Daniel Cooney – Mamaroneck High School

Title: The Effect of Bat Composition on Swing Speed and Ball Exit Speed

## Introduction

Aluminum bats were originally approved for National Collegiate Athletic Association (NCAA) play in 1974 as a cost effective substitute for the traditional wood bat, as they broke much less frequently. However, as the technology developed, bat manufacturers began to compete with one another in an attempt to create the best-performing product, utilizing cutting-edge aircraft grade scandium alloys in their bats. This arms race resulted in an increase in offensive statistics, as NCAA mean batting averages increased from .267 in 1974 to .306 in 1998, while home runs per game increased from approximately 0.41 to 1.05 over the same time span (Russell 2007). Additionally, from 1989 through 2004, pitchers and infielders suffered from 204 injuries as a result of batted balls, with pitchers accounting for 26% of severe batted ball injuries (Dick, Sauers 2007). The NCAA deemed the performance of aluminum bats and the rate of batted-ball injuries to be too high, so, in 1999, they required that all bats must weigh three ounces less than their length (in inches) and must conform to standards of Ball Exit Speed Ratio (BESR), which compares the speed of the input pitch and swing speed to the ball's exit speed. The two BESR formulas are:

$$BESR= [V_{ball\ exit} + 0.5\ (V_{pitch}-V_{bat})] / [V_{pitch} + V_{bat}]$$

and

$$V_{Ball\ Exit} = (\ BESR + .5\ )\ V_{Bat} + (\ BESR - .5\ )\ V_{Pitch}$$

(Petr, Halpin 2003) . The NCAA approved a testing protocol in which a ball was fired from an air cannon at 136 miles per hour (the sum of the assumed pitch speed of 70 mph and assumed swing speed of 66 mph) at a bat held in a fixed position. The ball exit speed would then be measured, and these three measurements would be used to determine the bat's BESR. The maximum legal BESR value was 0.728, which would result in a ball exit speed of 97 mph, the speed achieved by the highest performing wood bats under these methods. However, the BESR testing does not take into account moment of inertia (MOI), which is a property of the bat's resistance to rotation. MOI is measured with the formula $MOI = 9.7797T^2W ( L – D- 6 )$, where T is the period of the bat during pendulum testing, W is the weight of the bat in ounces, L is the length of the bat and D is the distance from the bat's handle to its center of mass. A lower moment of inertia would theoretically allow for a faster swing speed because the batter would encounter less resistance when attempting to swing the bat (Crisco, Greenwald 2002). Unlike wood bats which must be made of one solid piece of wood, aluminum bats are hollow and can be manipulated to alter their weight distribution. Bat manufacturers would put additional weight in the form of an epoxy-like substance in the handle of the bat, shifting the center of mass closer to the batter's hands than would be possible with a wood bat. Recently manufactured bats claim to be able to increase a batter's swing speed, including Nike's Aero Fuse whose manufacturers assert that "increases bat speed by 3 m.p.h. over the leading competitor" (Wilson 2008). Although NCAA testing was supposed to limit the performance of aluminum bats to the level of the highest-quality wood, the NCAA mean batting average reached a low of .290 in 2004, which was still much higher than the .267 from 1974 (Russell 2007). As the monitoring of BESR was not able to make the performance of aluminum bats similar to wood, this experiment focused on the differences in the MOIs between wood and metal bats. It was hypothesized that if an aluminum bat has a lower MOI than a wood bat, then it will be swung faster because a lower MOI allows this bat to rotate around a fixed point at a greater speed than a wood bat given the same force input. On the assumption that this first hypothesis was correct, it was further hypothesized that if an aluminum bat has the same force input as a wood bat, then it will achieve a greater ball exit speed because of its lower MOI.

Methods and Materials (Phase 1)

Subjects for this experiment were current and former players from the Mamaroneck High School baseball team. Subjects were advised of the risks involved in participating, and informed consent was required. Subjects were informed that participation was completely voluntary, and that they could withdraw at any time. Subject data was recorded anonymously using random subject numbers. This phase of the study was conducted in the batting cage at Mamaroneck High School. A certified baseball coach, certified in CPR was present for all testing sessions. Two baseball bats, one made from aluminum and the other from wood, were measured in length with measuring tape and massed using a balance so that they both conformed to this experiment's predetermined standard of 33 inches long and 30 ounces in mass. A bat swing speed radar manufactured by Sport Sensors, a type of radar gun used to measure the speed of a swung baseball bat, was attached to an L-screen within a batting cage. The height of the radar gun was based on the height of each subject's baseball swing. A batter, standing five feet away from the radar gun and holding either the aluminum or wooden bat, swung with the intention of having the path of the swing cross the plane of the radar (a coin toss determined whether a wooden or a metal bat was chosen first). The speed of the batter's swing was recorded by the Sports Sensor Bat Speed Rader and recorded by an objective observer standing ten feet to the right of a right handed batter or the converse for a left handed batter (see *Figure 1* for a visual representation of the experiment's setup). The objective observer was protected from the swung bat by standing outside of the batting cage. Each batter took five swings with the first bat and then exchanged it for the other bat. Then the batter took five swings with the second bat.

The subject alternated taking five swings with each bat until twenty-five swings had been completed with each bat, at which point a new batter entered the cage and begin the coin toss. This was repeated multiple times, with batters of varying height, weight, age and skill level until a large body of data had been collected and the sample size was large enough to be statistically analyzed.

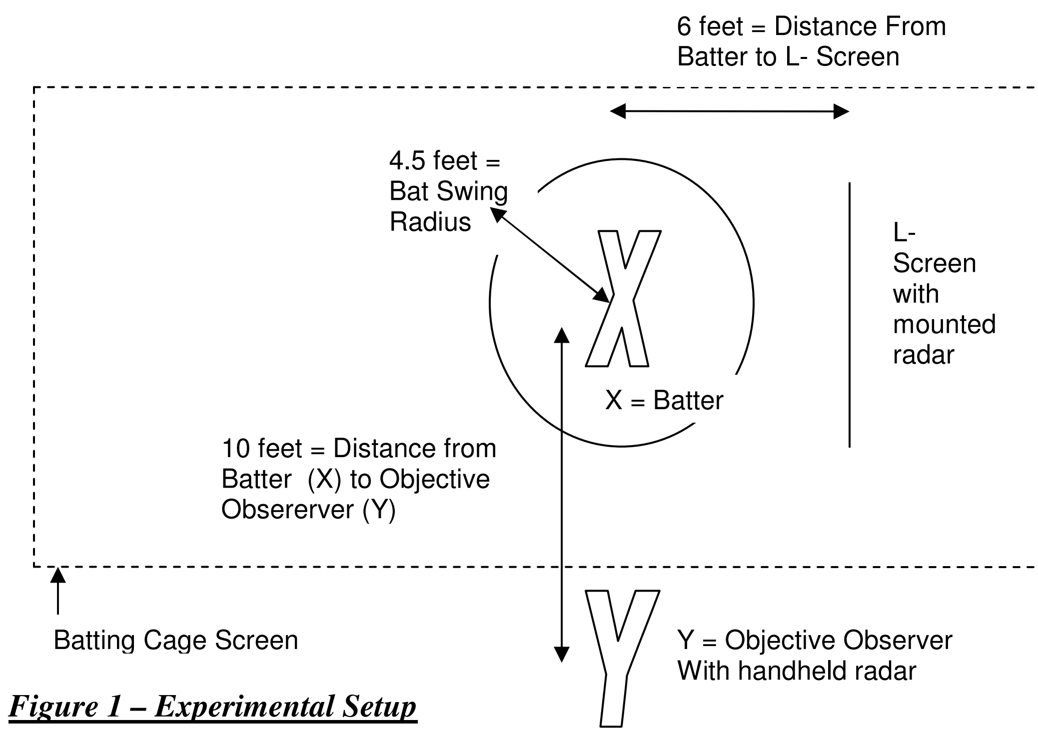


***Figure 1 – Experimental Setup***

Methods and Materials (Phase 2)

The second phase of the experiment was performed at the Baseball Research Center at the University of Massachusetts-Lowell, the site of official NCAA bat certification testing. The present study utilized the official procedures to measure MOI and BESR. Next, the moment of inertia (MOI) for each bat was measured. The bat was held by a collar-clamp that pivots about a knife edge at a point six inches from the handle. It was raised to an angle 5° from vertical, then released and allowed to swing freely. After the bat had completed five cycles, an electronic timer measured the speed of the next ten cycles. This process was performed five times to minimize error, and then the test was repeated with the other bat.

Next, ball exit speed testing was conducted. The wood bat was placed into a grip that could freely rotate six inches from the bat's handle. A baseball was fired out of an air cannon at the sum speed of 70 miles per hour (the assumed pitch speed) and 59 miles per hour (the average bat speed derived from previous experimentation), which came into contact with the bat at its vibrational node, or "sweet spot", which was assumed to be 6 inches from the barrel end of the bat. This was repeated six times in order to account for mechanical error and establish statistical significance. The ball exit speed test was then performed with the metal bat, however the air cannon fired the ball at the sum of the assumed pitch speed of 70 miles per hour and 67 miles per hour (the average speed of the metal bat derived from previous experimentation).

Results (Phase 1)

Twenty-four human subjects were used for this experiment, with the breakdown of their levels of experience being 1 Babe Ruth/ travel player, 13 High School Junior Varsity players, 8 High School Varsity player, 1 college player and 1 professional player at the low-A level. The mean swing speed for all subjects using the wood bat was 59 miles per hour, while the average swing speed for the metal bat was 67 miles per hour. This meant that, on average, the subjects swung the metal bat 8 miles per hour or 13.6 percent faster than its wood counterpart. The relationship between the subjects' age and mean bat speeds with the wood and metal bat is shown as a data table in Figure 2 and graphically in Figure 4. There was a direct relationship between age and swing speed, meaning that the older players in the NCAA pose more of a threat to the safety of the pitcher and infielders than a younger high school player. The results of swing speed testing were statistically analyzed using a matched-pair t-test, which was used to evaluate whether the difference between the aluminum and wood bats' swing speeds were statistically significant. The mean difference in swing speeds of 8 miles per hour resulted in a standard deviation of 2.1 and a highly significant p-value of $2.075 \times 10^{-15}$. This test is represented with a data table in Figure 4.

**Subject Age vs. Average Swing Speed**

| Subject Age | Metal Bat (in mph) | Wood Bat (in mph) | Difference |
|---|---|---|---|
| 14 | 69 | 62 | 7 |
| 15 | 52 | 48 | 4 |
| 15 | 56 | 51 | 5 |
| 15 | 62 | 56 | 6 |
| 15 | 59 | 52 | 7 |
| 15 | 66 | 58 | 8 |
| 15 | 72 | 64 | 8 |
| 15 | 72 | 64 | 8 |
| 15 | 70 | 61 | 9 |
| 15 | 75 | 66 | 9 |
| 16 | 59 | 54 | 5 |
| 16 | 63 | 55 | 8 |
| 16 | 71 | 63 | 8 |
| 16 | 67 | 58 | 9 |
| 16 | 68 | 59 | 9 |
| 16 | 68 | 57 | 11 |
| 16 | 77 | 65 | 12 |
| 17 | 72 | 67 | 5 |
| 17 | 59 | 51 | 8 |
| 17 | 63 | 55 | 8 |
| 17 | 75 | 66 | 9 |
| 18 | 50 | 45 | 5 |
| 19 | 72 | 67 | 5 |
| 22 | 84 | 74 | 10 |
| Average | 67 | 59 | 8 |

***Figure 2- Data Table***

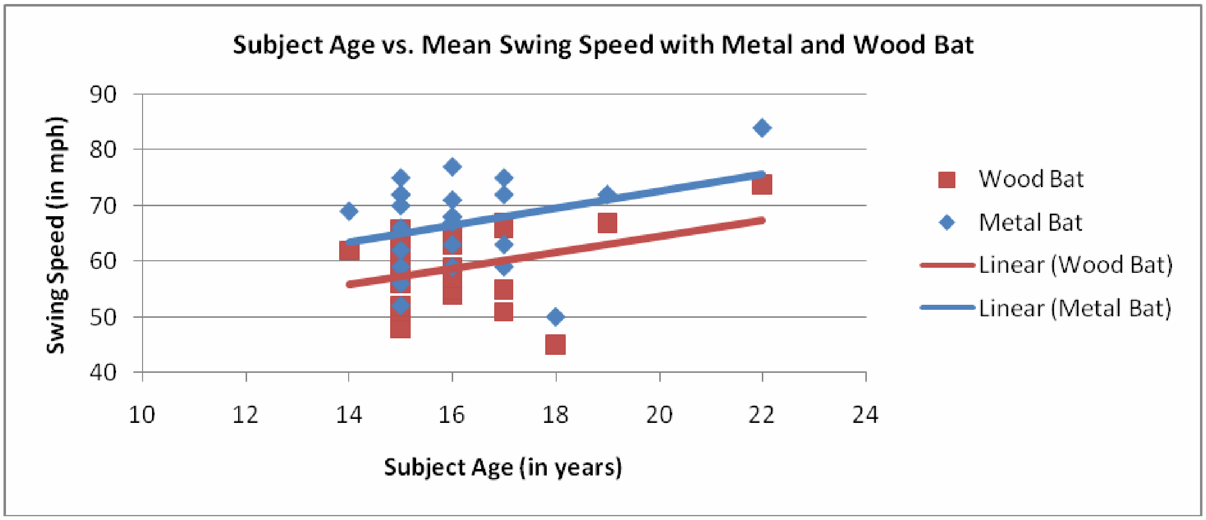


***Figure 3- Linear Regression***

| | |
|---|---|
| Mean | 8 |
| St. Dev. | 2.1 |
| N | 24 |
| T-Value | 18.66 |
| P-Value | 2.0758E-15 |

***Figure 4- Matched-Pair T-test***

Results (Phase 2)

The MOIs of the wood and metal bats were obtained, which were 10,000 oz-in$^2$ for the wood bat and 8,940 oz-in$^2$ for the metal bat. The average swing speeds of 59 mph for wood and 67 mph for metal were used as input data for BESR performance testing, which resulted in average ball exit speeds of 86.4 mph for wood and 97.6 for metal. There was a difference of 11.2 mph, or 12.96 percent, between the ball exit speeds of wood and metal bats using player swing speed data. These results are represented graphically in Figure 5. A matched-pair t-test was also used to analyze the results of the ball exit speed testing, which is shown below in Figure 6. The 11.2 mph mean difference between the aluminum and wood bats' ball exit speeds produced a standard deviation of 0.9 and a p-value of 8.88E-07, which indicates a high statistical significance. The values of this t-test are represented as a data table in Figure 6.

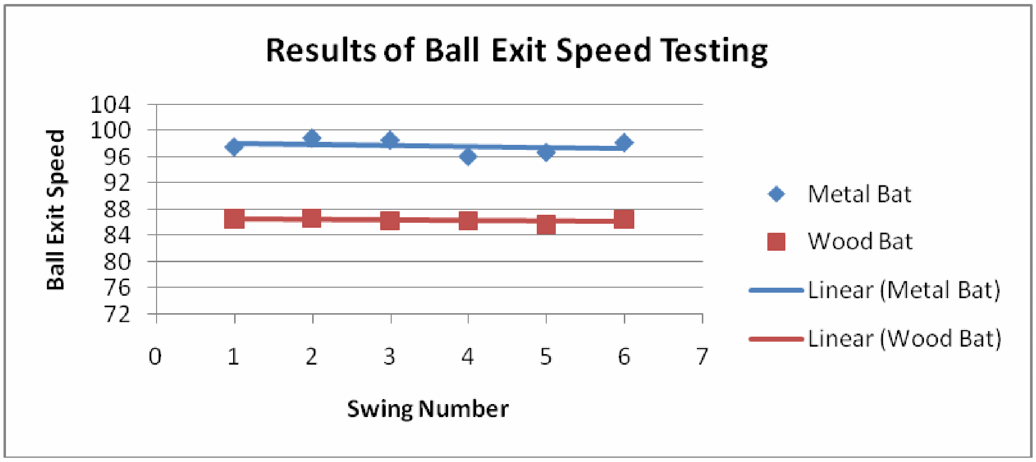


***Figure 5- Ball Exit Speed Testing***

| | |
|---|---|
| Mean | 11.2496 |
| St. Dev. | 0.944744 |
| N | 6 |
| T-Value | 29.16746 |
| P-Value | 8.88E-07 |

***Figure 6- Matched-Pair T-test***

Discussion

The NCAA's official BESR testing uses an assumed swing speed of 66 miles per hour, so it does not take properties of the bat that affect swing speed into account, such as MOI. The aluminum bat used in this study had an MOI of 8,940 oz-in$^2$ and produced a much higher swing speed, 67 mph, than that of the wood bat, 59 mph, which had an MOI of 10,000 oz-in$^2$. When these measured bats speeds were used in ball exit speed testing, the metal bats produced an average hit that was 11.2 mph faster than that of the wood bat. Although aluminum bats conform to the current NCAA standards on safety and performance based on laboratory testing, the results of this experiment reflect the actual swing speeds of high school baseball players. As the ball exit speed testing was performed based on the mean results of the swing speed tests, the BESR values of the mean swing speed were used to extrapolate the $V_{ball\ exit}$ for each subject's wood and aluminum bat swing speeds. The results of this extrapolation are displayed in Figure 7 as a data table and in graphically in Figure 8.

Subject Age vs. Projected Swing Speed

| Subject Age | Metal Bat Ball Exit Speed (in mph) | Wood Bat Ball Exit Speed (in mph) |
|---|---|---|
| 14 | 97.5 | 89.9 |
| 15 | 79.1 | 72.9 |
| 15 | 84.0 | 76.5 |
| 15 | 91.4 | 82.6 |
| 15 | 87.7 | 77.8 |
| 15 | 96.3 | 85.0 |
| 15 | 103.6 | 92.3 |
| 15 | 103.6 | 92.3 |
| 15 | 101.1 | 88.7 |
| 15 | 107.3 | 94.7 |
| 16 | 87.7 | 80.2 |
| 16 | 92.6 | 81.4 |
| 16 | 102.4 | 91.1 |
| 16 | 97.5 | 85.0 |
| 16 | 98.7 | 86.2 |
| 16 | 98.7 | 83.8 |
| 16 | 109.7 | 93.5 |
| 17 | 103.6 | 95.9 |
| 17 | 87.7 | 76.5 |
| 17 | 92.6 | 81.4 |
| 17 | 107.3 | 94.7 |
| 18 | 76.7 | 69.3 |
| 19 | 103.6 | 95.9 |
| 22 | 118.3 | 104.4 |

***Figure 7- Data Table***

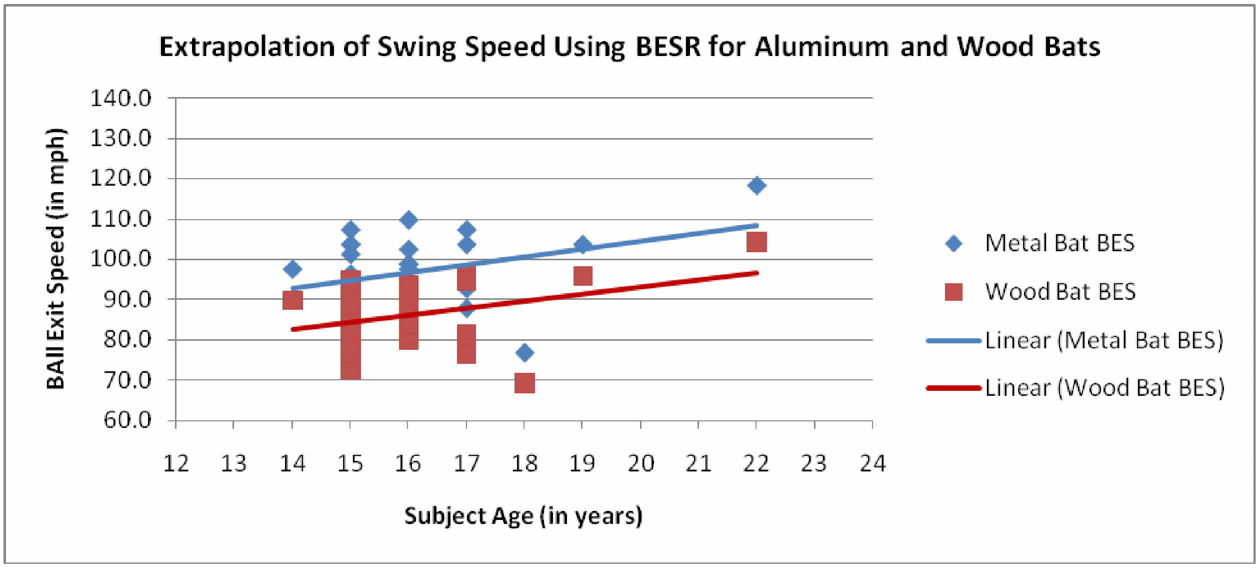


***Figure 8- Projected Ball Exit Speeds based on BESR Formula***

The upward trendlines in Figures 2 and 7 show a positive correlation between age and increased swing and ball exit speeds seem to indicate that older, stronger players at the collegiate level would be able to achieve greater absolute swing speeds than the high school players used in this study. As the mean metal bat swing speed was 13.6 percent faster than that of wood, the difference in weight distribution and the resulting MOIs may have a more dramatic effect in the highest level using metal bats. For instance, the oldest subject in the study, who was 22 years old and had just completed his college career, recorded bats speeds of 84 and 74 mph with aluminum and wood, respectively. His ball exit speeds were extrapolated using the BESR formula, which were 118.3 mph for metal and 104.4 for wood. Line drives of these ball exit speeds would reach the pitcher standing 54 feet away in 0.31 seconds with aluminum and 0.35 seconds with wood, so they 0.04 second extra reaction time for the pitcher with the wood bat could make the difference between avoiding the ball or sustaining a severe injury.

As bat manufactures continue to compete to create the highest performing bat, the altered weight distribution of aluminum bats will allow for a greater swing speed than possible with wood.

Further research would have the ultimate goal of the fabrication of a prototype aluminum bat with an MOI equal to that of wood. This could be achieved via the redistribution of the epoxy-like material in the bat's handle throughout the aluminum bat, causing the center of mass to move upwards on the bat to the same position as the balance point of a wood bat. This would allow the aluminum and wood bats to have equal MOIs, and therefore equal resistance to the batter's force input. This would mean that batters would achieve swing speeds more similar, if not identical to swing speeds achieved with the wood bat in this experiment. These similar swing speeds would result in more comparable ball exit speeds between aluminum and wood bats, and would thereby return aluminum bats to their original purpose, as cost effective substitute for wood bats with similar safety and performance.

The use of aluminum tape on the wood bat may have affected the results because the tape was placed on the barrel of the bat, while the end of the bat achieves the highest speed during the swing.  If the radar were to measure the speed of the barrel of the wood bat and compare it to the speed of the end of the aluminum bat, then the apparent difference in swing speeds would be exaggerated. However, the experimenter discussed the issue with Al Dilz, the inventor of the port Sensors Bat Speed Radar, and he said that the bat radar reads the highest and lowest measurements of swing speed and then obtains an average to approximate the speed at the assumed sweet sport 6 inches from the end of the bat. Therefore, both the measurements of swing speed from the entire barrel of the aluminum bat and from both ends of the tape would have maximum and minimum speeds that would average to the swing speed at the bat's sweet spot, so the measurements would be comparable for statistical analysis.

Conclusion

Aluminum bats have lower MOIs than wood bats because of their weight distribution closer to the bat's handle. It was hypothesized that aluminum bats could achieve faster swing speeds and resulting ball exit speeds than wood bats, because of their lower MOI, given the same force input. This was tested by human subject testing in which a group of mainly high school baseball players swung both an aluminum and wood bat into bat speed radar. The average of the recorded swings speeds for both bats was used as input data in NCAA ball exit speed protocol testing of the two bats. The hypotheses were confirmed, as aluminum bats produced a mean swing speed of 67 mph compared to 59 mph for wood, while aluminum's mean ball exit speed was 97.6 mph, while that of wood was 86.4 mph.

References

Almond B.J. (2005). Do metal bats offer more bang for the buck? Retrieved February 11, 2007, from The Magazine of Rice University. http://www.rice.edu/sallyport/2005/spring/scoreboard/metalbats.html

Ashton-Miller J., Carroll M., Johnson K., Nathan A., Petr T. & Halpin T. (2003). The BESR (ball exit speed ratio). The Baseball Research Journal.

Ashton-Miller J., Carroll M., Johnson K., Nathan A. (2006). National collegiate athletic association standard for testing baseball bat performance. Retrieved on September 30, 2007 from The Physics of Baseball: Wood Vs. Aluminum Bats. <http://www.ncaa.org/releases/miscellaneous/1999092901ms.htm>

Crisco JJ, Greenwald RM, Blume JD, and Penna LH, "Batting performance of wood and metal bats," *Med. Sci. Sports Exerc.*, **34**(10), 1675-1684 (2002)

Dick R, Sauers EL, Agel J, Keuter G, Marshall SW, McCarty K, & McFarland E. (2007). *Descriptive* epidemiology of collegiate men's baseball injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *Journal of Athletic Training. Apr-Jun;42(2):183-93.*

Nathan A.M. (2003) Some thoughts on wood vs. aluminum bats. Retrieved September 4, 2007, from The Physics of Baseball: Wood vs. Aluminum Bats. < http://webusers.npl.uiuc.edu/~a-nathan/pob/MIAA.pdf>

Russell, D. (2007). How have Aluminum Bats changed Baseball?. Retrieved March 2, 2008, from Physics and Acoustics of Baseball & Softball <http://www.bradley.edu/campusorg/psiphi/DS9/ep/503r.html>

Wilson, D. (2008, October 18). Effort to Get Metal to Act Like Wood. *The New York Times*.