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Major Connection Report

Cross, R., & Lindsey, C. (2018). The Slap Shot in ice hockey. *The Physics Teacher*, *56*(1), 7–9. https://doi.org/10.1119/1.5018677

In the 2018 article, *The Slap Shot in Ice Hockey,* Cross and Lindsey discuss and examine the physics of an ice hockey player's slap shot. They presumed that no energy will be added to the stick if the total energy is just kinetic energy, and when a player is preforming a slap shot when the stick hits the ice, kinetic energy will be less than if the stick just hits the puck without touching the ice. (Cross and Lindsey, 2018). Therefore, if the stick doesn't touch the ice, then the contact from the stick alone will make the puck reach a high optimal speed. For the procedure, a meter stick was on a pendulum and set a brass puck on a smooth wood surface. The experiments using this set up tested a puck's speed when the stick touched the wooden surface before the puck and the stick just hitting the puck. A camera with motion tracking analyzing software was used to test the speeds of the hands, stick, and puck if the stick encounters the wood surface or not while also measuring the time of impact with the surface, initial impact with the puck, and when the stick isn't in contact with the puck (Cross & Lindsey, 2018).

Cross and Lindsey found that when a hockey player takes a slap shot their stick must touch the surface and bend to storing conserve elastic energy before hitting the puck to ensure the puck can reach a high optimal speed, but when the stick did not come in contact with the wooden surface elastic energy was not involved conserved causing the puck to have a slower optimal speed(2018). This means to ensure a high maximum puck speed the stick much touch the surface before coming in contact with the puck because not only does it conserve elastic energy it gives evidence of transferring momentum due to the bending of the stick.

In this article, Cross and Lindsey discussed topics such as frictional and net forces, elastic energy, momentum, and speed versus time. It was awesome to see the topics I have been learning in class not only in the real world, but in a sport, I love! This article does a great job with describing the setup of the experiment and their results are clearly established through their graphic figures 1,2, and 3. Even thought they did great work with making their results easy to understand. Their procedure was confusing because they focused on their main experiment, but then also veered and talked about "additional experiments". This only made the article a bit confusing because Cross and Lindsey focused on the "main experiment" and it seemed to just be an add on. Also, they didn't include how many times they ran each experiment which could cause error since there isn't a huge sampling of results. good point

This article relates to my major of Exercise Science because not only does it involve physics, but biomechanics as well. Cross and Lindsey looked at the motion of the slap shot and broke down basically each instance within the motion as well to figure out how forces and placement effect how fast the puck is hit. This concept plays part of Exercise Science because this article is studying the way the body moves and how it effects an athlete's performance. Also, this article relates to my major of Exercise Science because they also study body positioning such as where the hand is placed on the stick which causes the stick to either slow down abruptly or more gradually. It is interesting to see how sports and physics can be related! I never thought how physics could have played into what I study as an exercise major.

well done
5/5

The Physics Teacher

The Slap Shot in Ice Hockey

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The Slap Shot in Ice Hockey

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An ice hockey player can strike a puck at speeds up to about 45 m/s (100 mph) using a technique known as the slap shot. There is nothing unusual about the speed, since golf balls, tennis balls, and baseballs can also be projected at that speed or even higher.[1] The unusual part is that the player strikes the ice before striking the puck, causing the stick to slow down and to bend. If a tennis player or a golfer did something like that, by hitting the ground before hitting the ball, it would be classed as a miss-hit and the ball would probably dribble away at low speed. Nevertheless, there appears to be a significant advantage in hitting the ice before hitting the puck, otherwise hockey players would have learned from experience not to do that.

It is commonly claimed[2,3] that the elastic energy stored in a bent stick more than makes up for the loss in kinetic energy when the stick slows down. That may be so, but at first sight there appears to be a violation of energy conservation. Suppose that a player swings the stick rapidly, and just before impacting the ice the kinetic energy of the stick is E. In most collisions of this sort, the impact duration is so short that nothing can be done during the collision to affect the outcome. If the kinetic energy decreases by S joules when the stick hits the ice, then the bending energy stored in the stick will be less than S since friction losses are involved.

The maximum energy that can be given to the puck is therefore E if the player hits the puck directly, and something less than E if the player hits the ice before hitting the puck. At least, that is the case if the total available energy is E and no energy is added to the stick during the collision with the ice or the puck. Even if there is no friction loss on the ice, some of the bending energy will be retained by the stick and will then be lost as a result of vibration of the stick after the puck leaves the stick. Vibration of a striking implement in any ball impact sport tends to lower the outgoing ball speed, which is partly why players prefer to strike the ball at the sweet spot of the implement. A sweet spot impact minimizes vibration and therefore reduces the stinging sensation in the hands.

In order to investigate the physics of the problem, the authors set up a simple experiment using a flexible meterstick to simulate a real hockey stick and mounted it as a pendulum so it could swing about an axis near the top end. The stick was pushed forward by hand so that the bottom end could strike a small 50-g, 25-mm diameter brass puck, as indicated in Fig. 1. The stick was held in a clamp and could be raised or lowered a few millimeters in the clamp so that the stick could either strike the puck directly or first strike a smooth, horizontal wood platform underneath the pendulum before striking the puck. In the latter case, a firm push on the stick was needed in order for the stick to strike the puck without sliding to a stop on the platform.

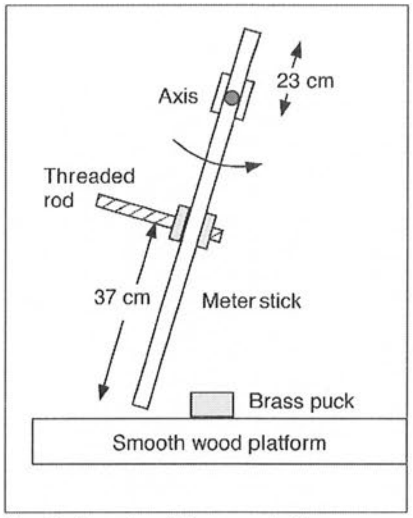

Fig. 1. A meterstick mounted as a pendulum to simulate a hockey stick. It was swung by hand by holding and pushing the threaded rod.

The arrangement shown in Fig. 1 could be used in a student laboratory since it takes up minimal space and since the impact speed is relatively small when pushing a meterstick through a small distance. Similar results were obtained when striking the brass puck with a one-foot long steel ruler and swinging the ruler by hand without mounting it as a pendulum. It would not be practical to swing a real hockey stick at high speed in a student lab. There is scope for additional student projects with the apparatus in Fig. 1, for example to study the effects of varying ice friction or stick flexibility or initial impact point on the ice.

Somewhat to our surprise, it was found that the puck was launched at a higher speed when the stick first struck the platform. Conservation of energy was not violated since stick bending and the recovery of stored elastic energy took place over a relatively long time, allowing the hand to add energy to the stick during the collision with the platform, and again during the collision with the puck. The total impact duration was about 100 ms, or about 100 times longer than the impact between a golf club and a golf ball, and about 20 times longer than the impact between a racquet and a tennis ball.

Modern tennis racquets and ice hockey sticks are constructed as hollow graphite tubes with similar transverse dimensions, but hockey sticks are slightly more than twice as long and are typically about 120 g heavier (about 420 g compared with 300 g for a racquet). As a result, hockey sticks are about nine times more flexible since the bending stiffness of a beam is inversely proportional to the cube of the beam length. The significance of this result is that the lowest vibration frequency of a hockey stick is about 10-15 Hz, depending on the location of the bottom hand, whereas the lowest vibration frequency of a handheld tennis racquet is about 150 Hz. A hockey stick therefore bends back and forth very slowly compared with a tennis racquet, allowing a hockey player to add energy to the stick during the impact with the ice and the puck.

The lowest frequency vibration mode of a

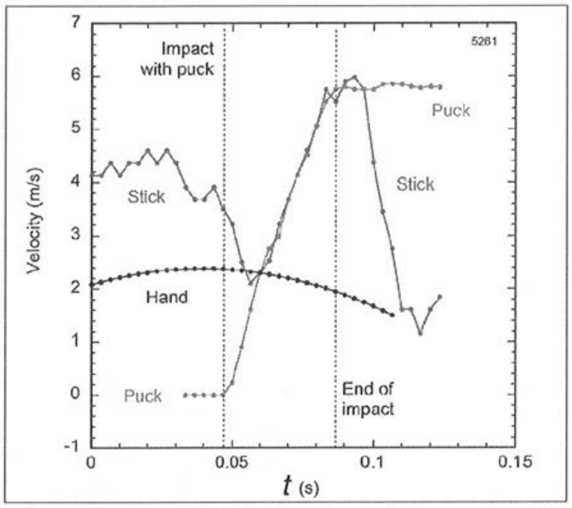

Fig. 2. Velocity of the hand, the stick, and the puck when the stick struck the puck directly.

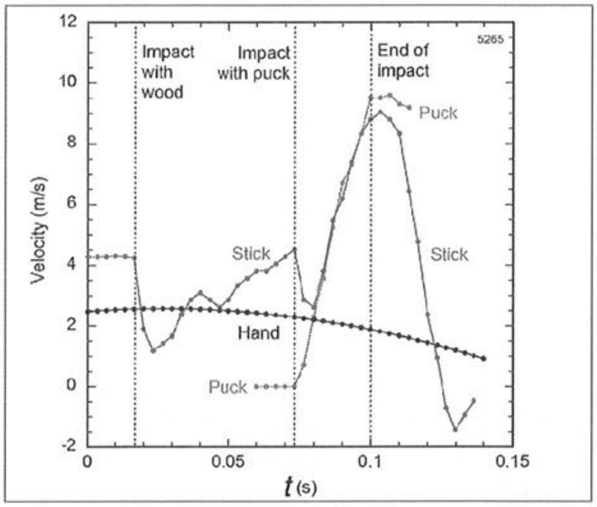

Fig. 3. Velocity of the hand, the stick, and the puck when the stick struck the wood platform before striking the puck.

hockey stick is the cantilever or diving board mode, where the middle of the stick remains almost at rest in the hand while the blade end vibrates back and forth. A low-frequency cantilever mode can also be observed with a tennis racquet, but only if the handle is held in a rigid vice. The cantilever mode is not observed when a racquet is handheld since the hand is much softer than a vice grip, allowing the stiff racquet frame to vibrate under the hand and along its whole length. A strong cantilever mode at about 25 Hz was also observed with the handheld meterstick.

Puck speed results

In order to measure the hand speed as well as the speeds of the bottom end of the stick and the puck, a short rod was inserted through the stick as a simple handle. That way, marks on the stick were not obscured by the hand. Motion of the stick and the puck was recorded with a Casio EX-F1 video camera at 300 frames/s and analyzed with Tracker motion analysis software. A typical result where the stick hit the puck directly is shown in Fig. 2, and a high-speed result where the stick first hit the platform is shown in Fig. 3. The results are also shown in supplementary videos 5261 and 5265.[4] In Fig. 2, the bottom end of the stick was incident on the puck at 4.29 ± 0.05 m/s and the puck was launched at a speed of 5.8 ± 0.1 m/s. In Fig. 3, the bottom end of the stick struck the platform at a speed of 4.27 ± 0.05 m/s and the puck was launched at a speed of 9.3 ± 0.2 m/s. The incident speed of the stick was essentially the same in both cases, but the puck speed was substantially higher when the stick first struck the platform.

In Fig. 2, there is a slight decrease in the stick speed at $t = 0.03$ s, probably because the stick brushed the wood platform lightly. At $t = 0.05$ s there is a more substantial decrease in stick speed when the stick strikes the puck, followed by a rapid increase in both the stick and the puck speed during the collision. The hand speed increased then decreased slightly during the impact, with the result that the digitized coordinates could be fitted accurately by a simple cubic function. The hand speed shown in Fig. 2 was determined by differentiating the cubic fit function, whereas the stick and puck speeds shown in Figs. 2 and 3 were determined by differentiating the digitized coordinates directly.

In Fig. 3, there was a rapid decrease in stick speed when the stick struck the platform, an increase in speed while the stick was sliding on the platform, another decrease in speed when the stick struck the puck, and a rapid increase in speed as the stick straightened out. Throughout this process, the hand speed remained relatively constant and was therefore not significantly affected by the forces acting on the bottom end of the stick. Motion of the stick after initial impact with the puck, and after loss of contact with the platform, is dominated by the low frequency cantilever vibration mode, and results in a negative stick speed when $t > 0.12$ s. In a real game of hockey, contact with the ice is maintained for only about 10 ms since the stick is incident on the ice at a much higher speed than in our experiment. Nevertheless, contact with the puck is maintained for about 30 to 40 ms, as was the case in the present experiment.

Additional experiments

Several additional experiments were undertaken to measure the properties of the meterstick. The mass of the stick alone was 114.2 g and the mass of the threaded rod was 37.9 g. When swung as a pendulum about an axis 23 cm from the top end, the period of oscillation was 1.527 s, giving a moment of inertia $I_A = 0.0239$ kg·m^2 about the swing axis, consistent with the calculated value. At a tip speed of 4.28 m/s, the stick angular velocity $\omega = 5.56$ rad/s, corresponding to an initial impact energy $E = 0.5 I_A \omega^2 = 0.37$ J. Since the outgoing puck kinetic energy was 0.84 J in Fig. 2 and 2.16 J in Fig. 3, it is clear that additional work was done by the hand on the stick during the collision.

The stiffness of the meterstick was measured by mounting the stick horizontally on a table with 37 cm of the stick protruding beyond the edge of the table. The stick was rigidly clamped at the other end, lightly clamped by hand at the edge of the table, and a 1.1-kg mass was hung on the end of the overhanging section. The end of the stick deflected vertically by 41 mm, indicating that the stiffness at the free end was 263 N/m.

The 50-g puck was then mounted on the free end of the stick, and the free end was displaced vertically downward by 60 mm by hand. The free end was then released quickly, with the result that the puck was projected vertically upward at 3.50 m/s. The stick then commenced vibrating at 25 Hz, with a vibration period of 0.040 s. The actual release time of the puck was 0.030 s since the relatively heavy puck added to the mass of the ruler to decrease the vibration frequency while the puck remained in contact with the ruler.

The elastic energy stored in the stick is given by $0.5ky^2 = 0.47$ J when $k = 263$ N/m and $y = 0.06$ m. The kinetic energy of the projected puck was 0.31 J, implying that part of the stored elastic energy was used to accelerate the stick itself. At the instant when the puck lost contact with the stick, both the tip of the stick and the puck were traveling at the same speed.

Discussion

In Fig. 2, wee the bottom end of the stick bent backwards by 26 mm when it impacted the puck, while in Fig. 3 the stick bent backwards by 76 mm while it was sliding on the wood platform. The elastic energy stored in the stick was therefore 0.09 J in Fig. 2 and 0.76 J in Fig. 3. These results can be compared with the outgoing kinetic energy of the puck, which was 0.84 J in Fig. 2 and 2.16 J in Fig. 3. The stored elastic energy therefore amounted to only 11% of the puck energy in Fig. 2 and 35% of the puck energy in Fig. 3.

The simplest interpretation of the bending energy is that it added 1.5 m/s to the puck speed in Fig. 2 and 4.4 m/s to the puck speed in Fig. 3, given that a 60-mm bend in the stick was observed to project the puck at 3.5 m/s. That is, one might expect that the puck speed in Fig. 3 should be 2.9 m/s greater than the puck speed in Fig. 2. In fact, the puck speed in Fig. 3 was 3.5 m/s greater than the puck speed in Fig. 2. While these results are roughly as expected, they do not include a possible increase in puck speed due to any additional force on the stick exerted by the hand. There is an additional effect that is worthy of comment.

If the bending energy in Fig. 2 acted to increase the puck speed by 1.5 m/s, from 4.3 m/s to 5.8 m/s, then the kinetic energy of the puck increased by 0.38 J, rather than by the 0.09 J of bending energy stored in the stick. Similarly, if the bending energy in the stick increased the puck speed in Fig. 3 by 4.4 m/s, from 4.9 m/s to 9.3 m/s, then the kinetic energy of the puck increased by 1.56 J, rather than by the 0.76 J of bending energy stored in the stick. This represents a slight paradox, since more energy is given to the puck than was stored in the stick as bending energy.

The resolution of the paradox is that the 3.5-m/s ejection speed of the puck, when the stick was displaced by 60 mm, was measured when the stick was initially at rest. The kinetic energy of the ejected puck was then 0.31 J. If the stick was moving forward at say 4 m/s when the puck was ejected at 3.5 m/s relative to the stick, then the kinetic energy of the puck would increase by 1.0 J. The additional energy arises because the same force acting on the puck acts over the same time, but it acts over a longer distance when the puck is already moving forward. That force acts backward on the stick and slows the stick, so the additional energy gained by the puck is extracted from the stick or the hand.

A more detailed analysis of the energy balance is provided in a separate paper.[5] It is shown in that paper that the collision between a hockey stick and a puck can be treated as a superelastic collision, with a coefficient of restitution greater than unity, since the bending energy stored before the collision adds to the total energy after the collision. In addition, the force on the stick by the player's hands adds to the total energy during the collision with the puck. Properties of real sticks are described in Ref. 6.

Conclusion

The results presented in this paper support the fact that hockey players know what they are doing when they slap the ice, even though the result appears at first sight to violate conservation of energy. The first sight conclusion is biased by the fact that most collisions are of such short duration that nothing can be done to affect the outcome during the collision itself. However, hockey sticks are very flexible and the impact duration can be as long as 50 ms with real sticks, which gives the player sufficient time to recover from the sudden decrease in stick speed when the stick strikes the ice. A larger force needs to be exerted on the stick to bend it, as opposed to the force required to accelerate the stick through the air, with the result that more energy can be imparted to the stick when it strikes the ice than when it strikes the puck directly.

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