EXAMINATION OF THE DIVING BOARD VIBRATION MODE OF SOFTBALL BATS

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The purpose of this study was to investigate the longitudinal oscillations of an aluminum softball bat during the swing and impact and to correlate the vibrations with characteristics of the swing. A highly skilled adult male baseball player hit 20 slow-pitched softballs and 35 balls placed on a tee with a high-performance aluminum softball bat (34 in, 28 oz) that was instrumented with strain gauges to measure strain along the long axis. Analysis of strain gauge records indicate that, in all cases, the bat bent back during the early part of the swing, peaked at approximately 45 ms prior to contact (PC), and was bending toward the ball at impact. The frequency of bat oscillations during the swing was 7.37$\pm$.87 Hz and 5.3$\pm$1.25 Hz for pitched and teed balls, respectively. For teed balls, strain magnitude was significantly related to swing time, bat velocity PC, and post-impact ball velocity.

KEY WORDS: softball bats, baseball bats, vibrations, equipment, striking implements

INTRODUCTION: For several years, baseball and softball manufacturers have been producing "high performance" bats that purportedly provide a "springboard" effect achieved by increasing the bats' flexibility. Several studies have provided theoretical models (Brody, 1986; Brody, 1990; Cross, 1998; Van Zandt, 1992) and empirical data (Noble and Walker, 1993; Noble and Walker, 1994a; Noble and Walker, 1994b) on the longitudinal vibrations of bats during impacts that do not support the assumptions underlying the utility of an enhanced springboard effect. However, none of these studies examined bat vibrations and performance while the bat was being swung at balls. The findings and recommendations from these theoretical and laboratory-based studies may not be fully applicable to actual playing conditions. In a recent review preliminary study, Noble (1999) examined bat vibrations during swings at pitched balls and found that, in over 200 swings with 7 different subjects of varying skill levels, the bat was bending back during the early part of the swing, peaked at 40-60 ms PC, and was bending forward toward the ball at impact. While these findings were encouraging and support the assumption that the diving board mode of the bat is used to store elastic energy during the first part of the swing and is then released during the last part at impact. While the timing and magnitude of the excitation of the springboard mode were significantly different across subjects, neither between-subject nor within-subject variability could be accounted for. The authors suggested two possible reasons for this failure: (1) the strain gauges were only sensitive to bending in one direction (hopefully, the horizontal direction during the latter part of the swing), and (2) the within-subject variability of the swing and waveform characteristics was very low. The purpose of this study was to further examine the bat bending characteristics of an aluminum softball bat during the swing while removing the two limiting elements of this preliminary study in order increase the likelihood of finding characteristics of the hitter and the swing that relate to the timing and magnitude of the bat's bending. Specifically, instrumentation of the bat was improved to indicate the onset, duration, and magnitude of the bat's bending irrespective of the bending direction. Also, one phase of this study involves procedures specifically designed to produce greater variability in bat velocity.

METHODS: In the first phase of this study, an elite college male baseball player (ht = 1.85 mass = 100 kg) 20 pitched softballs (9.3$\pm$3.6 ms^{-1}) softballs with a high-performance aluminum softball bat (34 in, 28 oz). The batter used a knob-end grip and was instructed to hit each ball as hard as possible while maintaining control. During the second phase of the study, the same subject hit 35 softballs placed on a hitting tee. Bat vibrations were obtained using two foil strain gauges bonded to the tapered region on the leading and lagging surfaces of the bat and two gauges bonded on the top and bottom surfaces. Two channels of strain gauge output (40 mv/microstrain) were interfaced to a computer and provided strain magnitude in each orthogonal direction. This output was later coupled to derive both the magnitude and direction of the bending of the bat. Wires from the strain gauge were routed underneath the handle wrapping, emerged from the knob end of the bat and were threaded underneath the knit shirt of the hitter. These wires were connected to the AD board of a microcomputer and the output signal ($\pm$10V DC) was sampled at 5000 Hz. Strain gauge output was used to determine the lowest vibration mode under free-free and clamped boundary conditions in the lab as well as during the swings and impacts of the field tests. A strip of white tape was placed on the barrel end of the bat so that bat orientation could be visually determined during and after testing and to facilitate interpretation of strain gauge output. The subject was instructed to hold the bat so that this tape was vertically oriented during the latter part of the swing prior to impact. A SVHS 60-Hz video camera was placed near first base so that the initiation of the swing and impact and the orientation of the bat could be clearly viewed. Post-impact ball velocity was measured with a radar gun with a resolution of.23 ms^{-1}. Subject rating of the quality of the swing and impact (1=worst, 10=best) and a description of the outcome of each hit were obtained for each trial. Only trials wherein the rating was 4 or above and acceptable recordings were obtained were selected for detailed analysis. A total of 20 trials were selected for examination.

Identical procedures were used for the second phase of the study, with the following exceptions: (1) 35 balls were hit off of a tee, (2) the velocity of the part of the bat impacting with the ball was measured electronically during the .15 m PC, and (3) the subject was instructed to swing with varying degrees of effort ranging from slight to maximum. This latter procedure was intended to increase variability in pre-impact bat velocity and examine the relationship between it and bat strain characteristics. Descriptive statistics and bivariate correlation coefficients were used to describe and compare waveform and swing

RESULTS AND DISCUSSION: The lowest mode of vibration for the bat under clamped boundary conditions (e.g., the diving board mode) was 13.3 Hz while the lowest mode under free-free (loosely held) conditions was 156 Hz. Figure 1 provides a characteristic waveform from the swing at the ball on the tee having the greatest PC bat velocity (36.3 ms^{-1}).
rating was 9 and the post-impact ball velocity was 38 m/s.

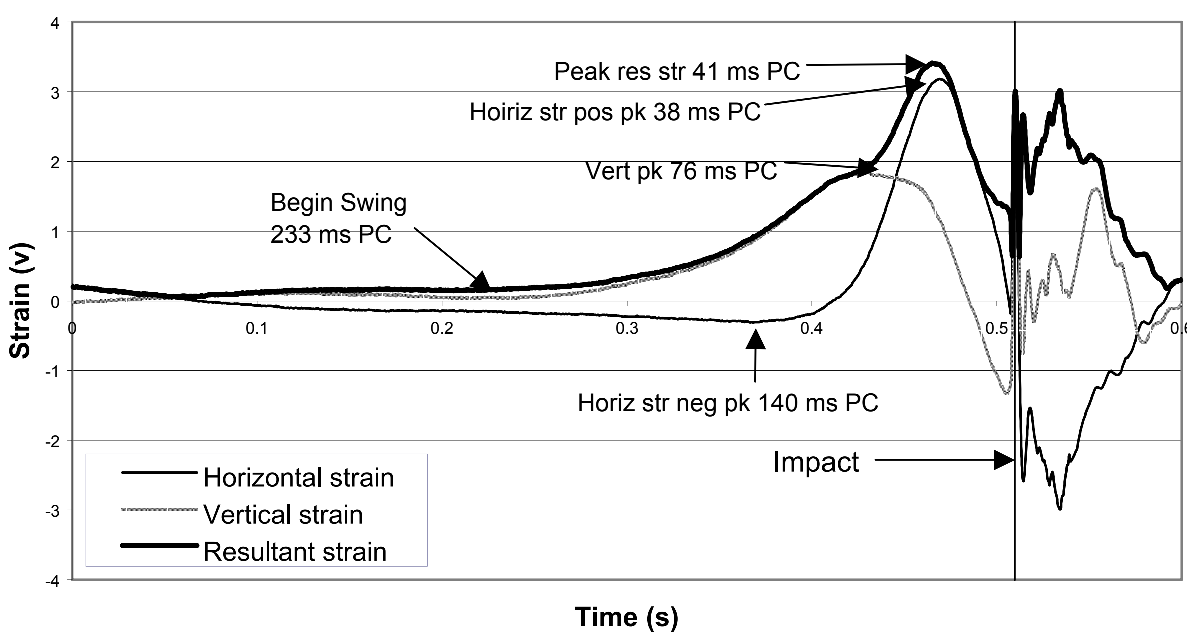

Figure 1 - Characteristic waveform of hit off of tee.

During the stance of this hitter, the bat was held in a nearly vertical orientation. Positive horizontal and vertical outputs indicate that the bat is bending backward and upward, respectively. The bat is bending both backward and upward during the swing until approximately 20 ms PC when the direction of vertical bending changes from upward to downward. The bat was in the process of straightening, releasing the stored elastic energy, at impact. In this swing, the resultant strain was approximately 25% of peak at impact. These characteristics were consistent for all swings by this hitter. In every trial selected for examination, the bat bent backward during the swing, and was restoring, or bending forward at impact. These observations support the claims of bat manufacturers that the diving board vibration mode is exhibited during the swing of softball hitters. Swing time was determined from videotape recordings. Swing strain frequency was calculated as 1/2T, where T was the elapsed time between the positive and negative horizontal strain peaks during the swing. In waveforms lacking a positive peak, the instant the waveform began decreasing was used as the onset of the swing waveform. Resultant strain was calculated using the Pythagorean Theorem from horizontal and vertical strain for each data sample. The ratio of bat strain at impact compared to peak strain is an estimate of the degree of elastic energy stored during the swing that was not released prior to and at impact. If all of the strain energy were released at impact, this ratio would be zero. Table 1 shows subject means and SDs for selected waveform and swing characteristics for both teed and pitched balls.

Table 1 Descriptive Statistics of Waveform Characteristics

Variable	**Ball on Tee**		**Pitched Ball**	
	N	**Mean±SD**	**N**	**Mean±SD**
Bat/ball velocity (ms^{-1})	32	31.793±3.688[1]	19	33.980±3.341[2]
Swing time (s)	35	.239±.036	20	.141±.013
Swing strain freq (Hz)	35	5.304±1.245	20	7.375±.871
Peak res strain(V)	35	3.147±.373	20	2.969±.218
Time of peak res str PC (S)	35	42.000±4.923	20	49.300±4.857
Peak horiz strain (V)	35	2.751±.367	20	1.878±.462
Time of peak horiz strain (ms)	35	36.057±4.583	20	35.000±9.073
Peak vert strain (V)	35	1.929±.435	20	2.992±.293
Time of peak vert strain (s)	35	63.257±14.551	20	62.800±5.834
Impact strain/peak strain	35	.463±.153	20	.524±.161

[1]Pre-impact bat velocity.
[2]Post-impact ball velocity.

The considerable within-subject variability in swing strain frequency is consistent with that noted in the previous study by Noble (1999). Mean values as well as variability in swing time and swing strain frequency were substantially greater for the teed ball trials. Other waveform characteristics were similar with peak strain values slightly higher and the timing of peak strain values PC were slightly lower for the teed ball trials. For teed ball trials, significant correlations were found between swing strain frequency and swing time derived from VTR (-.70), bat velocity (.83), and peak resultant strain (.72). Bat velocity was significantly related to swing time (.83) and peak resultant strain (.84). For teed trials, there was no significant relationship between relative bat strain at impact and any of the other variables. In contrast, for pitched ball trials, there were no significant correlations with these variables, except post-impact velocity was significantly related to perceived quality of the swing (.63) and relative impact strain (-.71). Significant correlations between relative impact strain and post-impact ball velocity for pitched balls were noted by Noble (1999) in only one of the 8 subjects used in the study (.74). However, significant correlations between quality of the swing and post-impact ball velocity were found in five of the eight subjects. Two factors inherently different between the teed ball and pitched ball conditions may account for these apparently inconsistent results: (1) the variability of swing time and ball velocity for pitched trials was comparatively very low, and (2) post-impact ball velocity (measured only for pitched ball trials) is affected by both pre-impact bat velocity (measured only for teed ball trials) and impact location. Impact location was not measured for either swing conditions.

Peak resultant strain occurred in most swings between 45 and 50 ms PC. This coincides closely with the timing of peak bat torque (.59-.63 ms PC) and peak acceleration (.025-.044 PC for males and females, respectively) that have been previously reported by Shapiro (1979) and Spragg (1986). Shapiro used a skilled college male varsity player hitting pitched balls while Spragg used both college skilled males and females hitting teed balls.

CONCLUSIONS: The following conclusions are supported by the findings of this study: (1) the bat consistently bends back during the early part of the swing and begins to release its stored elastic energy approximately 45 ms PC, (2) the magnitude of the stored energy is directly related to bat velocity, (3) the timing of the onset of storing energy and its release appears to be related to the initiation of the forward movement of the bat and to the timing of peak bat torque and acceleration. Furthermore, the degree of stored elastic energy that is released at impact may be a significant factor in post impact bat velocity. These conclusions provide increased credibility to bat manufacturers' claims that baseball and softball bats with greater longitudinal flexibility provide a "springboard" effect at impact through the release of elastic energy stored during the swing. Furthermore, increasing the flexibility of baseball and softball bats beyond those now being produced may improve the effectiveness of the bat in imparting velocity to the ball.

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