BAT LOADING STRATEGIES

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ABSTRACT

The effects of adding mass at different locations along the longitudinal axis of a softball bat on the effective hitting area were compared. Successive loads were added to the exterior of a standard, commercially available aluminum bat (length = 86.7 cm, mass = 741 g) in increments of 93.7 g. The loads were placed at the following sites: (1) at the knob end, (2) at the junction of the bat handle and knob end, (3) at a point 12 cm from the knob end, (4) at a point 16.8 cm from the knob end, (5) at the center of mass, (6) at the center of percussion, and (7) at the barrel end. The second and third points were selected to coincide with the swing axis and impact reaction axis, respectively. The effects of each of these loading conditions on each of the following mechanical parameters were determined theoretically, by physical pendulum testing, and empirically by impact testing: (1) moment of inertia about the swing axis, (I_1), (2) distance from the impact reaction axis to the center of percussion, and (3) slope of the impact reaction impulse as a function of impact location. The latter two variables were used to determine the effective hitting area of the bat.

Results from impact testing were consistent with theoretical expectations and with results from the physical pendulum tests. Knob end loading had the greatest effect on displacement of the effective hitting area toward the barrel end of the bat and on enlarging the effective hitting area. Loading at the impact reaction axis and center of percussion had no effect on the effective hitting area. Loading at the barrel end of the bat substantially moved the effective hitting area toward the barrel end of the bat, but also caused a large increase in I_1.

INTRODUCTION

When a player hits a ball on the sweet spot, or center of percussion (COP), there is no impact reaction impulse at the hands, and more momentum is imparted to the ball than at any other impact point. Also, for a given bat velocity, the more distal portion of the bat has greater linear velocity. Therefore, if the COP were farther away from the hands and if the swing resistance, I, did not change, greater momentum could be put into the ball. Further, a hitter cannot always target the COP to the ball. So, if we could somehow minimize the penalty for a given non-central hit, more momentum would be put onto the ball. This research is an attempt to ultimately achieve these objectives by strategically adding mass to the interior of hollow-wall construction bats.

PURPOSE

The purpose of this study was to determine the effects of loading locations on the effective hitting area of hollow-wall construction baseball and softball bats. Effects on relevant mechanical parameters were theoretically derived and compared to experimentally determined values.

THEORETICAL MECHANICAL CONSIDERATIONS

When swinging a bat, the axis around which the hitter places the accelerating forces on the bat is located between the hands (Eggeman and Noble, 1985). This axis is hereafter referred to as the swing axis and has been found to be approximately 12 cm from the knob end of the bat for adult males. However, during impact of the bat and ball, the bat behaves as a physical pendulum. The axis of rotation of the pendulum is at the most distal part of the hands of the hitter that is in contact with the bat. This point has been shown to be approximately 16.8 cm from the knob end of the bat for adult males (Noble, 1985).

In describing the mechanics of the impact of ball and bat, reference is made to Figure 1 in which the following notation is adopted:

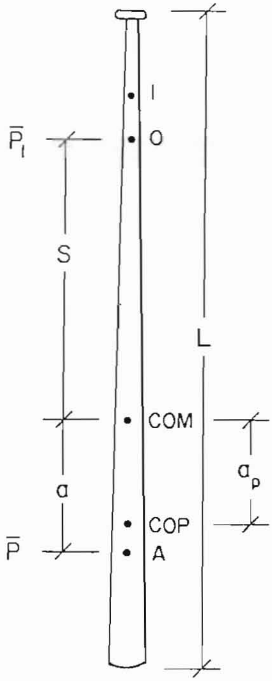


Figure 1. Schematic of mechanical system describing the impact of ball and bat

0 = impact

1 = swing axis

v_c = velocity of center-of-mass (COM)

s = distance from point of suspension to COM

a = distance from COM to point of impact

$\overline{P}$ = impulse applied at A by ball striking bat

$\overline{P}_1$ = reaction impulse at point of suspension (16.8 cm from knob end)

I_o = moment-of-inertia about point of suspension

I_1 = moment-of-inertia about the swing axis (12 cm from knob end)

M = mass of bat

w = angular velocity of bat

L = length of bat

From Newton's Second Law of Motion the change in momentum of the bat as a result of the impact is equal to the net impulse (Becker, 1954). This is expressed as:

$$(\overline{P} - \overline{P}_1) = M\Delta v_c = M\Delta ws \qquad (1)$$

where Δv_c and Δw are the change in linear and angular velocity, respectively.

The net rotational impulse about the axis, 0, gives rise to a change in angular momentum. This is expressed as:

$$I_o \Delta w = \overline{P}\ (a+s) \qquad (2)$$

Combining (1) and (2) yields the net reaction impulse, $\overline{P}_1$:

$$\overline{P} = \overline{P}_1\ \left(1 - \frac{Ms(a+s)}{I_o}\right) \qquad (3)$$

The sweet spot, which is technically called the COP is that value of a hereafter designated a_p, for which $\overline{P}_1 = 0$.

Setting $\overline{P}_1 = 0$ and solving for a yields:

$$a_p + s = \frac{I_o}{Ms} \qquad (4)$$

For a ball striking a bat at A there is no reaction impulse on the axis of rotation (or point of suspension) and a maximum transfer of momentum from bat to ball occurs (Sears and Zemansky, 1963). However, it is very difficult to target the COP of the bat to a pitched ball. Therefore, it is desirable to develop a bat that will minimize $\overline{P}_1$ for impacts not at the COP, hereafter called non-central hits.

If the relationship given by eq. 3 is plotted, the ratio of reaction impulse to the applied impulse as a function of the distance, a, we obtain the linear graph shown in Figure 2. To minimize the reaction impulse due to a given non-central impact is equivalent to making the slope of the line for $\overline{P}_1/\overline{P}$ as small as possible.

Eq. 3 can be written in a slightly different form with $\overline{P}_1$ the dependent variable, a the independent variable and the applied impulse assumed to be constant. Comparison of eq. 5 with the standard equation for a straight line obtains:

$$y = mx + b \tag{5}$$

where y is the dependent variable, x is the independent variable, m is the slope, and b is the y intercept, shows that the slope of the line in Fig. 2 is given by

$$m = \frac{d(\overline{P}_1/\overline{P})}{da} = \frac{Ms}{I_o} \tag{6}$$

Insert Figure 2 about here

Inspection of eq. 4 provides a way to identify strategies for increasing the distance from the axis of impact to the center of percussion and, corres-

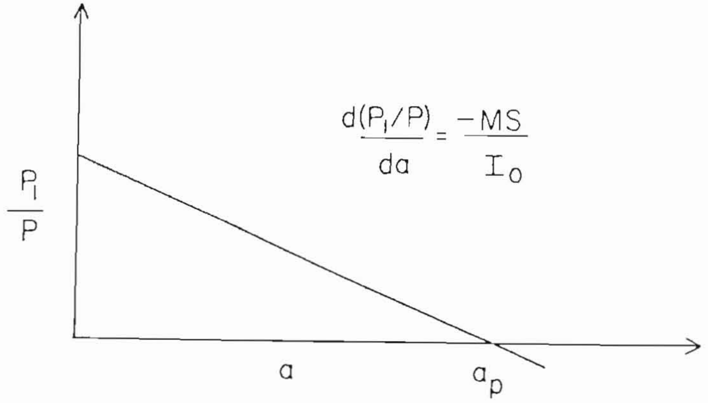


Figure 2. Ratio of reaction impulse to applied impulse, P_1/P, as a function of distance from the center of mass to impact, a

pondingly, to decrease the value of $\frac{d(\overline{P}_1/\overline{P})}{da}$. Note that $\frac{d(\overline{P}_1/\overline{P})}{da}$ is the reciprocal of the radius of percussion. Thus, if one is minimized $\frac{d(\overline{P}_1/\overline{P})}{da}$, one must maximize the radius of percussion. Both the size and location of the effective hitting area can therefore be controlled to the extent that the value of $\frac{I_o}{Ms}$ can be controlled.

The effective hitting area (EHA) is defined as the zone along the longitudinal bat axis within which a hitter can strike the ball and meet his/her mechanical objectives. The maximum proportion of the applied impulse that can be tolerated by the hitter must be specified. For example, if this proportion is determined to be .1, then the EHA is that area within which less than 10 percent of the impact impulse is lost as mechanical reaction on the hands. This value is provided by:

$$-.1 < \frac{P}{1} < .1$$

substituting from eq. (3):

$$-.1 < \frac{1 - Ms(a+s)}{I_o} < .1$$

and

$$(.9)\left(\frac{I_o}{Ms}\right) > (a+s) > ((1.1)\frac{I_o}{Ms})$$

substituting the physical pendulum values:

$$(.9)\left(\frac{T^2 g}{4\pi^2}\right) > (a+s) > (1.1)\left(\frac{T^2 g}{4\pi^2}\right) \quad \text{where } T = \text{period of oscillation},\ g = \text{acceration due to gravity} \qquad (7)$$

This relationship provides the distance from the impact axis to the inner and outer limits of the effective hitting area in cm given here:

$$22.355\ \text{cm/sec}^2 \cdot T^2 > a+s > 27.323\ \text{cm/sec}^2 \cdot T^2 \qquad (8)$$

It is clear from the relationships given above that the EHA of a given bat can be displaced away from the hands and enlarged by increasing the value of $\frac{I_o}{Ms}$.

This can be accomplished by interior loading which will increase I_o. Barrel end loading will accomplish this; however, the increased moment of inertia makes the bat difficult to swing. The other effective loading strategy is to decrease s, the distance from the impact axis to the COM. The placement of mass on the portion of the bat toward the knob end will not only decrease s, but increase I_o only slightly. This will result in a much larger increase in the radius of percussion and the size of the power zone for a given additional mass.

The relationship given in eq. 9 provides an easy way to determine the location of the COP and EHA; however, if these values are to be design features, then they must be accurately estimated.

The effect of adding an amount of mass, $M\Delta$, to a hollow metallic or other lightweight bat can best be calculated by considering the following equations for the relevant mechanical parameters:

$$I'_o = I_o + \Delta M(s - X)^2 \qquad (9)$$

where I'_o is the moment of inertia of the loaded bat, I_o is the moment of inertia of the unloaded bat, s is the distance of the center of mass from the percussion axis and X is the distance of the added mass from the center- of-mass;

$$M' = M + \Delta M \qquad (10)$$

where M' is the total mass of the loaded bat, M is the mass of the unloaded bat and ΔM is the added mass;

$$s' = \left(s - \frac{\Delta Mx}{M+\Delta M}\right) \qquad (11)$$

where s' is the distance of the center of mass of the loaded bat from the impact axis and the other parameters are defined as above, and finally;

$$a'_p + s' = \frac{I'_o}{M's'} \qquad (12)$$

where $a'_p + s'$ is the distance of the COP from the impact axis for the loaded bat.

The EHA is defined as the region where the reaction impulse at the axis is 0.1 of the applied impulse. This region lies between

$$0.9\ (a'_p + s') \text{ and } 1.1\ (a'_p + s') \qquad (13)$$

Using equations 1 through 5 allows a bat to be designed with the following important features:

(1) the EHA can be located anywhere along the length of the bat, the preferable location being at the barrel end where the linear velocity is the greatest and the EHA is the largest.

(2) this can be accomplished without a significant increase in the moment of inertia by placing the additional mass at or near the knob end of the bat

(3) the mass of the bat can be increased to any legal value depending on the hitter's preference with advantage gained in improving (1) and (2).

In order to clarify these design possibilities, a few sample calculations are given based on equations 9-13 above. In Figure 3 we have calculated the location of the COP for placing various masses at (a) the knob end of a conventional 26 oz. hollow aluminum bat and (b) the swing axis of the same bat. The effect of adding mass to the knob end produces a much more dramatic effect on the location of the COP than when the mass is placed at the swing axis.

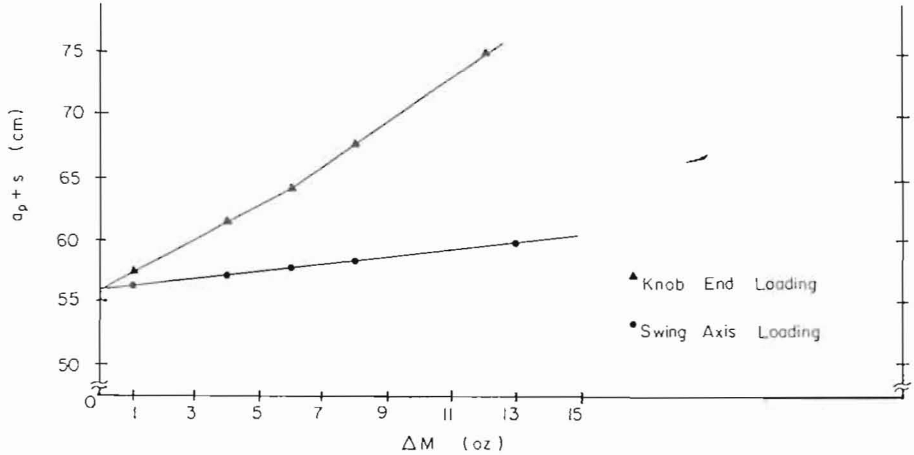


Figure 3. COP location as a function of knob end and swing axis loading

This is expected from intuitively inspecting equations 9-13 where adding a given mass to the knob end produces a larger value for I_o, a larger decrease in s and, therefore, a much larger change in $a_p + s$.

In Figure 4 we have graphed the location of the COP for the addition of a 6.5 oz. mass at various locations along the bat (solid line) and the EHA as defined by eq. 13 (dashed lines). Inspection of this figure reveals that the largest EHA is for knob end loading as measured by the width of the shaded area.

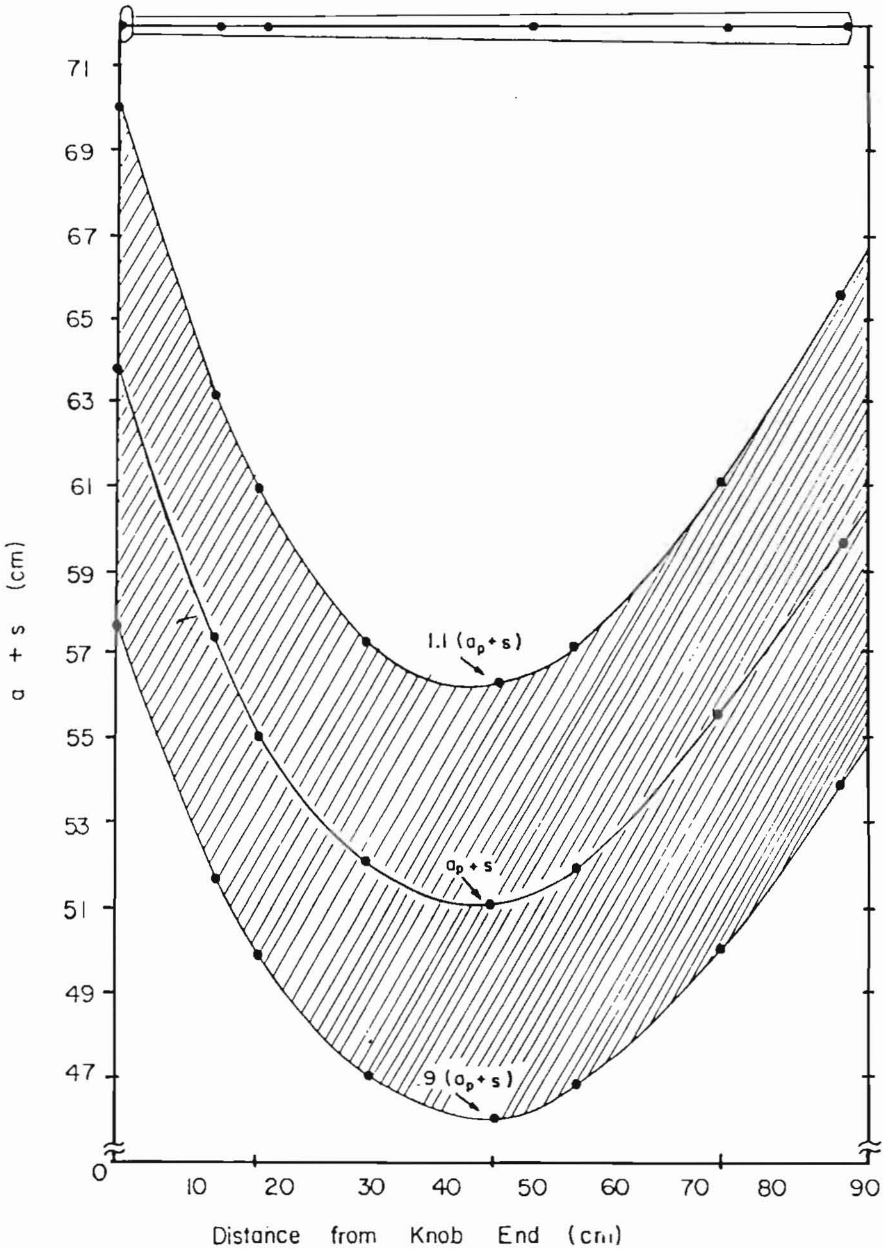


Figure 4. Effective Hitting Area as a function of location of 6.5 oz load

Although a similar change in location of the center of percussion and increase in the effective hitting area can be obtained by placing the additional 6.5 oz. mass in the barrel end the moment of inertia of the barrel end loaded bat is significantly increased making the bat much more difficult to swing effectively. The moment of inertia about the swing axis for the various locations of the added 6.5 oz. mass is shown in Fig. 5. This figure demonstrates that the moment of inertia for barrel end loading increased by 50% while that for knob end loading increased only 1% over that of the unloaded bat.

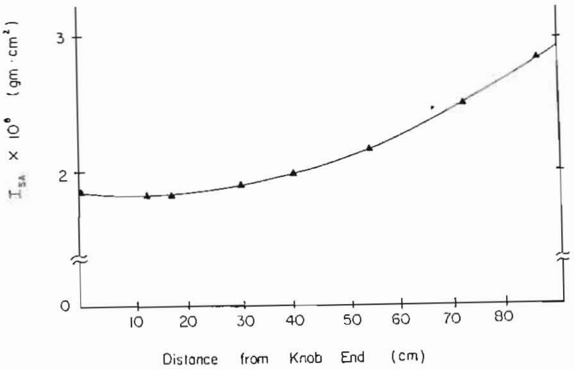


Figure 5. Moment of inertia about the swing axis as a function of location of 6.5 oz load

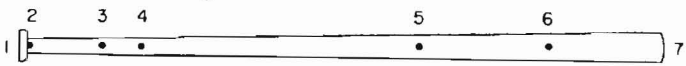
The design of the optimum bat using a 6.5 oz. mass, as indicated from this figure, would entail placing the EHA precisely at the end of the bat. This strategy produces the largest EHA with no significant increase in the moment of inertia. Should it be desirable to use a larger mass (i.e. $>$ 6.5 oz) and still place the EHA at the end of the bat, the added mass would have to be placed slightly away from the knob end. Using the strategies detailed here, a bat with almost any desired location for the EHA can be achieved without any significant change in the moment of inertia.

EMPIRICAL VERIFICATION

The effects of adding mass to a standard, commercially-available aluminum bat were verified empirically. The values of the relevant mechanical parameters were determined from physical pendulum testing and from impact testing. Impact testing was deemed necessary because previous research on softball bats indicated that their behavior during impact is not entirely what would be expected from a rigid body (Bryant, et al, 1977; Noble and Eck, 1985). Values from physical pendulum and impact testing were then compared to those calculated from theoretical considerations.

Bat Loading Procedures

A standard commercially available aluminum bat with a mass of 741 g (weight = 26 oz.) and length of 86.7 cm (34 in.) was selected for testing. Lead strips were secured firmly with metal clamps to the exterior of the bat at selected points along the long axis. Figure 6 illustrates the loading sites.



1 – Knob end
2 – Knob – Handle
3 – 12 cm from Knob end
4 – 16.8 cm from Knob end
5 – 54.3 cm from KE(COM)
6 – 72.3 cm from KE(COP)
7 – Barrel end

Figure 6. Loading sites

Physical Pendulum Testing Procedures

The distance from the reaction axis to the COP, $a_p + s$, was found by suspending the bats a point 16.8 cm from the knob end, finding the period, T, and using the expression for the distance to the COP of a physical pendulum in terms of its period (Noble, 1985):

$$a_p + s = \frac{T^2 g}{4\pi^2}$$ where g is the acceleration due to the gravity.

The moment of inertia about the swing axis (I_1) was found by suspending the bats at a point 12 cm from the knob end and applying the relationship for the moment of inertia of a physical pendulum in terms of its period of oscillation (Sears and Zemensky, 1963):

$$I_1 = \frac{T^2 Mgs}{4\pi^2}$$ where s = rotation radius, and M = mass.

The computed values for the slope of the $\overline{P}_1/\overline{P}$ relationship as a function of impact location were found from eq. 7.

Impact Testing Procedures

Apparatus. A ball track was constructed from steel so as to accurately propel a wooden ball (diameter = 7.6 cm, mass = 205 g) horizontally against a suspended bat with a velocity of approximately 658 cm/sec. The track allowed the ball to drop 220.7 cm vertically from release to bat contact. The average vertical and horizontal deviation of the impact point across trials was less than 2 mm.

An aluminum clamp was constructed to attach the bat to a load beam sensitive only to a bi-directional load (BLH electronics Alpha) with a maximum rated capacity of 150N. The interface with the clamp and load beam was low-friction so that the bat could swing freely about the clamped axis. The load beam was attached to a sturdy lab table with an aluminum bracket so that the orientation of the load beam remained horizontal and so that the distance from the point of impact with the ball to the axis could be accurately controlled. The load beam was activated by 18 VDC and the output signal was monitored with a Tektronix storage Oscilloscope. The oscilloscope was triggered by the ball rolling down the track and contacting a microswitch 10 msec prior to contact with the bat so that the reaction force-time curve could be stored. The wave form was then photographed using a standard 35 mm camera and a telephoto macro-zoom lens. Slides of the oscillotraces were projected onto a digitizing surface (Grafpen 18" by 18") interfaced to a microcomputer (Apple II+). The area under the impact reaction force time curve was then computed in order to obtain the total reaction impulse, $\overline{F}_1$.

Method. Each bat was attached to the clamp at a point 16.8 cm from the knob end. The spherical wooden ball was then released and allowed to roll down the track and impact with the bat while the bat was positioned so that the impact point would be at selected intervals along its longitudinal axis. Observations were made for a minimum of 4 impacts for each loading condition. Impact locations were selected at 5 cm intervals but were changed in some situations to correspond with the COP as predicted from physical pendulum testing. This procedure was used to obtain the most accurate information regarding the relationship between the reaction impulse and impact location. Reliability of this procedure has been demonstrated in a previous communication (Noble and Eck, 1985).

TABLE I
COMPARISON OF THEORETICALLY-DETERMINED RELEVANT MECHANICAL PARAMETERS WITH PHYSICAL PENDULUM TEST RESULTS

Load Condition	I* ($g \cdot cm^2$)		$a_p + s$** (cm)		EHA *** (cm)	
	Theoret.	Pend.	Theoret.	Pend.	Theoret.	Pend.
No Load	1.826×10^6	1.826×10^6	55.6	55.6	50.0-61.1	50.0-61.1
6.5 oz at knob end	1.849×10^6	1.875×10^6	64.2	65.0	57.8-70.3	58.5-71.5
6.5 oz at knob end of handle	1.842×10^6	1.854×10^6	62.6	62.8	56.3-68.8	56.5-69.2
6.5 oz at swing axis	1.826×10^6	1.831×10^6	57.4	58.0	51.7-63.2	52.2-63.8
6.5 oz at impact axis	1.831×10^6	1.840×10^6	55.5	56.0	49.9-61.0	50.4-61.6
6.5 oz at COM	2.158×10^6	2.167×10^6	51.9	52.1	46.7-57.1	46.9-57.3
6.5 oz at COP	2.499×10^6	2.499×10^6	55.6	55.6	50.0-61.1	50.0-61.1
6.5 oz at Barrel end	2.823×10^6	2.807×10^6	59.7	59.1	53.7-65.6	53.4-65.0

*Moment of inertia about the swing axis
**Distance from impact axis to COP
***Distance from impact axis to limits of the EHA

RESULTS

Table 1 compares the theoretically determined values for moment of inertia about the swing axis, location of the COP, and the EHA with those obtained by physical pendulum testing for each load location. The values are similar in all cases for all variables. The average difference in obtained values for location of the COP was only 3 mm. Thus, physical pendulum test results verify theoretical expectations for bat load location. The effects of the placement of 6.5 oz. at various points on the bat on the location of the COP and the EHA are graphically shown in Figures 7 through 14. Values for these figures were determined from physical pendulum testing.

Impact testing was conducted under progressively increasing loads and with the load placed at the points indicated in Figure 6. Results for knob end and barrel end loading are shown in Figures 15 and 16, respectively. The horizontal axis indicates the distance from the impact axis to the impact and the vertical axis indicates the reaction impulse due to the impact. The zero point on the vertical axis was expected to coincide with the COP as predicted from the calculated and physical pendulum values. Also, the slope of the reaction impulse was expected to decrease as the distance to the COP increased. A third expectation was a linear relationship between the reaction impulse and impact location. All of these expectations were met by the impact test results except when impact points were near the knob end and the axis. This nonlinearity was also noted by Bryant and others (1977) and is thought to be a result of the elastic properties of the bat. A somewhat detailed discussion of this phenomenon is presented in a previous communication (Noble and Eck, 1985).

CONCLUSIONS

Methods involving adding mass to the interior of hollow-wall construction bats were developed from theoretical mechanical considerations to improve relevant mechanical parameters. Physical pendulum and impact testing verified the expected effects of displacement of the COP, slope of the normalized impact reaction impulse as a function of impact location, and moment of inertia about the swing axis. Thus, these methods were demonstrated to be effective in moving the COP toward the barrel end of the bat and increasing the size of the effective hitting area. Further, these methods did not cause a substantial increase in the moment of inertia.

Figure 7. COP and EHA of unloaded bat ($a_p + s$ = 55.5cm, EHA = 11.10cm)

Figure 8. COP and EHA with 6.5oz in knob end ($a_p + s$ = 65cm, EHA = 13.00cm)

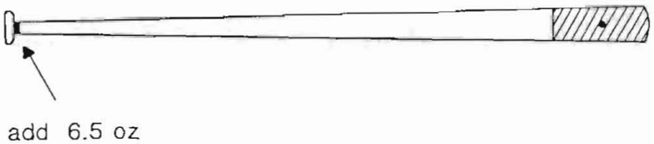


Figure 9. COP and EHA with 6.5oz at knob end of handle (a_p+ s = 62.8cm, EHA = 12.56cm)

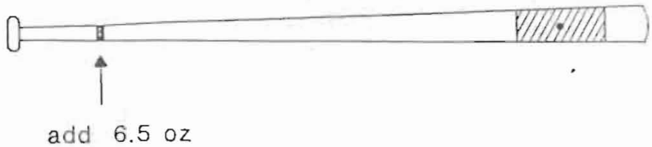


Figure 10. COP and EHA with 6.5oz at swing axis (a_p+ s = 58cm, EHA = 11.6cm)

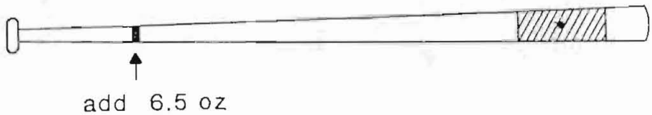


Figure 11. COP and EHA with 6.5oz at impact axis (a_p+ s = 56cm, EHA = 11.2cm)

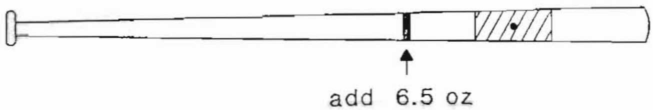


Figure 12. COP and EHA with 6.5oz at COM (a_p+ s = 52.1cm, EHA = 10.42cm)

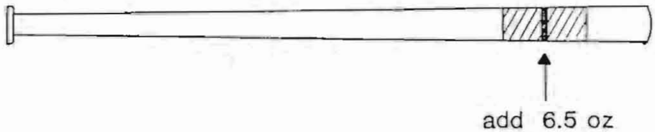


Figure 13. COP and EHA with 6.5oz at COP (a_p+ s = 55.5cm, EHA = 11.1cm)

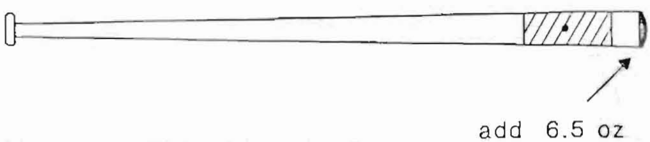


Figure 14. COP and EHA with 6.5oz at barrel end (a_p+ s = 59.1cm, EHA = 11.82cm)

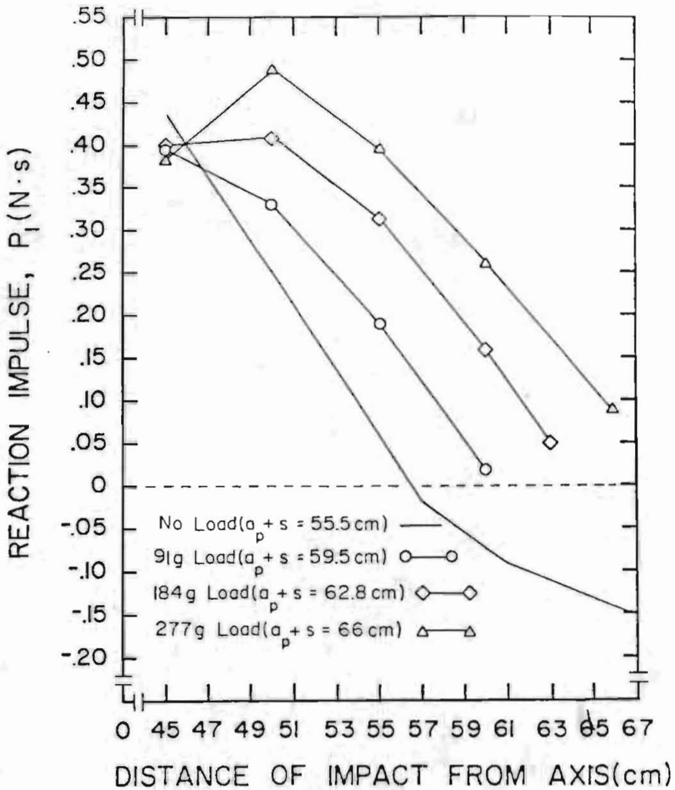


Figure 15. Knob and loading effects on impact reaction impulse

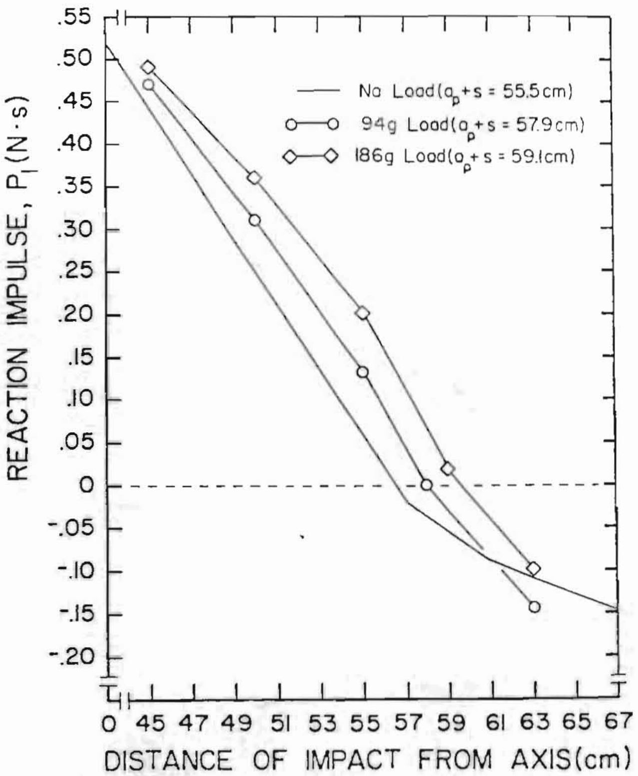


Figure 16. Barrel end loading effects on impact reaction impulse

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*FOOTNOTES

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