AC 2011-169: APPLYING DYNAMICS TO THE ENGINEERING OF THE PERFECT BOUNCE: EXPERIMENTAL INVESTIGATION OF WHY THE NBA REQUIRES A SPECIFIC INFLATION PRESSURE FOR BASKETBALLS USED IN PROFESSIONAL GAMES.

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Engineering the perfect bounce from a basketball: Why the NBA requires a specific inflation pressure for basketballs used in professional games

Abstract

This paper discusses the bouncing of a basketball as an application of what is learned in dynamics. The National Basketball Association (NBA) has definite specifications for balls that are used in its games. The ball must be orange in color, have a circumference of 29.5 inches, and weigh 22 ounces (size 7); it must also have an internal pressure between 7.5 and 8.5 psi. The WNBA has similar requirements. Why is it necessary to specify the test height and the internal pressure?

Three sets of experiments are presented; they were done as a class assignment in a Dynamics course in order to answer this question. These experiments show that the results from the central impact of two particles can be used to explain and demonstrate why these two requirements are necessary. It is shown that increasing the height from which a basketball is dropped decreases its rebound height relative to the original drop height but that increasing the internal pressure of a basketball increases its rebound height and, hence, compensates for the effects of increasing the drop height. Therefore, it is possible to achieve the same rebound height with a given ball by using various combinations of the internal pressure and the drop height. Accordingly, specifying the height from which a basketball is dropped during a ball-drop test and its internal pressure during the subsequent fall is essential in order to interpret the quality of the bounces of different basketballs accurately and without ambiguity.

1. Introduction

Experienced basketball players use the ability of a ball to bounce to assess its adequacy for use in games. This is related to the extent to which the balls dissipate energy during impact with the surface of the court. Such bouncing tests relate directly to the concept of the collision of particles [1-3]. This author and others have shown how software commonly available online and in Microsoft Windows XP can be used to demonstrate and analyze the energy dissipation that occurs when a ball bounces off the court during a game [4-10]. For this paper, data were collected directly from different kinds of bouncing balls by students and used in class to illustrate a practical application of the coefficient of restitution that students learn in the dynamics of impacts and collisions [6].

The impact process between a ball and a hard surface involves a change, albeit temporary, in the shape of the ball [1]. A frame-by-frame study of the pictures of bouncing tennis balls obtained using high-speed cameras (2000 frames per second) in our laboratory demonstrated that this process consists of four separate and distinct phases: initial contact, deformation of the original shape, restitution and recovery of the shape of the ball, and separation and takeoff [6].

In general, impulses that act on the ball during the deformation phase are different in magnitude and direction from those that arise during the restitution phase of the collision[11]. It is conventional, therefore, to compare their magnitudes by means of a ratio called the coefficient of restitution.

For two particles A and B that are, say, assumed to be moving in the same direction before as well as after central impact with absolute velocities v_A and v_B, respectively, analysis shows that the coefficient of restitution is related to the relative speeds of the particles before and after impact, as shown below [1-3].

$$e = \frac{(v_B)_{after} - (v_A)_{after}}{(v_A)_{before} - (v_B)_{before}} \qquad (1)$$

If particle B represents the ball and particle A the rigid surface of the court, then, in this case, the coefficient of restitution becomes

$$e = -\frac{(v_B)_{after}}{(v_B)_{before}} \qquad (2)$$

When collision is perfectly elastic, the two impulses are equal. When it is not, the restitution impulse is smaller than the deformation impulse, leading to a coefficient of restitution that is less than one.

Experiments by many authors over the years have shown that, for a given ball, the energy dissipated by an impact varies with the height from which the ball was dropped. The higher the initial drop height, the smaller the rebound height. That is, the ratio of the rebound height to the drop height decreases as the drop height increases and it increases as the drop height decreases [4-6].

Energy dissipated by a bouncing ball can be measured using the sound produced when a ball strikes a solid surface. The sound produced by successive impacts is recorded and analyzed to give the time intervals separating consecutive impacts. It has been shown that these time intervals are related to the coefficient of restitution [6]. The use of this technique is relatively common. Bernstein used this procedure in1977[7]. Smith, Spencer, and Jones automated this process using a microcomputer in 1981 [8]. Stensgaard and Laegsgaard adapted it to a PC in 2001 [9]. Aguiar and Laudares[10] extended the work of Bernstein [7], Stensgaard, and Laesgaard [9] and used data related to the coefficient of restitution of a bouncing ball to determine of the acceleration of gravity in 2003. Foong, Kiang, Lee, March and Paton [12] applied this work to an examination question aimed at determining how long it took a bouncing ball to bounce an infinite number of times in 2004 and Njock Libii [6] used it in 2010 to compare old tennis balls with new ones.

The remainder of the paper is organized in the following manner: First, three sets of experiments are described and their results are presented; this is followed by a discussion of the mechanics of rebound and the associated loss of energy. The purpose of that discussion is to relate the results of the experiments to the requirements made by the NBA regarding drop heights and the inflation pressures of professional basketballs. Finally, the impact of the project on student learning is discussed.

2. Experiments

Three sets of experiments are presented: drop-ball experiments, inflation-pressure experiments and duration-of impact experiments. A drop-ball experiment is one in which a ball is released from rest from a given height (drop height) above a rigid surface; it is allowed to strike the surface of the court, and the height to which the ball rebounds is measured. Drop-ball experiments measure rebound heights and compare them to the corresponding drop heights; inflation-pressure experiments measure the effect of the inflation pressure of a basketball on its rebound height; and duration-of impact experiments measure the duration of the impact between the falling ball and the rigid surface on which it falls and correlate these durations to the magnitudes of the corresponding drop heights. After the experiments have been described and the corresponding results presented, the mechanics of rebound and associated energy dissipation are discussed as they relate to professional basketballs.

2.1. Drop-ball experiments

The purpose of these experiments is to measure the effects of the nature of the ball and drop heights on the magnitude of the rebound heights. Results of these experiments verify what is reported in the literature, which is that increasing the drop height of a ball decreases the rebound height relative to the drop height. These results held true for all balls that were tested.

The white wall of a laboratory with a very high ceiling was used as a background. Height levels were marked on that wall to measure both the height from which the ball was dropped and the maximum height to which the ball bounced. A continuously running digital video camera and a microphone were used to record the movement of the ball and the sound it made when it hit the floor during drop trials, Fig. 1. The resulting footage was slowed down, studied, and the appropriate heights and sound waves were extracted from it.

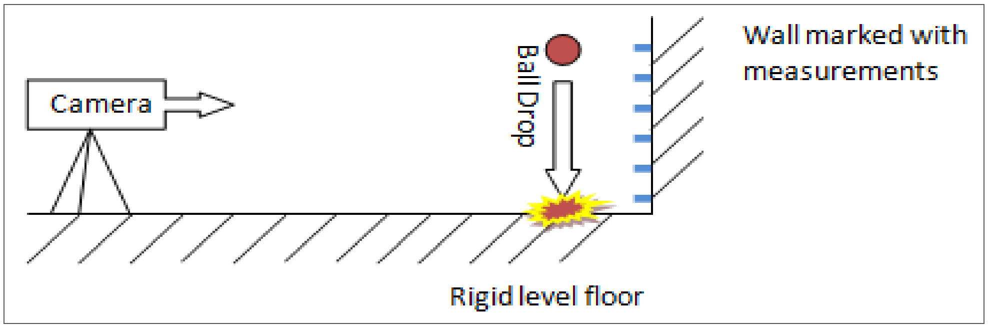

Figure 1: A setup that shows how data were collected (Courtesy of Group 2[18]).

Three different kinds of balls were used to collect data: basketballs, tennis balls, and ping pong balls. Each ball was dropped from the same predetermined height onto a rigid and level floor. Three trials were run at each height and for each ball; students took special precautions to avoid rotation of the ball during the experiment. For example, in order to ensure that the balls would be dropped with minimal rotation, chalk marks were placed on the balls to indicate a horizontal dropping point and to help detect rotation, if any. Each ball's horizontal axis of symmetry was lined up with the desired height, the ball dropper's hands were placed on the ball's vertical axis to ensure that the ball fell only due to gravity and all balls were monitored to prevent them from striking the wall nearby. The ball's rebound height was recorded by the camera and extracted from the footage later. The measurement of the balls' height was taken about the horizontal axis of symmetry axis of the balls during both the drop and the rebound. While the falling balls were allowed to impact the ground several times before they were retrieved, only the first rebound height was used in the data shown below. The same fifteen drop heights were used for each ball: 17 ft, 16 ft, 15 ft, 14 ft …3 ft. Each ball was tested four times at each height.

Rebound data collected from these experiments are shown in Figure 2, which displays height ratios as a function of the drop heights. A height ratio is defined as the rebound height divided by the height from which the ball was dropped. It represents a ratio consisting of the maximum gravitational potential energy of the ball after rebound divided by the initial gravitational potential energy that the ball had when it was dropped. In Figure 3, these same data were presented using the coefficient of restitution, which, in these tests, is the vertical speed of the ball immediately after impact divided by the corresponding vertical speed just before impact. Figure 4 presents these same data in terms of the percentage of the initial energy that was dissipated during impact. It was calculated by taking the difference between the mechanical energy that the ball had when it was dropped and the energy that it had immediately after impact and dividing that difference by the energy that the ball had when it was dropped.

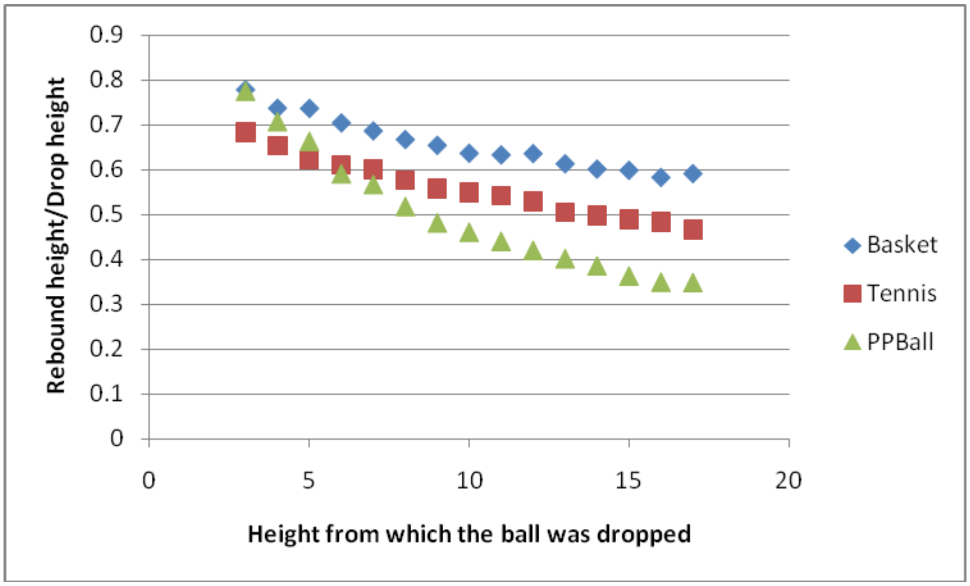

Figure 2: Variation of height ratios with drop heights (ft) (data from Group [19]).

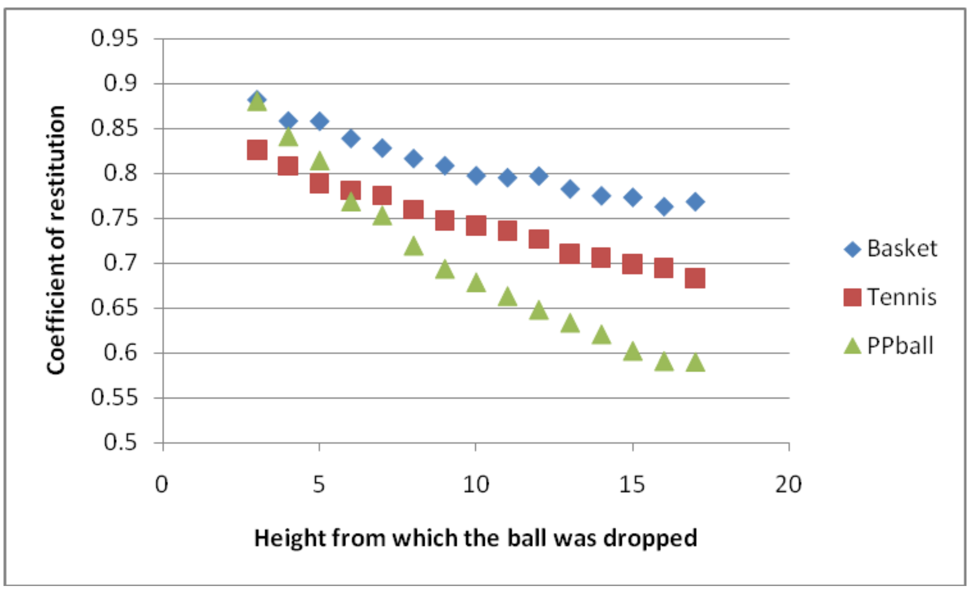

Figure 3: Variation of the coefficients of restitution with drop heights (ft).

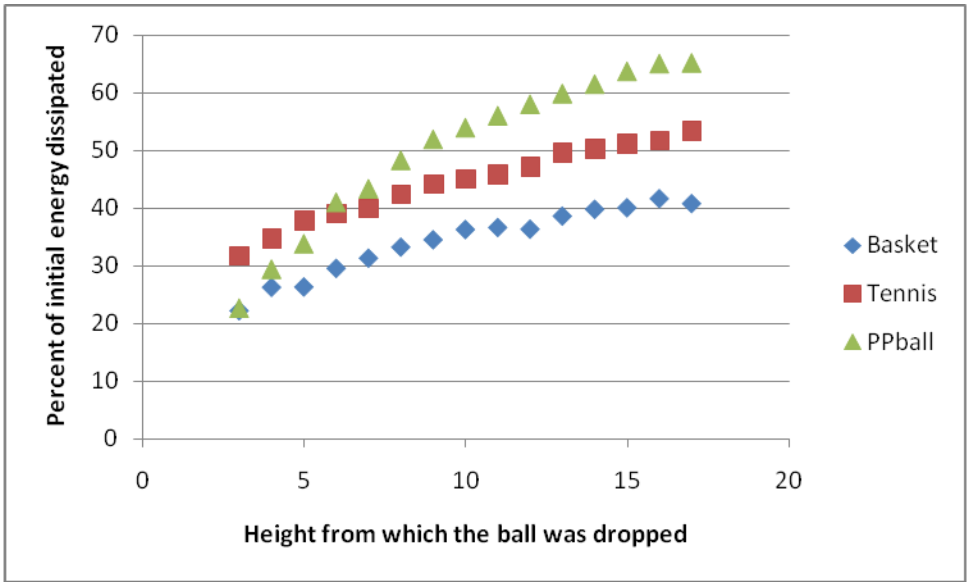

Figure 4: Percent of energy dissipated by the impacts vs. drop heights.

Two observations can be made from these plots: First, the height ratios, shown in Fig. 2, and the coefficient of restitution, shown in Fig. 3, decrease with increasing drop height, indicating that the higher the drop height, the larger the energy dissipated by the impact. This interpretation is verified by the pattern of energy dissipation that is shown in Fig. 4. The results that are shown in Figures 2, 3, and 4 are consistent with what is reported in the literature[4-10]. Secondly, it can also be seen that all three balls perform better at relatively low drop heights. Indeed, when drop heights were larger than seven feet, the relative magnitudes of the height ratios and those of the coefficients of restitution of all three balls maintained a consistent pattern throughout the heights that were tested: the values for the basketballs were the highest; those of the ping pong ball were the lowest, while those of the tennis ball lay between the former two. However, for the heights below seven feet, the rank ordering changed and the tennis ball and the ping pong ball switched positions: the values for the basketballs were still the highest; but those of the tennis balls became the lowest, while those of the ping pong balls now lay between the former two. It can be seen that, for all practical purposes, drop heights during basketball, tennis, and ping pong games occur below seven feet.

On average, the ball bounces about 2500 times during a basketball game[11], making the reduction of energy dissipation during impacts very important; also, usually, Guards are between 6 feet and 6 feet 6 inches tall; Forwards between 6 feet 6 inches and 6 feet 11 inches tall; and Centers are at least 6 feet 9 inches tall [20]. This means that the average heights of professional basketball players are between 6 and 7 feet, which is in drop heights where the basketball is very elastic and dissipates little energy during bounces. It is quite remarkable, therefore, that these three balls are designed to perform best in the ranges of height that are useful during the games in which they are used. It can also be seen that the magnitudes of the coefficients of restitution of the three types of balls maintain a consistent pattern that supports this conclusion.

2.2. Inflation-pressure experiments

Each student group designed an experiment to see how the pressure with which a professional basketball is inflated affected rebound heights. A basketball was inflated to a given level and used in drop tests, as described earlier. The basketball was inflated to a new level and the test was repeated. The process continued until all preselected inflation pressures were tested. Three rounds of tests were conducted: In the first, a drop height of four feet was used in all tests; in the second, the drop height was changed to 6 ft; and in the third, it was moved to 8.7 ft. In all tests, the inflation pressure of the basketball was increased with a simple sportball pump, while the pressure itself was measured with a sportball pressure gauge. In each round of tests, eight different pressure levels were used: 1.4, 2.9, 4.4, 5.9, 7, 9.25, 11.1, and 13.6 psig, where psig designates pounds per square inch of pressure above ambient atmospheric pressure. Five drop trials were run for each tested pressure and the results for that pressure were averaged. A sample plot of the results of these tests is shown in Figure 6 for a drop height of 4 ft.

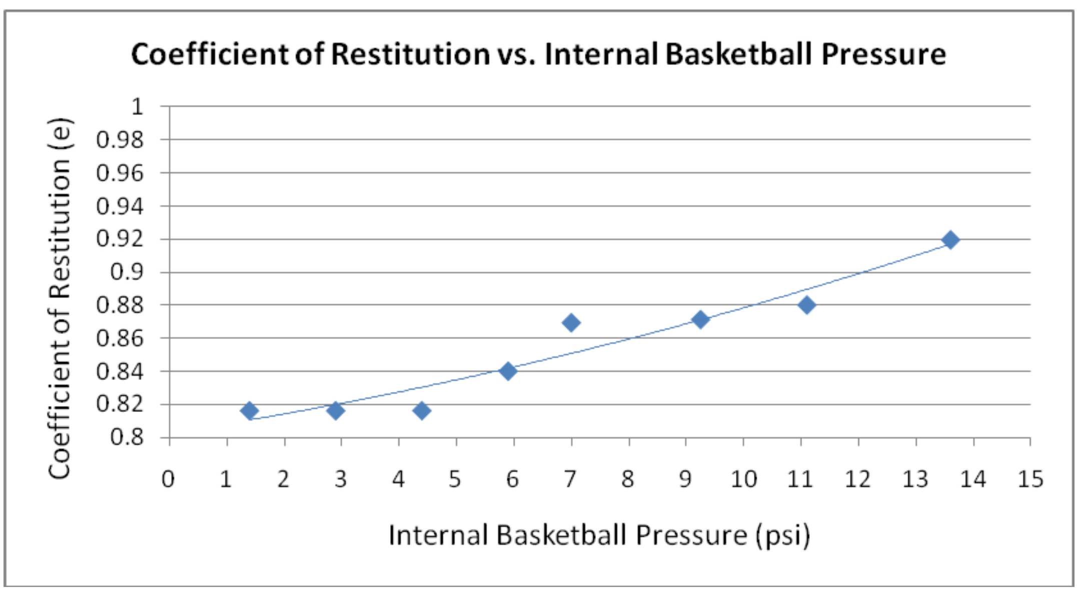

Fig. 5. The coefficient of restitution vs. internal pressure of the basketball at 4 ft.

It can be seen from Figure 5 that the coefficient of restitution of a basketball increases with increasing inflation pressure, indicating that the higher the internal pressure, the smaller the energy dissipated during impact, and consequently, the higher the rebound height. These results are consistent with those reported by Fontanella[11]. This interpretation can be verified by using a direct plot of the variation of rebound heights vs. inflation pressure, as shown in Figure 6.

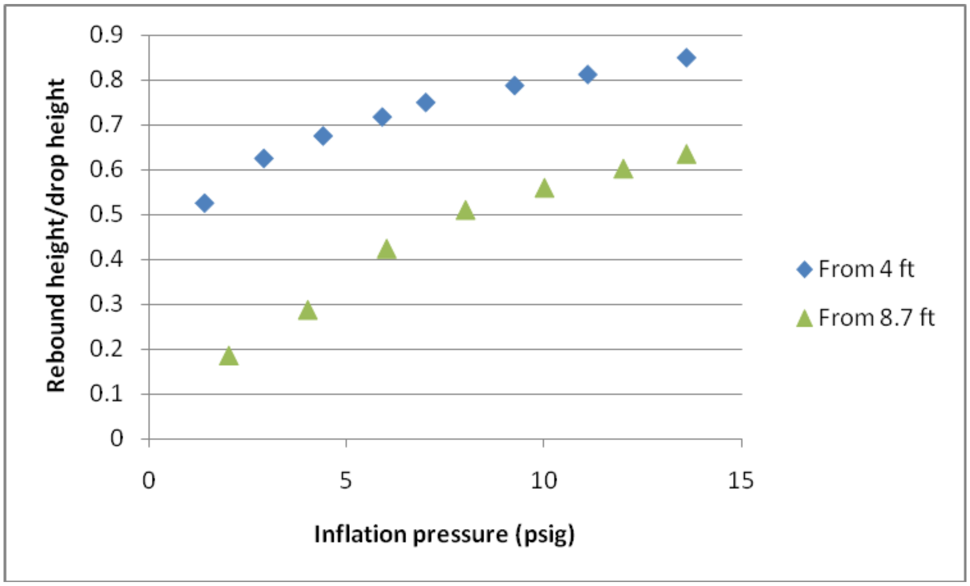

Figure 6: Height ratios vs. inflation pressures for two drop heights.

2.3. Duration-of-impact experiments

Designing an experiment to measure the duration of impact was a little more complicated. At first, students tried to use film footage obtained from the measurements of bounce heights. It proved inadequate to measure the durations of impact because the speed of the camera was too slow for the phenomenon being observed. They inferred from this that the longest duration of impact was shorter than what the camera could record. Since the speed of the digital camera that was used was about thirty frames per second, they concluded that the duration of the longest impact was less than 1/30 of a second, or 0.034 seconds.

It was decided to use a microphone and sound recording software to record the duration of the impacts of all three balls. Two types of software were popular among students: Audacity[13] and Goldwave [14]. Hundreds of waves were recorded, identified, and processed. Students could identify the specific portion of the waveform that corresponded to an impact; and, by highlighting it, the chosen software displayed the duration of that part of the waveform. It was determined that an impact that lasted 0.0015 seconds could be detected using either software.

First, the durations of impact from varying drop heights were tested. The same wall and markings that were used during drop-ball experiments were used in this experiment. The computer's microphone was placed close to where the balls would make contact with the floor and the position of the microphone was the same spot through all trials. The sound made by the impact of the basketball on the floor was recorded from each of the heights that were used in the first experiment. The tests were repeated in the same manner; first using a tennis ball, then, a ping pong ball.

Some practice was needed in using software to view and analyze the recorded sounds. However, it was possible, after some practice to identify the portion of the waveform that corresponded to an impact relative to background noise, because impact caused the intensity of the recorded sound to increase suddenly for a short time. By highlighting the segment of the waveform that corresponded to the impact, the software displayed the start and end times of the wave pulses created by the impact. The duration of the corresponding sound could be calculated by taking the difference between the two displayed times. The results collected from this process are shown in Figure 7. Data in that Figure show bands wherein the durations of impact are constant. This is due to the fact that the corresponding durations were very close to each other but the resolution of the software did not allow for refined separation of the durations of impact from drop heights that were close to each other. Nevertheless, the general trends are clear: duration of impacts increase as one increases drop heights. By comparing the durations shown in Figure 7 with the dissipations of energy shown in Figure 4, it can be seen that they combine to explain some of the mechanics of impacts. For each of the tested balls, experimental data showed that, when the duration of impacts increased, so did the amount of energy that was dissipated. Similarly, when the duration of impact decreased, so did the amount of energy that was dissipated. We postulated that when a ball was dropped from a high elevation, its impact with the floor was associated with larger deformations, hence larger times of impact, than when it was dropped from a lower height.

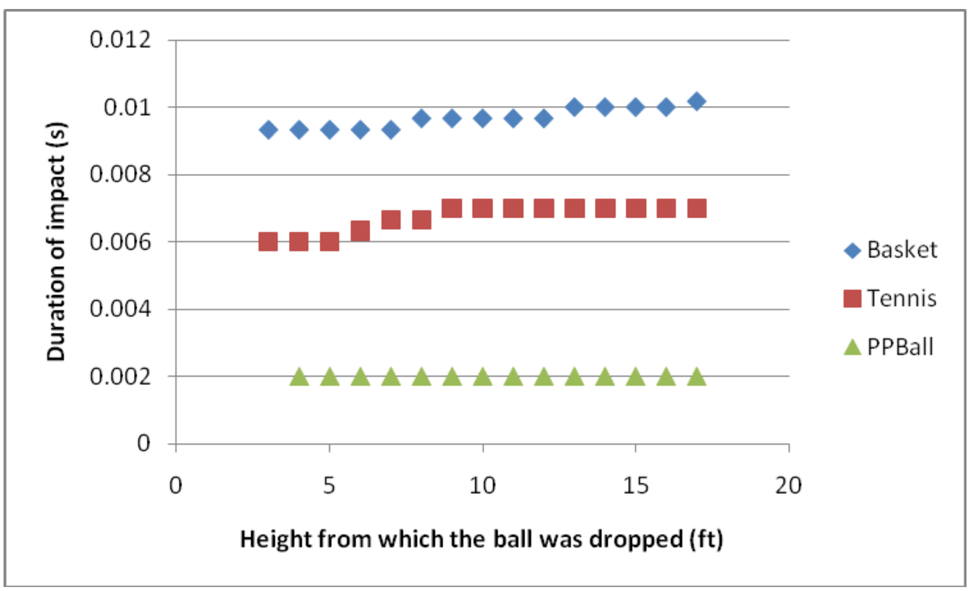

Figure 7: Duration of the impacts vs. drop heights.

3. Summary

At the outset, students had hypothesized that inflation pressures affected the durations of the impact between a basketball and the floor. To test that hypothesis, students tested the same basketball multiple times; the basketball was progressively inflated to different levels of pressure. Before each test, the ball was inflated to a different level of internal pressure. It was found that increasing the inflation pressure of a basketball reduced the duration of its impact with the floor, reduced the energy dissipated during the impact, and increased the height to which the ball rebounded, Figure 6. Internal pressures between 7.5 and 8.5 psi yielded excellent results in that the durations of impacts were low and the rebound heights very large.

It has been established experimentally that, for a given drop height, the rebound height depends upon the nature of the ball; and that, for a given ball, the rebound height depends upon both the drop height and the inflation pressure. Therefore, it is possible to achieve the same rebound height with a given ball by using various combinations of the internal pressure and the drop height. Accordingly, specifying the height from which a basketball is dropped during a ball-drop test and its internal pressure during the subsequent fall is essential in order to interpret the quality of the bounces of different basketballs accurately and without ambiguity.

4. Impact on learning

It is reasonable to ask what impact this dynamics project had on student learning. The impact of the project has three parts: Part one has to do with specific learning outcomes in dynamics; part two has to do with what students learned to do during the projects; and part three has to do with what they gained in the process.

4.1. Learning outcomes.

Specific learning outcomes in the dynamics course are mixed: quizzes and exams that covered central impact and the conservation of energy yielded very good results in that more than 90% of the class could solve the corresponding problems correctly. However, the knowledge that was acquired in central impact did not transfer to the solution of problems involving oblique impact in that only about 40-57% of the class could solve oblique impact problems correctly. However, there was a net reduction in the number of students who failed dynamics compared to what happened before the project was introduced: On average, the percentages of A's and B's in the course did not increase appreciably; but the percentages of C's and D's increased. The specific amounts varied with the class being taught.

4.2. What students learned to do. They learned to:

- Create a model for a real bouncing ball using particle mechanics.
- Apply the use the conservation of energy in the analysis of a bouncing ball.
- Apply the use of the conservation of linear momentum in the analysis of a bouncing ball.
- Apply central impact, inelastic impact, and the coefficient of restitution to a real problem.
- Design experiments.

- Carry out their experiments and to collect data using software found on the web.
- Interpret data and relate results to what analysis had led them to expect.
- Write report
- Present reports orally
- Work in group

4.3. What students gained. They:

- Engaged another dimension of learning by working on a hands-on project.
- Discovered that, even though the project required a lot of time and energy, the project was fun and more popular than taking an exam. Indeed, when given a choice between an exam and a project of equal weight, students overwhelmingly choose to do a project.
- Had some control over what they did, how they did it, and when they did it.
- (Who started work early) discovered that they could do things over and ask for help, if/ when things did not work well the first time.
- Had ample time do the work in and could pace themselves.
- Experience with working in groups of their peers
- Could divide work among group members and share experiences, skills, and knowledge.
- Had something practical to talk about with their friends who are not studying engineering.
- They found a subculture that provides opportunities for support and commiseration.

4.4. Other forms of impact

Matusovich, Streveler and Miller reported the results of their research on why students choose engineering[15-16]. Their work was focused on the subjective task value (STV) construct of Eccles, which is based upon the observation that an individual assigns a personal importance to engaging in an activity. Their salient conclusion is that many students choose engineering because they believe that it is consistent with their sense of self. However, in order to persist in engineering, that belief must be reinforced by the student's personal experience of what engineering is. Accordingly, it appears that whether or not to persist in engineering is not a decision that is made once and forgotten. Rather, it is one that engineering students revisit continually. Accordingly, The authors recommend that, given the diversity of students in engineering, instructors need to give students many examples of ways in which engineering is practiced. Projects in a variety of classes serve that purpose; this dynamics project is one of them.

Finally, in a recent article on adding value to teaching, Chachra asked the following question: "what can we offer that students can't get online? [17]" She suggested three things: "Membership in a learning community, individualized mentorship, and hands-on practice (including access to scientific and engineering equipment)". A project such as the one described in this paper adds all three.

5. References

1. Hibbeler, R.C., Engineering Mechanics: Dynamics, 12th edition, Prentice Hall, 2010, 248-251.
2. Morgan, Joseph, Introduction to University Physics, Volume One, Second Edition, Allyn Bacon, Boston, MA,1969, 239-240.
3. Sandor, Bela I., Engineering Mechanics Statics and Dynamics, Prentice Hall, Englewood Cliffs, NJ, 1983, 678-683.
4. Brody, Howard,"The tennis-Ball Bounce Test" in The physics of Sports, Edited by Angelo Armenti, Jr., American Institute of Physics, New York, 1992, 164-166.
5. Brody, Howard, "Physics of the tennis racket" in The physics of Sports, Edited by Angelo Armenti, Jr., American Institute of Physics, New York, 1992, 141- 147.
6. Njock-Libii, Josue USING MICROSOFT WINDOWS TO COMPARE THE ENERGY DISSIPATED BY OLD AND NEW TENNIS BALLS, Proceedings of the 2010 National Conference and Exposition of The American Society for Engineering Education, Louisville, Kentucky, paper AC 2010-269.
7. Bernstein A D 1977 Listening to the coefficient of restitution Am. J. Phys. 45, 41- 44.
8. Smith PA Spencer C D and Jones D E, Microcomputer listens to the coefficient of restitution, Am J. Physics, 49, 1981, 136-140.
9. Stensgaard, I., and Laegsgaard, E., Listening to the coefficient of restitution-revisited, Am. J. Phys. 69, 2001, 301- 305.
10. Aguiar, C. E. and Laudares, F., Listening to the coefficient of restitution and the gravitational acceleration of a bouncing ball, Am. J. Phys., 71, 2003, 499-501.
11. Fontanella, John Joseph, The physics of basketball, Baltimore: Johns Hopkins University Press, 2006, pp. 101, 97, 111.
12. S. K. Foong, D Kiang, P Lee, R H March and B E Paton, How long does it take a bouncing ball to bounce an infinite number of times? Physics Education, January 2004, 40- 43.
13. Audacity(http://audacity.sourceforge.net/). Retrieved on January 4, 2011.
14. Goldwave (http://www.goldwave.com/). Retrieved on January 4, 2011.
15. Holly M. Matusovich, Ruth A. Streveler and Ronald M. Miller, Why do Students choose Engineering? A Qualitative, Longitudinal Investigation of Students' Motivational Values, Journal of Engineering Education, October 2010, October 2010. http://findarticles.com/p/articles/mi_qa3886/is_201010/ai_n56442207/?tag=content;col1 Retrieved on January 4, 2011.
16. Holly M. Matusovich, Ruth A. Streveler and Ronald M. Miller, How They See Themselves: Students who identify with engineering persist in the field. ASEE Prism, Vol. 20, Number 3, November 2010, page 47.
17. Debbie Chachra, Adding Value to Teaching: what can we offer that students can't get online? .ASEE Prism, Vol. 20, Number 3, November 2010, page 84.
18. Group2: Drew Hudson, Jordan Knerr, and Jacques Janssens, Dynamics, CE/ME 251, Spring 2010.
19. Group4: Blake Pettit, Joshua Schrock, and Zaadvinder Singh "Tony", Dynamics, CE/ME 251, Spring 2010.
20. http://wiki.answers.com/Q/Average_height_pro_basketball_player#ixzz1AO9jH4Ed