RELATIONSHIP BETWEEN BAT MASS PROPERTIES AND BAT VELOCITY

Glenn Fleisig, Nigel Zheng, David Stodden, James Andrews
American Sports Medicine Institute, Birmingham, Alabama, USA

Seventeen male collegiate baseball players and seventeen female collegiate softball players were tested hitting with aluminum alloy bats with various weights and moments of inertia. The ball and bat were tracked with a motion analysis system. ANOVA revealed significant differences in bat linear velocity among the baseball bats and among the softball bats. Variations in bat angular velocity were non-significant for both the baseball bats and softball bats. There was a linear correlation between linear velocity and moment of inertia for both baseball and softball bats. To limit bat velocity, regulating both bat weight and center of gravity location would be a practical solution.

KEY WORDS: baseball, softball, bats, weight, moment of inertia, speed

INTRODUCTION: Wood bats break. To avoid this problem, aluminum alloy bats were developed for baseball and softball as a less expensive, more durable alternative. As bat technology advanced, questions arose regarding the relationship between bat design, performance, safety, and stricter regulations.

Welch *et al.* (1995) quantified bat and body biomechanics for seven minor league players hitting standard baseballs off a practice tee with standard wood bats. Data from this study showed that all hitters used rotational and linear movements, but the emphasis between rotation and linear motion varied between hitters. Because of the complexity of batting biomechanics shown, there is no reason to assume that linear bat velocity would be simply proportional to bat weight. Bahill and Freitas (1995) studied the effects of varying bat weight in maximizing ball velocity. Each subject was tested swinging six different bats at imaginary baseballs. Bat velocity data were analyzed with collected anthropometric measurements to determine guidelines for selecting ideal bat weight. While the studies by Welch *et al.* and by Bahill and Freitas provided information about batting, both were limited by simulated batting (i.e. hitting imaginary baseballs and baseballs off a tee). The current study attempted to control for swing timing and mechanics by utilizing a pitching machine, thus placing more emphasis on bat velocity changes due to changes in bat mass properties.

The purpose of this study was to determine the relationship between bat mass properties (weight and moment of inertia – or "MOI") and bat velocity (linear and angular velocity). It was hypothesized that for both baseball and softball, there is a significant correlation between decreased bat mass properties and increased bat velocity.

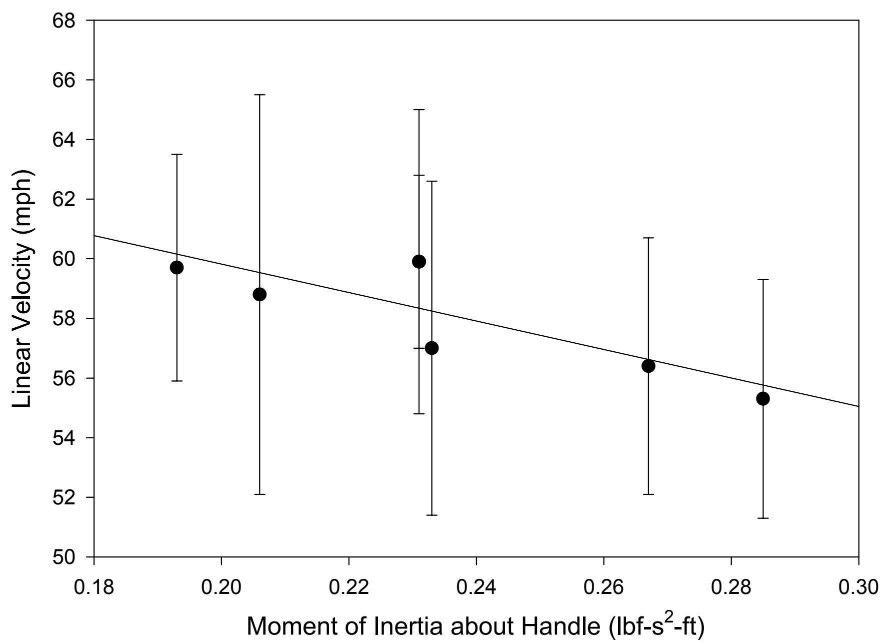
METHODS: Seventeen male collegiate baseball players and seventeen female collegiate softball players were used as volunteer participants. Five variations of a Louisville Slugger TPS softball bat were used, including an unmodified bat, a light weight added into the handle, a heavier weight added into the handle, a light weight added into the barrel, and a heavier weight added into the barrel. Five similar variations of an Easton B5 baseball bat were used, including an unmodified bat, a light weight added into the handle, a heavier weight added into the handle, a light weight added into the barrel, and a heavier weight added into the barrel. Nine male participants were also randomly selected to test two lighter unmodified bats - an Easton BE40W and a Louisville Slugger TPX. Reflective tape was wrapped around each bat at the barrel end and top of the handle (56 cm from the barrel end).

All testing was conducted in a large indoor laboratory equipped with a four-camera 200 Hz automatic digitizing motion analysis system (Motion Analysis Corporation, Santa Rosa, CA). A pitching machine pitched standard collegiate baseballs and softballs covered with reflective tape. The order of bats was randomized for each participant. After taking one or two warmup swings with a given bat, the batter took three swings for data collection. If the batter did not like a swing for any reason (bad pitch location, uncomfortable swing, etc.), the trial was repeated.

Three-dimensional motion of the reflective tape on the bat and ball were calculated with the motion analysis system. The three-dimensional position of the bat's "sweet spot" was calculated in each frame as a point 15 cm from the barrel marker toward the handle marker. This selection for sweet spot location was similar to the center of percussion data found by Noble and Eck (1986) and by Brody (1986). Sweet spot linear velocity and bat angular velocity right before ball impact were then calculated for each swing. Linear and angular velocity were calculated for all trials that could be accurately digitized and analyzed. When velocity data for more than one trial for a particular subject using a particular bat were available, the data for the multiple trials were averaged.

Velocity differences among the different baseball bats were tested using a one-way repeated-measures analysis of variance (ANOVA), with an alpha level of 0.05. Correlation coefficients were determined for bat mass properties (weight and MOI) and bat velocity (linear and angular). A linear regression analysis was performed to quantify the relationship between bat mass properties and bat velocity. An identical statistical approach was used for the softball bat data.

Figure 1. Relationship Between Baseball Bat Linear Velocity and MOI.



RESULTS: For both baseball and softball, the ANOVA revealed significant differences for linear velocity between various bats. Differences in angular velocity were not significant. As hypothesized, decreased bat mass properties correlated with increased bat velocity. In particular, baseball bat linear velocity had a significant correlation with bat MOI, but not with bat weight (Figure 1). Baseball bat angular velocity had a significant correlation with both bat weight and bat MOI. Softball bat linear velocity had a significant correlation with bat MOI, but not with bat weight (Figure 2). Similarly, softball bat angular velocity correlated significantly with bat MOI, but not with bat weight. Simple linear regressions were calculated for each of these significant correlations. In addition, multiple linear regressions were calculated between bat velocity and the two bat mass properties, MOI and weight. Because U.S. bat design specifications and league regulations are in U.S. customary units (i.e. ounces, inches, mph), these units were used in reporting the results. The regressions were as follows:

BASEBALL

Linear Velocity = 69.6 – 48.7·(MOI) $R^2 = 0.657$

Linear Velocity = 63.6 – 71.5·(MOI) + 0.367·Weight $R^2 = 0.699$

Angular Velocity = 3070 – 28.7·Weight $R^2 = 0.499$

Angular Velocity = 2740 – 2390·(MOI) $R^2 = 0.692$

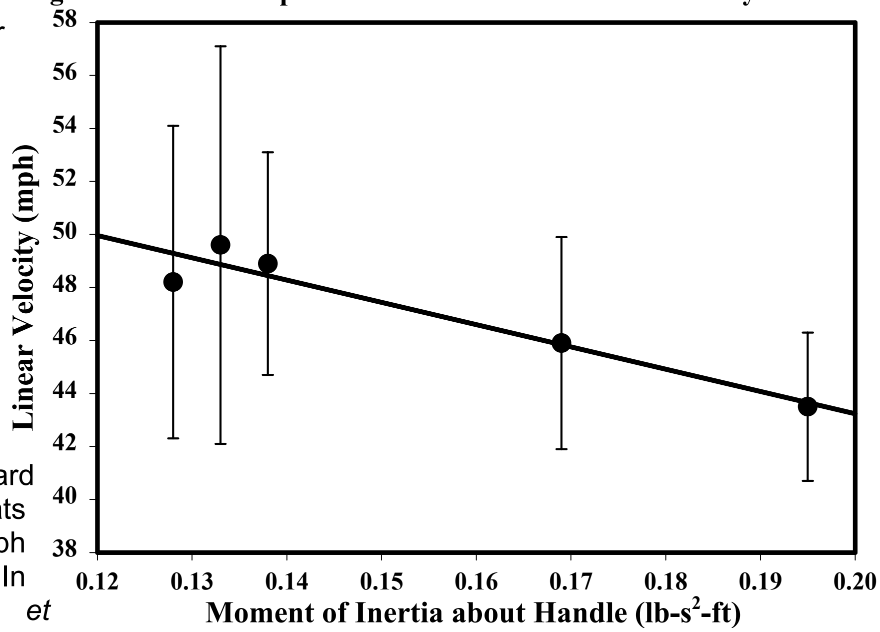
Angular Velocity = 2670 – 2680·(MOI) + 4.73·Weight $R^2 = 0.695$

SOFTBALL

Linear Velocity = 60.0 – 83.5·(MOI) $R^2 = 0.922$
Linear Velocity = 62.1 – 79.6·(MOI) + 0.106·Weight $R^2 = 0.926$
Angular Velocity = 2130 – 1940·(MOI) $R^2 = 0.922$
Angular Velocity = 2240 – 1740·(MOI) - 5.51·Weight $R^2 = 0.939$

with the following units -
Linear Velocity: miles/hour
Angular Velocity: °/s
Weight: ounces
MOI: poundforce·second^2·feet

Figure 2. Relationship Between Softball Bat Linear Velocity and MOI.



DISCUSSION: The complex biomechanics of batting yielded bat trajectories that included both linear and rotational motion. Sweet-spot linear velocity mean values for standard unmodified baseball bats ranged from 59 to 60 mph in the current study. In comparison, Welch *et al.*(1995) measured bat tip velocity as 73 mph for minor league batters hitting a ball on a tee. Sweet-spot linear velocity with a 23-ounce softball bat averaged 50 mph in the current study, and 59 mph for one elite softball batter swinging at an imaginary ball in the study by Bahill and Freitas (1995). Comparison of angular velocity to these previous works is not possible since neither previous study reported data on angular motion of the bat through space.

The interest in bat velocity is based upon its effect on batted ball velocity, and resulting batting performance and fielding safety. Hendee, Greenwald, and Crisco (1998) explained that batted ball velocity depends on bat velocity, pitched ball velocity, the ball's coefficient of restitution (or "liveliness"), the bat's flexural properties (the "trampoline effect"), the bat's curvature, and the impact location on the bat. During impact, momentum (mass x velocity) is transferred from the bat to the ball. Increasing bat velocity increases the bat's momentum, momentum transfer, and batted ball velocity. However, reducing a bat's weight and MOI decrease the bat's effective mass, resulting in decreased ball velocity. The current study showed the effects of bat mass properties on bat velocity, but did not investigate the effects on batted ball velocity. Although batted ball velocity could be calculated from the data collected, the results would not be relevant because the weighting and machining of the bats in this study affected the bats' flexural properties and momentum transfer. Future research to measure batted ball velocity from commercially available bats would be insightful.

Controlling bat velocity by regulating MOI would be difficult. Bat manufacturers would have to measure MOI during their design and testing. Leagues and organizations would have to be able to measure MOI, both before a bat model was approved and when a specific bat used requires scrutiny. Furthermore, most league officials, coaches, and players would never understand the concept of MOI. While weight is not as strongly related to bat velocity as MOI is, bat weight is much easier to understand and measure. A practical compromise may be for organizations to regulate both bat weight and center of gravity (or "balance point") since MOI is a function of mass and mass distribution [MOI = Σ $(m \cdot r^2)$].

In addition to regulating bat dimensions and mass properties, organizations are now looking into dynamic bat testing devices. The basic premise is to determine velocity of a ball hit with a bat in a realistic simulation. Typically, the handle of a bat is mounted into a device that rotates the bat. A ball is projected towards the rotating bat, with the initial velocity of the ball and bat predetermined. Velocity of the batted ball is then measured. There are many limitations of such testing, including the motion, grip, and torque applied to the bat. This study found that pure rotation is not an accurate model of bat motion. Secondly, the tightness of the grip on the bat handle will effect batted ball velocity. A loose grip will have a lower batted ball velocity than a tighter grip. A third limitation of current bat devices is that they test different bats at constant bat speeds. The data from the current study clearly shows that this is not realistic. A better simulation would be if all bats were tested with a similar applied torque.

CONCLUSION: Batting biomechanics are complicated and controversial. Advances in bat materials and design have led to aluminum alloy bats that are stronger and lighter than their predecessors. As hypothesized, the current study found that bat velocity increased with decreased bat mass properties. The strongest relationship for both baseball and softball was a linear correlation between bat MOI and bat linear velocity. Results from this study can help in understanding and regulating baseball and softball bats in order to maintain the balance of play and safety of these great games.

REFERENCES:

Bahill A.T. and Freitas M.M. (1995) Two methods for recommending bat weights. *Annals of Biomedical Engineering*, **23**, 436-444.

Brody H. (1986) The sweetspot of a baseball bat. *American Journal of Physics*, **54**, 640-642.

Hendee S.P., Greenwald R.M., and Crisco J.J. (1998) Static and dynamic properties of various baseballs. *Journal of Applied Biomechanics,* **14**, 390-400.

Noble L, Eck J. (1986) Effects of selected softball bat loading strategies on impact reaction impulse. *Medicine and Science in Sports and Exercise*, **18**, 50-59.

Welch C.M., Banks S.A., Cook, F.F. and Draovitch P. (1995) Hitting a baseball: a biomechanical description. *Journal of Orthopaedic & Sports Physical Therapy*, **22**, 193-201.

ACKNOWLEDGEMENTS: This study was funded by a grant from the NCAA. Modified and unmodified bats provided by Keith Koenig, Ph.D., Mississippi State University.