ISSN 0262 4079

6 April 1991 No 1763 Weekly

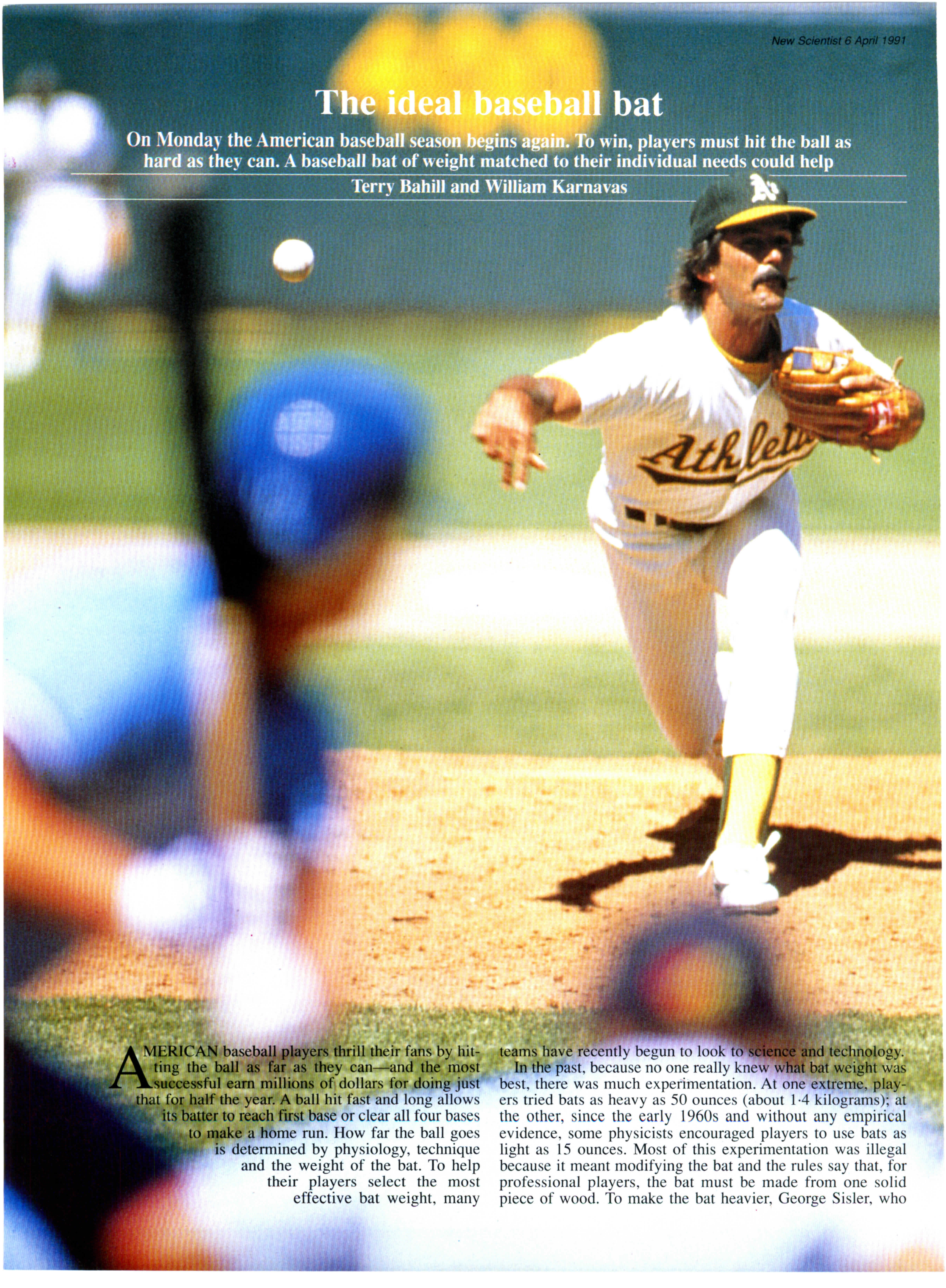
newscientist

A BETTER BASEBALL BAT

The ideal baseball bat

On Monday the American baseball season begins again. To win, players must hit the ball as hard as they can. A baseball bat of weight matched to their individual needs could help

Terry Bahill and William Karnavas



AMERICAN baseball players thrill their fans by hitting the ball as far as they can—and the most successful earn millions of dollars for doing just that for half the year. A ball hit fast and long allows its batter to reach first base or clear all four bases to make a home run. How far the ball goes is determined by physiology, technique and the weight of the bat. To help their players select the most effective bat weight, many teams have recently begun to look to science and technology.

In the past, because no one really knew what bat weight was best, there was much experimentation. At one extreme, players tried bats as heavy as 50 ounces (about 1·4 kilograms); at the other, since the early 1960s and without any empirical evidence, some physicists encouraged players to use bats as light as 15 ounces. Most of this experimentation was illegal because it meant modifying the bat and the rules say that, for professional players, the bat must be made from one solid piece of wood. To make the bat heavier, George Sisler, who played first base for the Saint Louis Browns in the 1920s, hammered Victrola phonograph needles into his bat barrel, and in the 1950s Ted Kluszewski of the Cincinnati Reds knocked in big nails. To make the bat lighter, many players have drilled a hole in the end of the bat and filled it with cork. Norm Cash of the Detroit Tigers admits that he used a corked bat in 1961 when he won the American League batting title with a ·361 batting average (he hit the ball and reached first base safely in 36·1 per cent of his batting attempts). However the corked bat may have had little to do with his success, because he presumably used a corked bat the next year when his batting average slumped to ·243. Some players have been caught publicly using doctored bats. In 1974 the bat of Graig Nettles of the New York Yankees shattered as it made contact with the ball, and out flew six bouncy Super Balls. In 1987 Billy Hatcher of the Houston Astros hit the ball and his bat split open spraying cork all over the infield.

In continuing the attempt to discover the best bat weight, we applied the principles of physics and physiology. First we used two equations from physics. The principle of conservation of momentum states that the momentum (mass multiplied by velocity) of the bat plus the ball before the collision must be the same as that after the collision. For the science of baseball, mass and weight are interchangeable. Figure 1 shows a collision between a ball and a bat, and the associated equation for the conservation of momentum. It also shows the relationship associated with the bounciness of objects, known as the coefficient of restitution. This is the ratio of the speed of the ball relative to the bat after a collision compared with that before the collision.

Spalding Sports Worldwide, which has exclusive rights to make baseballs for the professional game, carefully controls the manufacturing process to ensure that the coefficient of restitution of the bat-ball collision is 0·55, the figure enshrined in the rule book. If fans suspect an error they are quick to point it out. For instance, every time there are a dozen or so home runs more than normal they yell from the grandstand or complain through the press of a "rabbit ball". The manufacturer then has to publish its test results or demonstrate in public that the ball is not livelier than normal, or both. If the coefficient of restitution were found to be higher than 0·55, the manufacturer's embarrassment would be akin to that of a supplier of cricket balls if one of them was found to be hollow.

Combining the two equations for the conservation of momentum and for the coefficient of restitution shows that the ball's speed after its collision with the bat, called the batted-ball speed, depends on the weight of the ball and bat, the coefficient of restitution and the pre-collision speed of the ball and bat. Most of these parameters are readily available; the properties of the bat and ball are well known and television commentators routinely use radar guns to measure the speed at which the ball is pitched. Although combining the two equations allows us to ignore the bat's speed after its collision with the ball, we still need to know the bat's speed before the collision. There was little information about bat speeds, so we performed experiments to measure them.

Our instrument for measuring bat speed, the Bat Chooser, has two vertical light beams, each with associated light detectors similar to the electric eyes on lift doors. The subjects were positioned so that when they swung, the centre of mass of the bat passed through the light beams. A computer recorded the time between interruptions of the light beams. Knowing the distance between the light beams and the time required for the bat to travel that distance, the computer calculated the speed of the bat's centre of mass for each swing. Players were positioned so that bat speed was measured at the point where they normally try to make contact with the ball.

We told the batters to swing each bat as fast as they could while still maintaining control. We said: "Pretend you are trying to hit a Nolan Ryan fastball." (Nolan Ryan is one of the greatest contemporary pitchers in the US.)

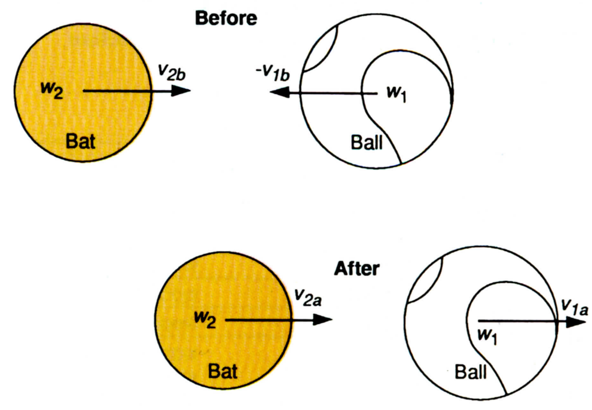


Figure 1 *Conservation of momentum in a bat-ball collision*

The equation for the conservation of momentum is

$$W_1V_{1b} + W_2V_{2b} = W_1V_{1a} + W_2V_{2a}$$

where the subscript 1 represents the ball, 2 the bat, b stands for "before collision" (top diagram), and a stands for "after collision" (bottom diagram).

For baseball, the coefficient of restitution is

$$e = -\frac{V_{1a} - V_{2a}}{V_{1b} - V_{2b}}$$

Combining the two equations, the batted-ball speed is

$$V_{1a} = \frac{(W_1 - eW_2)V_{1b} + (W_2 + eW_2)V_{2b}}{W_1 + W_2}$$

In our experiments each adult swung six bats through the light beams. The bats ran the gamut from super-light to super-heavy; yet they had similar lengths and weight distributions. In our developmental experiments we tried about four dozen bats. We used aluminium bats, wooden bats, plastic bats, heavy metal warm-up bats, bats with holes in them, bats with lead in them, major league bats, college bats, softball bats, Little League bats, brand-new bats and bats more than 40 years old.

In one typical set of experiments, we used six bats of significantly different weights but which were all about 35 inches (89 centimetres) long, with a centre of mass about 23 inches from the end of the handle (see Table 1).

Our Little League players, from 10 to 12 years old, could not swing the extremely heavy bats and tired before the experiments were over. So we let them use fewer, lighter ones (see Table 2). However, even with this set we still saw signs of fatigue in half the subjects.

In a 20-minute interval, every subject swung each bat through the instrument five times. The order of presentation was randomised. The selected bat was announced by a speech synthesiser, for example: "Please swing bat Hank Aaron, that is, bat A." (We named our bats after famous baseball players who had names starting with the letter assigned to the bat.)

We recorded the bat weight and the speed of the centre of mass for each swing, which allowed us to calculate the batted-ball speed. But that was as far as physics could take us; we then had to look to the principles of physiology.

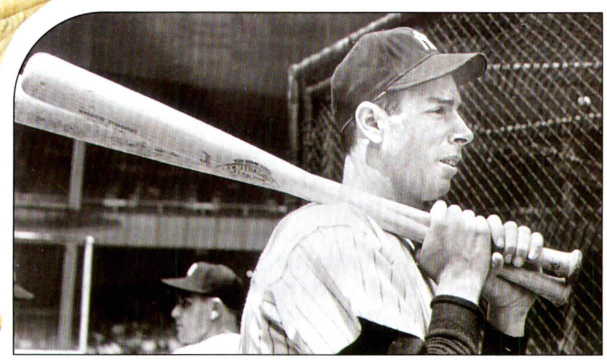
Physiologists have long known that muscle speed decreases with increasing load and that, because muscle power depends

Robert Beck/ AllSport

Table 1 Test bats used by professional players

Name	Weight (ounces)	Distance from the end of the handle to the centre of mass (inches)	Composition
D	49·0	22·5	aluminium bat, filled with water
C	42·8	24·7	wooden bat, filled with lead
A	33·0	23·6	wooden bat
B	30·6	23·3	wooden bat
E	25·1	23·6	wooden bat
F	17·9	21·7	wooden handle mounted on a light, steel pipe with a 6-ounce weight at the end

Terry Bahill



Photographs: Bettmann Archives

Joe Di Maggio hit home runs without "fixing" his bat…

on speed as well as on load, there is a speed at which muscles produce most power. This is why bicycles have gears; gears enable riders to maintain the muscle speed that imparts maximum power through the pedals, while the load, as reflected by the bicycle speed, varies greatly. To discover how the muscle properties of individual baseball players affect their best bat weights, we plotted bat speeds as a function of bat weight to produce graphical numerical models of each player, known as muscle force-velocity relationships (see Figure 2). The lower curve is for Alex Bahill, a 10-year-old Little League player; the upper curve is for a professional baseball player, a member of the San Francisco Giants. (Unless they remain anonymous, professional players can demand high fees from researchers.) The circles represent the average of the five swings of each bat; the vertical bars on each circle represent the standard deviations.

Over the past 50 years physiologists have used three equations to describe the force-velocity relationship of muscles: straight lines, hyperbolas and exponentials. Each of these equations has produced the best fit for some experimenters, under certain conditions, with certain muscles. But usually the hyperbola fits the data best. In our experiments, we tried all three equations and chose the one that best fitted the data of each subject's 30 swings. For the data of the force-velocity relationships illustrated in Figure 2, we found that hyperbolas provided the best fits.

These curves indicate how bat speed varies with bat weight. We now want to find the bat weight that will make the ball leave the bat with the highest speed and thus have the greatest chance of eluding fielders. We call this bat weight the maximum-batted-ball-speed bat weight. To calculate this bat weight we must couple the muscle force-velocity relationships to the equations of physics.

For one of the professional players we tested, we found that the best fit for his force-velocity data was a straight line. When we substituted this straight line for the bat speed before collision (v_{2b}) in the batted-ball speed equation (see Figure 1), we were able to plot the ball speed after collision as a function of bat weight (see Figure 3). This curve shows that the maximum-batted-ball-speed bat weight for this subject is about 40 ounces, which is heavier than that used by most batters. However, this batted-ball speed curve is almost flat between 34 and 49 ounces. There is only a 1·3 per cent difference in the batted-ball speed between a 40-ounce bat and the 32-ounce bat normally used by this player. Evidently the greater control permitted by the 32-ounce bat outweighs the 1·3 per cent increase in speed that could be achieved with the 40-ounce bat.

Table 2 Test bats used by Little Leaguers

Name	Weight (ounces)	Distance to the centre of mass (inches)	Composition
A	40·2	17·8	wooden bat with iron collar
C	23·1	17·6	aluminium bat
D	16·9	17·0	wooden junior bat
B	5·2	17·6	plastic bat

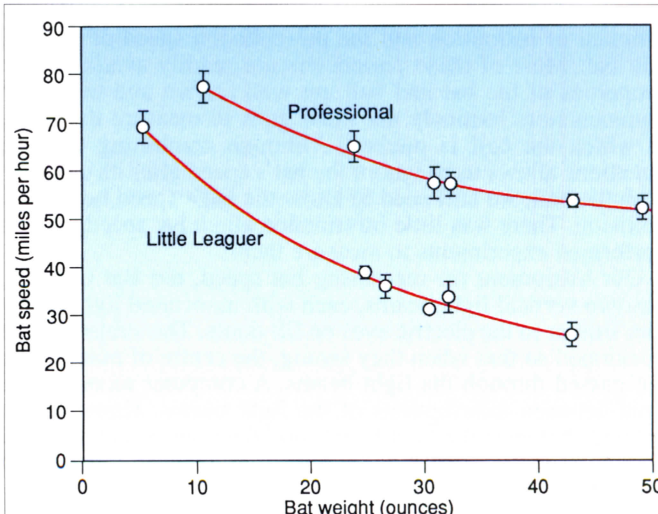
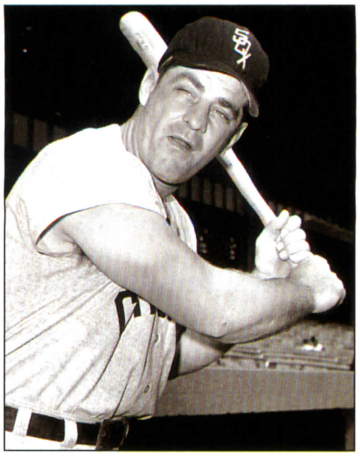


Figure 2 *Bat speed as a function of bat weight, illustrating the classical force-velocity relationship of muscles*

The maximum-batted-ball-speed bat weight is not the best bat weight for any player, however. A lighter bat will give a player better control and more accuracy. Obviously a trade-off must be made between batted-ball speed and control. Because the batted-ball speed curve is so flat around the point of the maximum-batted-ball-speed, we believe there is little advantage in using a bat as heavy as the maximum-batted-ball-speed bat weight. Therefore, we have defined the ideal bat weight to be the weight where the ball speed curve drops 1 per cent below the maximum-batted-ball speed. Using this criterion, the ideal bat weight for this subject is 33 ounces. We believe this gives a reasonable trade-off between distance and accuracy.



...Ted Kluszewski knocked in nails

What might Babe Ruth have achieved with a modern lightweight bat instead of a heavy hickory one?

...and George Sisler in his day tried phonograph needles

How significant is the 1 per cent parameter used to define the ideal bat weight? For all our subjects, successive swings of the bat usually differed by more than 1 per cent. For our major league players, we calculated the average variation of bat speed when the normal major league bats (bats weighing 31 and 33 ounces) were swung. The average variation was 5·4 per cent. The bat speeds of younger players varied even more. This means that the normal variability between consecutive swings of a normal bat would produce more than the 1 per cent reduction in ball speed used to define the ideal bat weight.

Of course, our 1 per cent rule is subjective and each player might want to give different weights to the two factors, distance and accuracy. It does, however, give a quantitative basis for comparison. The player we measured is a typical member of the San Francisco Giants, except that his swings were slower but more consistent than most. He is a "control hitter". He tries to control his bat accurately and just get "singles"—hits that enable him to reach first base.

For contrast, we studied a San Francisco Giant who was a less consistent hitter. He is a "slugger". He controls his bat less accurately, but when he does make contact he often gets home runs. Indeed, our slugger hit 47 home runs in 1989 to lead the major leagues. His data are a best fit with a straight line, which yields an ideal bat weight of 32 ounces (see Figure 4). It is surprising that although the two players and their data are so dissimilar, their ideal bat weights are nearly the same. These data contrast dramatically with data from 10-year-old Alex (see Figure 5). A hyperbola fits his bat speed data best and yields an ideal bat weight of 15 ounces.

The ideal bat weight varies from person to person. We calculated the means and the standard deviations of ideal bat

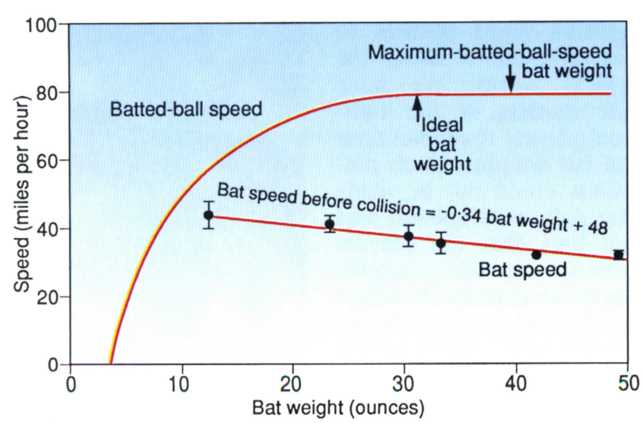


Figure 3 *Bat speed and calculated batted-ball speed as functions of bat weight for a 90 miles-per-hour pitch to a "control hitter" of the San Francisco Giants baseball team*

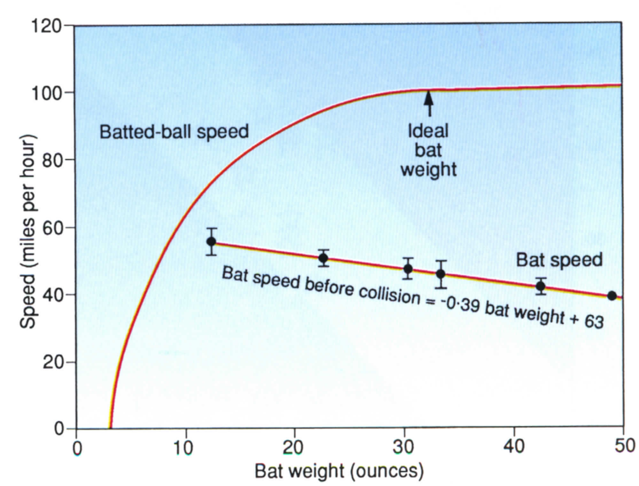


Figure 4 *Bat speed and calculated batted-ball speed as functions of bat weight for a 90 miles-per-hour pitch to a "slugger" of the San Francisco Giants baseball team*

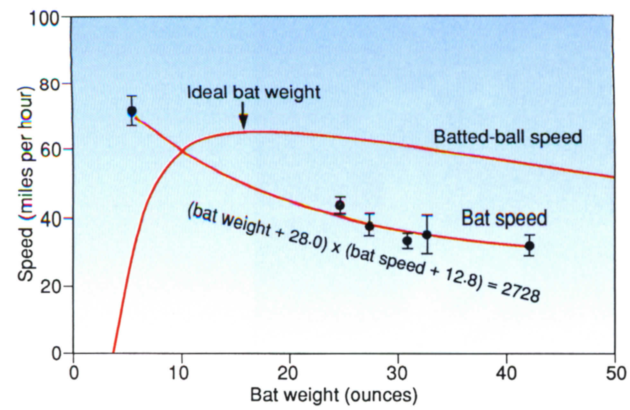


Figure 5 *Bat speed and calculated batted-ball speed as functions of bat weight for a 50 miles-per-hour pitch to Alex Bahill, a 10-year-old Little Leaguer*

weights for batters in various organised leagues (see Table 3). These calculations were made with the pitch speed each player was most likely to encounter, for example, 50 miles per hour (80 kilometres per hour) for children playing in the Little League and 20 miles per hour for university professors playing slow-pitch softball, in which the ball is bigger (about 3·82 inches in diameter against 2·85 inches) and softer than a regular baseball. The coefficient of restitution for a softball colliding with a bat is smaller than that of a baseball, but this did not affect our calculations because the ideal bat weight is independent of the value of the coefficient of restitution.

Although the ideal bat weight is specific to each individual, it is not correlated with height, weight, age, circumference of the upper arm, or any combination of these factors, nor is it correlated with any other obvious physical factors.

We compared the ideal bat weights for members of the San Francisco Giants with the weights of the bats they used before our experiments. We found that most players used bats close to their ideal weight (see Figure 6). The dashed lines in the figure (derived from data and calculations not shown in

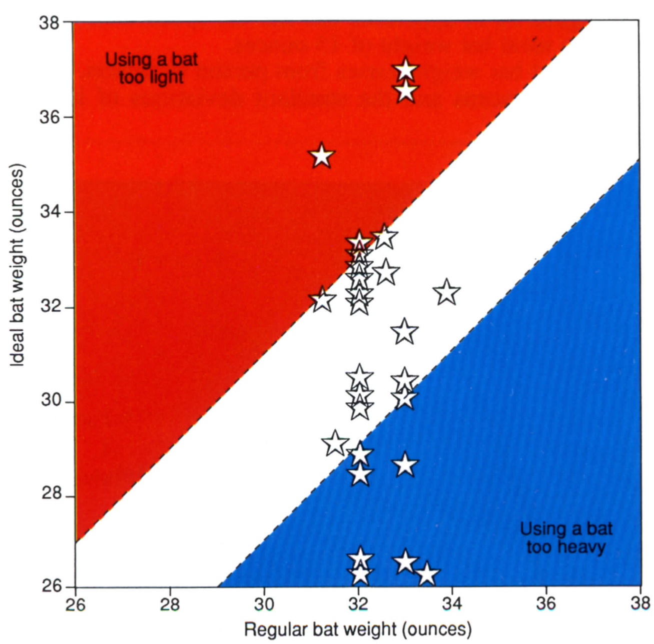


Figure 6 *Ideal bat weight versus normal bat weight for the San Francisco Giants. Most players use bats in their recommended range (between the dashed lines)*

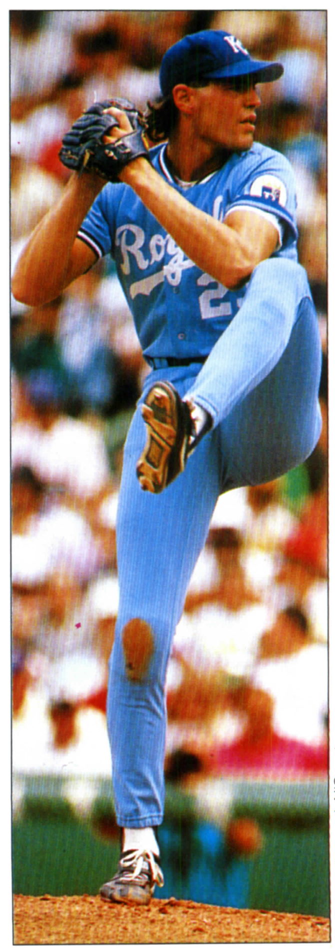
Table 3 Ideal bat weights for different players

Team	*mean ideal bat weight (ounces)*	*Standard deviation*	*Pitch speed (miles per hour)*	*Number of subjects*
San Francisco Giants	31·7	3·8	90	28
University baseball	29·7	3·8	80	17
University softball	28·3	3·7	60	14
Little League	21·1	2·8	50	38
Slow pitch softball	19·4	1·0	20	4

this article) delineate the range of recommended bat weights. We suggested that batters above the upper dashed line switch to heavier bats and that batters below the lower dashed line switch to lighter bats. Though 75 per cent of the professionals we measured were using bats in their recommended range, we found only 50 per cent of the college players and 25 per cent of the Little Leaguers were.

We also discovered that the ideal bat weight depends on whether a player is swinging right-handed or left-handed. We measured four players who can bat either right or left-handed, known as switch hitters: two Little Leaguers, one university player and one professional. Their ideal bats weights for batting left versus right-handed differed by 1/4, 3, 5 and 1 ounces. The difference between left and right-handed swings for the switch hitters was so great that we treated the data as belonging to different players.

Physical conditioning also helps to determine the ideal bat weight for an individual. We measured a team of Little Leaguers at the beginning and at the end of their four-month season. With three exceptions, all players changed as the one highlighted in Figure 7. This player's bat speeds increased and his ideal bat weight also rose from 21·75 to 23 ounces. The three exceptions were a boy who broke his wrist a few weeks into the season and played very few games as a result, and the two sons of the team's manager, who has a batting cage and a pitching machine in his back yard. The manager's sons hit 50 balls every day all year round, so the games and practices did not change their conditioning.



B. Schwartzman/ AllSport

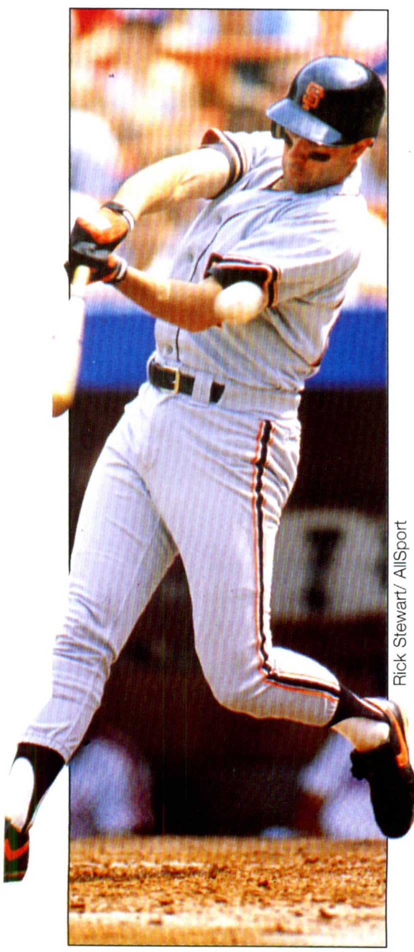
The numerical modelling we have done is common scientific practice. Scientists and engineers build models to make predictions about the physical world. We have made models of the individual players to predict their ideal bat weights. Such predictions could not be made using only experimental data from bats that the players normally use. For example, imagine an experiment where a pitcher alternately throws 20 white balls and 20 yellow balls to a batter who alternately hits with a 31 and a 33-ounce bat. Imagine then going into the outfield and looking at the distribution of the balls. You would not see

Dave Stock/ AllSport

the yellow balls or the white balls consistently farther out. Variability in the pitch and the location of the contact point between the bat and the ball would obscure any differences.

Bat Chooser's advice has produced success. Before the 1989 season, we measured the batting performance of every member of the San Francisco Giants and recommended an ideal bat weight for each one. The Giants jumped from fourth to first place in their division. Last season, we made no recommendations and they dropped to third place. Though it is true that the Giants also finished top of their division in the 1987 season without our help, the following evidence suggests that our contribution was significant in their later success.

In 1988, Alex was the worst batter on his team and he would do almost anything to avoid hitting the ball. His *modus operandi* was to wait for the pitcher to throw four bad pitches so that he could walk to the first base, a tactic known as "waiting for a walk". If those prospects did not look good, then he would "bunt the ball" so that it rolled only 10 to 15 feet and he would run very fast to reach first base. We discovered that the 26 to 28-ounce bats he used were much too heavy for him; his ideal bat weight was 15 ounces, the lightest for any of our subjects. Manufacturers do not make bats as light as that for Little Leaguers and so we bought him the lightest bat we could find, one that weighed 22 ounces. In 1990 he led his team with a ·600 batting average. Not all of this improvement was due to changing his bat weight, some must have been due to increased confidence. With the lighter bat he found out that he could hit, and instead of waiting for walks he became a first-pitch hitter.



Rick Stewart/ AllSport

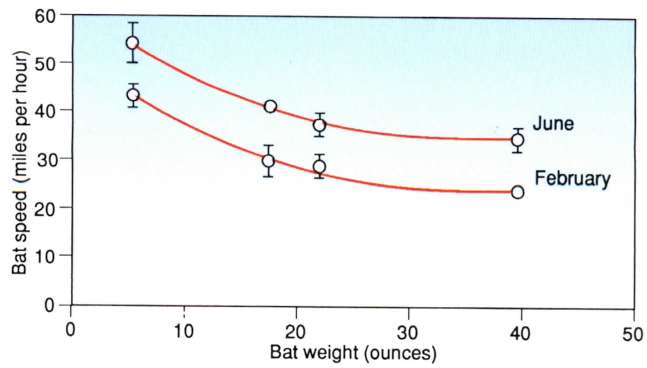


Figure 7 *Bat speeds for a 12-year-old Little Leaguer before (bottom curve) and after the baseball season*

Otto Greulle Jr/ AllSport

Some players choose to "bunt the ball" when they cannot hit it hard

Many of our recommendations for university and Little League players have been for light weight bats. In the last few years the fastest growing line of Little League bats is the ultra-lights, that is those weighing 22 ounces and less. In the collegiate ranks light weight bats have been so successful that the National Collegiate Athletic Association created a new rule restricting light weight bats. Now the weight in ounces can be no more than four less than the length in inches.

Our experiments have not yet brought us anything like the financial rewards that the professional players we advise enjoy, but we remain optimistic. The main reason is that manufacturers of baseball equipment have not yet taken our experiments seriously enough to invest in a less dense wood that would enable them to produce lighter bats. At the moment, when players seek the lighter bats we recommend from their suppliers they also stipulate that the length of the bat should remain unchanged at around 35 inches. This leads manufacturers to save weight by making the handles thinner, which produces a more fragile bat that often breaks in practice. The answer is to go for a less dense wood and keep the geometry the same. The manufacturers of professional bats are still not convinced, even though bats for collegiate and Little League teams, which need not be made of solid wood, are getting lighter every year. But history is on our side. Until about 20 years ago, dense hickory was the traditional wood for making baseball bats; now it is the less dense wood of the ash.

We do not know if the results of our experiments are directly applicable to cricket. For the moment we wonder only if it is worth investigating the density of the wood used to make the bats. Is willow less dense than ash? □

Terry Bahill is a professor of systems engineering at the University of Arizona, Tucson. He is the author of *Bioengineering: Biomedical, Medical, and Clinical Engineering*, 1981, and *Verifying and Validating Personal Computer-Based Expert Systems*, 1991. Both books are published by Prentice-Hall, Englewood Cliffs, New Jersey. **William J. Karnavas** is studying for a PhD in systems engineering at the University of Arizona.

Further reading: Robert G. Watts and A. Terry Bahill, *Keep Your Eye on the Ball: The Science and Folklore of Baseball*, published by W.H. Freeman and Co, New York, 1990.