/s^2$

B. On the diagram below, draw an arrow showing the direction of the centripetal force acting on the skater when she is at the position shown.



2. Calculate the time required for a 200-Newton net force to bring a 70-kilogram skater initially traveling at 5 meters per second to a full stop (at constant acceleration).

Answer: t = 1.75s

3. A roller derby skater weighs 750 newtons. The skater races around a cement track, crossing over the whole time. The coefficient of friction is 0.3.

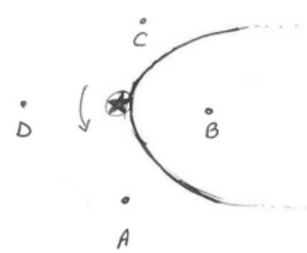
A. Determine the magnitude of the normal force exerted by the cement floor on the skater's wheels as the skater skates across the horizontal surface.

Answer: $F_N = 750N$

B Calculate the magnitude of the force of friction acting on the wheels as the skater skates across the horizontal, cement surface.

Answer: $F_f = 225N$

4. The diagram below shows a skater, represented with a star, skating counter-clockwise at a constant speed around a horizontal track.



At the instant shown, the centripetal force acting on the skater is directed toward which lettered point?

Answer: B

5. A 60-kilogram roller derby skater skates around the track following a circular path during a bout. The radius of her path is 9 meters. She completes 3 laps in 30 seconds.

A. Determine the speed of the skater.

Answer: v = 5.65m/s

B. Calculate the magnitude of the centripetal force on the skater.

Answer: $F_c = 210N$