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Title: Experiments in Bat Design: Testing an Aluminum Bat with a Wood Bat's Weight Distribution and Do Aluminum Bats Have a Larger "Sweet Spot" than Wood Bats?

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 because 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 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 204 injuries as a result of batted balls, with pitchers accounting for 26% of severe batted ball injuries (Dick et al, 2007). An experimental study showed that a college pitcher needed a minimum of 0.368 seconds to catch or avoid a ball hit directly at him (Brandt, 1998), which would protect him from balls hit up to approximately 100 miles per hour (mph). Because the NCAA deemed the performance of aluminum bats and the rate of batted-ball injuries to be too high, in 1999 they required that all bats must weigh three ounces less than their length (in inches) and must conform to standards of the Ball Exit Speed Ratio (BESR), which relates the speed of the input pitch, swing speed and ball exit speed. The two BESR formulas are:

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

and

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

(Ashton-Miller et al, 2003).

In an attempt to monitor the BESR of aluminum bats used in college play, the NCAA approved a testing protocol in which a ball was fired from an air cannon at 136 mph (the sum of the assumed pitch speed of 70 mph and assumed swing speed of 66 mph) at a bat held initially at rest. The ball exit speed would then be measured, and these three variables 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 the moment of inertia (MOI) about the bat's handle, which is a property of the bat's resistance to rotation. The MOI is calculated using the formula $MOI = 9.7797T^2W (L - D - 6)$, where T is the period of the bat during pendulum testing in seconds, W is the weight of the bat in ounces, L is the length of the bat in inches and D is the distance in inches from the bat's handle to its center of mass (National Collegiate Athletic Association, 2006). A lower MOI would theoretically allow for a faster swing speed because the batter would encounter less resistance when attempting to swing the bat (Crisco and 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 add additional weight in the form of an epoxy-like substance to the interior of the bat's handle, shifting the center of mass closer to the batter's hands. This results in a lower MOI when compared to a wood bat of similar overall mass and barrel diameter. Today, manufactured bats are advertised as having higher swing speeds, including Nike's Aero Fuse, whose manufacturer asserts that the bat's design "increases swing 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 bats, after the implementation of the BESR standard the NCAA mean batting average reached a low of .290 in 2004, which was still much higher than .267 from 1974 (Russell, 2007). Because the existing BESR testing procedures did not appear to be completely effective in making the performance of aluminum bats similar to wood bats, this student designed a previous experiment to test whether the NCAA's assumed swing speed of 66 miles per hour was reflective of the actual swing speeds of aluminum and wood bats. Twenty-four human subjects were used for this prior experiment, in which each subject took twenty five swings with an aluminum and wood bat. The swing speeds were measured with a bat speed radar device, and the sample achieved average swing speeds of 67 mph with the aluminum bat and 59 mph with the wood bat. The average swing speeds were subsequently used in as input values for another experiment performed to obtain the ball exit speeds of an aluminum and wood bat that could be achieved with the swing speeds of real players. This experiment yielded average ball exit speeds of 97.6 mph for the aluminum bat and 86.4 mph for the wood bat. Overall, these two prior experiments showed that a sample of primarily high school baseball players achieved 13.6 and 13.0 percent faster swing and simulated ball exit speeds with the aluminum bat than with the wood bat (Cooney, in-press).

Because aluminum bats have been arbitrarily manipulated to have lower MOIs than wood bats, an aluminum bat could conceivably be produced with the same weight distribution and MOI as a wood bat. For this project, such an experimental aluminum bat was used, and an experiment was designed to determine whether this aluminum bat would achieve similar or dissimilar swing and ball exit speeds to a commercial wood bat.

<u>Hypothesis (Phase 1)</u>

It was hypothesized that if an aluminum bat is manipulated to have a similar MOI to a wood bat, then a batter will achieve similar swing speeds using the two bats, given the same force input.

Methods and Materials (Phase 1)

Three baseball bats were used for this experiment, the commercial aluminum and wood bats used in prior experimentation, as well as an experimental aluminum bat with a weight distribution similar to that of a wood bat. The three bats were measured in length with measuring tape and massed using a balance so that all three bats conformed to this experiment's predetermined standard of 33 inches long and 31 ounces in mass. However, the bats differed in their weight distributions, with the center of mass measuring 19.375, 21.937, and 22.486 inches from the handle for the commercial aluminum, wood and experimental aluminum bats, respectively. Since the center of mass is located closer to the batter's hands with the commercial aluminum bat, the commercial aluminum bat will have a lower moment of inertia (MOI) than the other two.

Eighteen human subjects were used for this experiment. Subjects were current and former players from the Mamaroneck High School baseball team. Human subject testing was approved by the Institutional Review Board at Mamaroneck High School. 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 high school baseball coach, certified in CPR, was present for all testing sessions.

A swing speed radar device manufactured by Sport Sensors was attached to an L-shaped screen within a batting cage. Because the radar device could only read the speed of metal objects, the wood bat was wrapped in an aluminum tape of negligible mass over a four-inch range of the barrel in the vicinity of the assumed vibrational node or, "sweet spot," of the bat. The height of the radar gun was based on the height of each subject's baseball swing. A batter, standing six feet away from the radar gun and holding either the aluminum or wooden bat, swung across the plane of the radar (the order with which the subjects swung the bats was varied to account for the variable of fatigue). The speed of the batter's swing was recorded by the Sports Sensor Bat Speed Rader device 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 another other bat. Then the batter took five swings with the second bat, and repeated this process with the third bat. The subject alternated taking five swings with the three bats until fifteen swings had been completed with each bat, at which point a new batter entered the cage and began the experiment. 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.

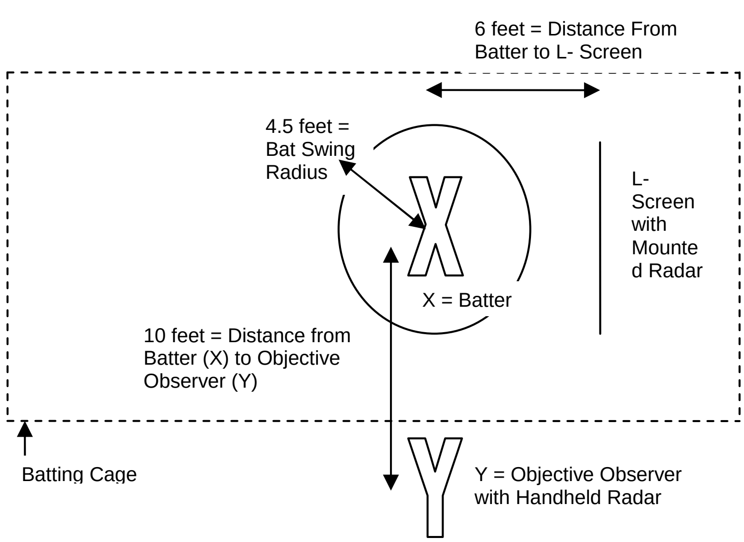

Figure 1. Experimental setup for swing speed

<u>Results (Phase 1)</u>

Eighteen human subjects were used for this experiment, of whom 5 were playing for Babe Ruth/ travel teams, 5 played high school Junior Varsity, 7 were on the high school Varsity team and 1 was a recent college graduate playing in Low-A level professional baseball[1]. For the entire group, the average swing speed with the commercial aluminum bat was 72 mph. However, the average swing speed for both the commercial wood bat and the experimental aluminum bat was 66 mph. This meant that, on average, this group of subjects swung the commercial aluminum bat about 9.1 percent faster than they swung the experimental aluminum bat and the commercial wood bat[2]. Both the difference in swing speed between the commercial aluminum and wood bats, as well as the difference between the wood bat and experimental aluminum bat were analyzed using matched-pair t-tests. With the difference of 6 mph between the commercial aluminum and wood bats, there was a standard deviation of 2.76 and a highly significant p-value of 5.00E-08. To analyze the difference in swing speed between the experimental aluminum and commercial wood bats, the actual difference of 0.03 mph was used to distinguish from the negligible difference produced when rounded to significant figures. The difference of 0.03 mph produced a standard deviation of 0.57 and a p-value of 0.83. This p-value is very insignificant, and implies that any difference between a typical wood bat and this modified aluminum bat is most likely due to chance.

<u>Hypotheses (Phase 2)</u>

The results from Phase 1 of this experiment demonstrated that if an aluminum bat has an MOI similar to that of a wood bat, then the two bats will achieve a similar swing speed. The results also confirmed the Phase 1 finding that the commercially available aluminum bat achieves a

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[1] Although a 23-year-old professional player's data was used, it did not significantly alter the percentage difference in swing speeds between the two bats. However, his data did help to demonstrate a positive correlation between age and absolute swing speed.

significantly higher swing speed than the wood bat, even after the modification of the wood bat wrapping described previously. Using the swing speeds obtained in Phase 1, an experiment was designed to explore how the swing speeds of real players would affect the ball exit speeds of the experimental aluminum bat and the commercial wood bat. It was hypothesized that the experimental aluminum bat would achieve a ball exit speed similar to that of the wood bat, given the same force input.

In addition, another experiment comparing the simulated game performance of the commercial aluminum and wood bats was designed. The greater mean NCAA batting average since the introduction of aluminum bats implies not only that players have been hitting the ball at a higher velocity with aluminum bats, but also that they are doing so more frequently. If aluminum bats do, in fact, result in greater ball exit speeds at a greater frequency than wood bats, then pitchers and infielders are at a greater risk of being injured by a batted ball. While the NCAA certification measures the ball exit speeds and ball exit speed ratios of bats at multiple points along the bat (National Collegiate Athletic Association, 2006), no experiment has ever compared how the ball exit speed of wood and aluminum bats vary at locations away from the point of maximum collision efficiency, or its “sweet spot”. To explore this idea, it was further hypothesized that if a commercial aluminum bat and a wood bat are swung with the same force, the aluminum bat will achieve a greater ball exit speed over a range of points of contact than a wood bat could achieve at its fastest point, its sweet spot.

Methods and Materials (Phase 2)

The second phase of this experiment was performed at the Baseball Research Center at the University of Massachusetts-Lowell, the site of official NCAA bat certification testing, and utilized the NCAA’s official procedures for measuring MOI and BESR. First, 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 two bats.

The next step was measuring ball exit speed for contact at the assumed sweet spot of 6 inches from the barrel end of the bat. This, which were represented by adjusted swing speeds of 67 mph for the commercial aluminum bat and 61 mph for the wood bat and experimental bat, due to limitations in the facility's testing capabilities[3] 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 mph (the assumed pitch speed) and 61 mph (the average bat speed measured in Phase 1), 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 experimental aluminum bat and commercial aluminum bats, with input swing speeds of 61 and 67 miles per hour, respectively.

After ball exit testing at the assumed sweet spot was completed, the wood bat was again placed into the testing apparatus to measure how the bat's ball exit speed varied when contact was not made at the assumed sweet spot. The purpose of this portion of the experiment was to determine whether the commercial aluminum bat would produce high ball exit speeds over a

[3] Because the NCAA's testing apparatus is only capable of producing combined pitch and swing speeds of up to 140 mph and the conventional assumed pitch speed is 70 mph, the measured swing speeds of 72 mph for the commercial aluminum bat and 66 mph for the wood and experimental aluminum bats from Phase 3 were reduced to 67 and 61, respectively. This was an absolute change of 5 mph for both bats, and the change also most accurately preserved the percentage difference in swing speed and kept the assumed pitch of 70 mph as used by NCAA testing.

greater range of points of contact than the wood bat. If this is true, then a real batter using a commercial aluminum bat would be more likely to achieve a high ball exit speed and pose a greater risk of injury to the pitcher and fielders. Testing a new point of contact at 5 inches from the barrel end of the bat, the ball was fired out of the air cannon at the sum of the assumed pitch speed of 70 mph and 64 mph (the previously measured 61 mph bat speed plus an assumed 3 mph because the points further away from the bat's handle travel a greater distance over the same time). This was repeated three times, and then the point of contact was moved to 7 inches from the barrel end of the bat. The cannon then fired the ball at the sum of the assumed pitch speed of 70 mph and 58 mph (the previously measured swing speed minus 3 mph) for three repetitions.

The commercial aluminum bat then replaced the wood bat in the testing apparatus, and the bat's ball exit speed was measured three times at points both 5 and 7 inches away from the barrel end of the bat (which are also points 1 inch on either side of the assumed sweet spot of 6 inches from the barrel end). The assumed pitch speeds were again 70 mph, while the input swing speeds were 70 and 64 mph for the points 5 and 7 inches away from the barrel end of the bat, respectively.

Results (Phase 2)

While the MOI for the commercial aluminum bat was 8,940 oz-in^2, the wood bat and experimental aluminum bat had higher MOIs of 10,600 oz-in^2 and 10,800 oz-in^2, respectively. At the assumed sweet spot of 6 inches from the barrel end of the bat, the experimental aluminum bat achieved an average ball exit speed of 97.9 mph, which was substantially higher than the wood bat's average speed of 89.7 mph. However, this bat had a Ball Exit Speed Ratio of 0.781, which is higher than the NCAA limit of 0.726 and thus would be deemed illegal for college and high school play. This would imply that shifting the weight distribution of the aluminum bat had an unexpected effect on the bat's collision efficiency. This idea will be addressed in greater detail in the discussion section of this paper.

At all three points of contact, the ball exit speed off of the commercial aluminum bat exceeded that of the wood bat by between 8.3 and 10.2 mph, while the percentage difference varied from 8.90 to 12.41 percent. The wood bat achieved ball exit speeds of 93.3, 89.7 and 82.2 mph at the points 5, 6 and 7 inches away from the barrel end of the bat, respectively. At the same points, the commercial aluminum bats achieved ball exit speeds of 101.6, 98.7 and 92.4 mph. A comparison of the ball exit speeds of the two bats at these three points is presented with a data table in Table 1.

Table 1. Distance from barrel end of bat (in inches) vs. ball exit speed for aluminum bat and wood bat (in mph)

Distance (in inches)	Wood Bat (in mph)	Aluminum Bat (in mph)	Difference (in mph)	Percentage Difference
5	93.3	101.6	8.3	8.90
6	89.7	98.7	9.0	10.03
7	82.2	92.4	10.2	12.41

Discussion

Although aluminum bats conform to the current NCAA standards on safety and performance based on laboratory testing with an assumed swing speed, the results of this experiment reflect the actual mean swing speed of a sample of mainly high school baseball players. As the ball exit speed testing in Phase 2 was performed based on the mean results of the Phase 1 swing speed tests, the BESR values of the mean swing speed were used to extrapolate the $V_{\text{ball exit}}$ corresponding to each of the subject's wood and aluminum bat swing speeds obtained in Phase 1 experimentation. The results of this extrapolation are displayed graphically in Figure 2.

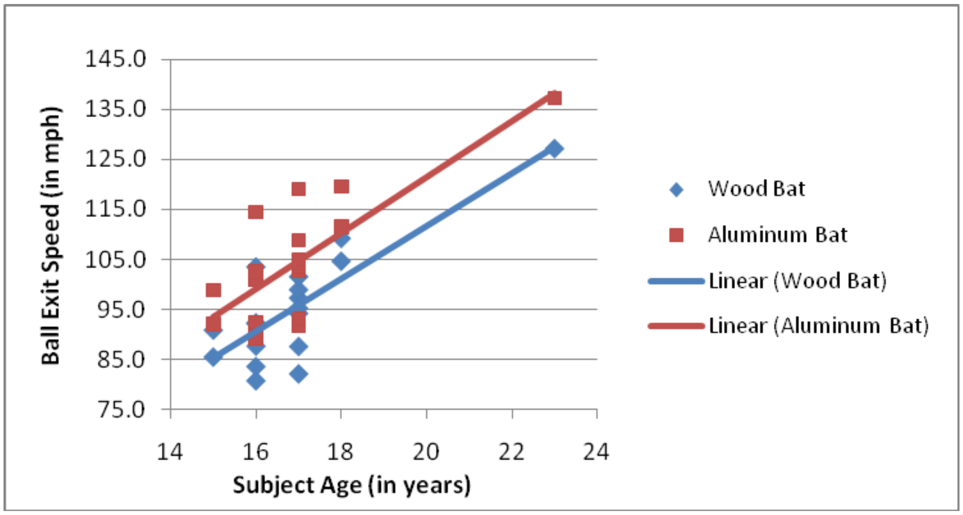

Figure 2. Scatter-plot and linear regressions of extrapolated projected ball exit speeds for commercial aluminum and wood bats (in mph) using BESR formula and swing speeds from Phase 3, compared with subject age.

The upward trendline in Figure 2 show a positive correlation between age and increased swing and ball exit speeds, and seem to indicate that older, stronger players at the collegiate level would be able to achieve greater absolute swing and ball exit speeds than the high school players used in the previous study. However, even with this experiment, which used the swing speeds of predominately high school players as its source data, the minimum reaction time for a pitcher to catch or avoid a ball hit at him, as defined in the 1998 study by Brandt, came into play. Using the wood bat, Brandt's limits of 100 mph and 0.368 seconds was exceeded by only one 17 year old as well as both 18 year olds and the 23 year old professional. By contrast, these limits were exceeded with commercial aluminum bats by half of the 16 year old players, all but one of the 17 year olds and all three older players.

The NCAA's official BESR testing uses an assumed swing speed of 66 mph, so it does not take into account properties of the bat that affect swing speed, such as MOI. In Phase 4 testing, as hypothesized, the commercial aluminum bat produced higher ball exit speeds than the wood bat, due to the greater swing speeds that result from its lower MOI. This occurred at all three points that were tested, which covered a two inch range on the bat. On the aluminum bat, the point seven inches from the barrel end of the bat yielded its slowest ball exit speed of 92.4 mph. This measurement was faster than the ball exit speeds of the wood bat at the 6 and 7 inch points, and was only slightly slower than the wood bat's fastest average reading of 93.3 mph at the point 5 inches from the barrel end. Over the points measured on the two inch range, a quadratic regression of the aluminum bat's ball exit speed yielded the curve with the equation $y = -1.6683x^2 + 15.385x + 66.415$. The curve intersects with the fastest wood bat speed of 93.3 mph at the point 6.88 inches from the barrel end of the bat, which implies that an aluminum bat produces ball exit speeds equal to or greater than the fastest speed possible for a wood bat over 1.88 of the 2 inches measured. The distribution of ball exit speeds for both bats is shown graphically in Figure 4.

Due to limited availability of the laboratory equipment, it was only possible to test three points of contact for this experiment: 5,6 and 7 inches from the barrel end of the bats. Although the sweet spot was assumed to be 6 inches from the barrel end, the fastest ball exit speed for both bats was recorded at the 5-inch point. This may mean that the actual sweet spot is located at the 5 inch point, or it may be located somewhere between the 5 and 6 inch points, or somewhere closer than 5 inches from the barrel end. Experimental data did show that the commercial aluminum bat's ball exit speed exceeds the fastest ball exit speed recorded for the wood bat over at least a range of 1.88 inches; however, it is likely that if contact points on the entire barrel were tested, the range would be substantially larger.

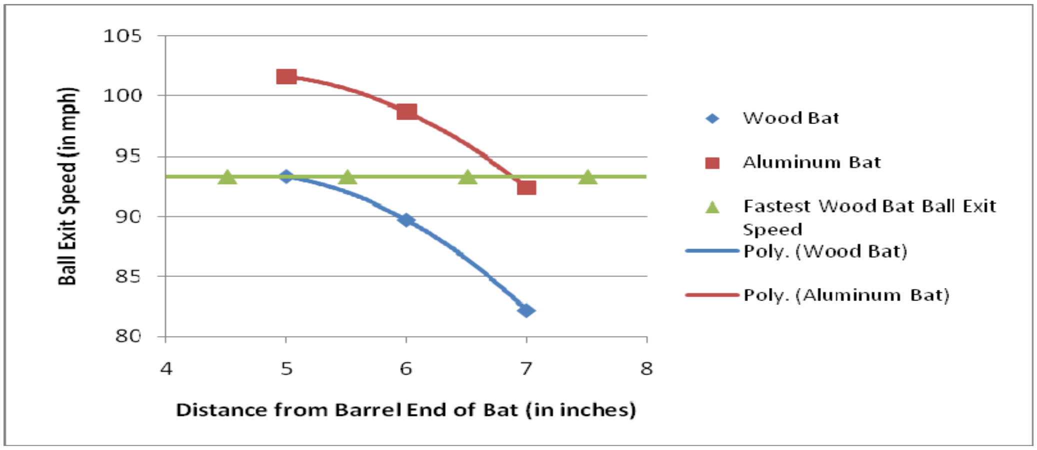

Figure 3. Ball exit speeds and polynomial (specifically quadratic) regression for commercial aluminum and wood bats at points of contact 5, 6 and 7 inches away from the barrel end.

Even with the minimum possible range of 1.88 inches, the results imply that in actual game play, a hitter has a greater probability of achieving a high ball exit speed with an aluminum bat, which may explain why the NCAA's mean batting average experienced a large increase of 39 points since the introduction of the aluminum bat in 1974. This also means that a batter has a greater probability of hitting a line drive that poses a risk of injury to the pitcher and infielders.

The experimental aluminum bat produced for this experiment had an MOI of 10,800 oz-in^2, which was only very slightly greater than the wood bat's MOI of 10,600 oz-in^2. The results of swing speed tests in Phase 1 of the experiment confirmed that this bat achieves a very similar swing speed to the wood bat, both of which were approximately 66 mph. Although the experimental aluminum bat achieved a very similar swing speed to the wood bat, the hypothesis that this would result in similar ball exit speeds was not confirmed, as the experimental aluminum bat achieved a ball exit speed approximately 8.2 mph faster than that of the wood bat. Most likely this meant that the actions taken by Rawlings to create the shift in MOI had an unintended effect on the bat's collision efficiency, causing it to have an illegally high BESR of 0.781.

While the barrel of a wood bat is made of solid wood, the aluminum bat's barrel is composed of a thin, elastic wall of aluminum. When ball exit speed testing is performed on commercial aluminum and wood bats, the BESR, which measures the efficiency of the ball-bat collision, is the same for both bat types. However, the collision efficiency was much higher for the experimental aluminum bat, which had the same MOI as the wood bat. This appears to imply that by shifting the aluminum bat's center of mass further from the batter's hands, there is now a larger mass in its barrel. Because the barrel of the experimental aluminum bat remained more elastic than that of the wood bat, the increase in the aluminum bat's barrel mass could be the primary cause for the bat's dramatic increase in BESR.

This possibility introduces an interesting question for future research: How would one be able to create an aluminum bat with both the same weight distribution and collision efficiency of a wood bat? One possible design would be to take an aluminum bat with the MOI of a wood bat, and then increase its wall thickness. This would make the wall of the aluminum bat stiffer, and could eventually result in this bat having a collision efficiency similar to that of a typical wood bat. In order to minimize cost, design and analyses of this bat and its performance could be conducted using finite element analysis, which would allow researchers to experiment with different design variables until the desired bat properties are reached. If such an aluminum bat could be produced, then aluminum bats would finally fulfill their original purpose, as cost effective substitutes for wood bats with similar safety and performance characteristics.

Conclusion

It was hypothesized that the commercial aluminum bat would achieve ball exit speeds equal to or greater than those of a wood bat over a significant range of the bat's barrel, not just at the optimal point. These hypotheses were confirmed. The average of recorded swing speeds for the commercial aluminum and wood bats were 72 and 66 mph, respectively. When these swing speeds were then used as input values[4] for ball exit speed testing, the commercial aluminum bat produced a mean ball exit speed of 98.7 mph, while wood bats produced a mean ball exit speed of 89.7 mph at the assumed sweet spot six inches from the barrel end of the bat. It was also demonstrated that an aluminum bat could achieve a greater ball exit speed over a range of points of contact than a wood bat could achieve at its fastest point. The experiment showed that when the swing speeds of real players are used, a commercial aluminum bat both achieves a greater absolute ball exit speed and a greater likelihood for a high exit speed than a wood bat can. This means that aluminum bats enable a batter to achieve a better performance than wood bats, but may also increase the risk of injury to the pitcher and fielders.

Additionally, it was also hypothesized that if an experimental aluminum bat is designed to have the same or nearly the same MOI as a wood bat, it would achieve the same or nearly the same swing speed as the wood bat. This hypothesis was confirmed, as the bats were both swung at a speed of 66 mph. However, the manipulation of the experimental aluminum bat's MOI apparently had an effect on that bat's collision efficiency causing its BESR to become illegally high. This means that although it has been well demonstrated that current commercially available aluminum bats allow batters to achieve greater swing and ball exits speeds than wood bats (and thus are more likely to cause injury to other players), further design and testing research would be required in order to develop an aluminum bat that performs identically to a wood bat.

[4] As noted in the methods of Phase 2, a limitation in the testing capabilities required that the swing speeds of all three bats be reduced by 5 mph for their use as inputs in ball exit speed testing.

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