Experimental Characterization of Ice Hockey Sticks and Pucks

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Nomenclature

e_a	Collision efficiency
F_i	Peak impact force
I	Mass moment of inertia
m_p	Puck mass
Q	Stick impact location
v_p	Puck velocity before impact
v_p'	Puck velocity after impact
v_s	Stick velocity

Abstract
The following describes experimental methods for characterizing ice hockey pucks and sticks at game-like speeds. Pucks were characterized according to their coefficient of restitution (COR) and dynamic stiffness (DS) for different brands, speeds, and temperatures. The COR provided a measure of the puck's elasticity, while the DS provided a measure of puck hardness. At room temperature, puck COR and stiffness differed by 10% and 33%, respectively between two brands. Puck response was highly dependent on temperature, where COR decreased by 32% and stiffness increased over 600% when frozen. Sticks were characterized in terms of their natural vibrational frequencies, mode shapes, and performance. A performance measure of puck speed (PS) was derived from the collision efficiency between a stick and puck found from experimental high speed impact testing. Modal analysis revealed little difference in the first two bending modes for composite or wood sticks, while high speed cannon testing showed a performance difference of 21% for different types of sticks. The results suggest that modern materials used in stick design have a significant effect on the game that may not be apparent using indirect performance measures.

1.0 Introduction

The ice hockey stick is a fundamental piece of equipment in terms of player performance. The stick is primarily used for maneuvering and propelling the puck. This study aimed to employ experimental methods to characterize hockey pucks and sticks.

The puck is a round disc 3 inches in diameter and 1 inch thick. It is made of vulcanized rubber and weighs between 5.5 – 6 ounces [1]. Pucks are sometimes frozen before play to reduce bouncing and increase controllability. Vertical drop tests to determine the puck's coefficient of restitution (COR) have been performed and found COR values in the range of .45-.55 at room temperature and .12-.27 for frozen pucks [1]. No data exists in the literature of puck characterization at game speeds. Professional hockey players can achieve speeds in the range of 70 to 110 mph during game play [1].

Players use several different methods to propel the puck with the stick, the fastest of which is the slap shot [2]. During a slap shot, the stick contacts the ice slightly before the puck and the shaft is deflected, or loaded. As the stick travels forward and moves the puck, the loaded shaft acts as a spring and recoils, adding to the initial swing speed of the stick. The point of the shaft that deflects most during the loading phase of a shot is referred to as the kick point, which is near or below the lower hand.

Early studies of the slap shot were concerned with the technical aspects of shooting regardless of the stick type [4, 3]. In 1978 Sim and Chao used high speed video analysis to conduct a biomechanical analysis of hockey shots and puck velocities up to 90 mph for high school hockey players and up to 120 mph for college and professional players [4].

More recently, the shaft recoil effect for elite and recreational players has been considered, where a correlation between shaft deflection and puck speed has been found [5]. Stick speed in the slap shot, however, has been shown to depend more on the player than on the stick stiffness [4]. Thus, stronger players who generate increased stick speed, also achieve more shaft deflection.

Hardness, flexibility, and wear resistance are crucial properties for hockey sticks, making hardwoods such as elm, birch, aspen, or ash good materials for the first hockey sticks [2]. Wood sticks offer a good feel for the puck, but are among the heaviest hockey sticks and tend to degrade or soften with repeated use [1].

The most recent generation of hockey sticks are made entirely of composite materials, mainly a combination of fiberglass, Kevlar, or carbon fiber in a polymeric resin [1]. Composite sticks are the lightest on the market. Properties such as weight, stiffness, vibration damping, and geometry can be finely controlled during fabrication. Composite sticks can be more consistently manufactured and wear or soften less than wood [1]. The high strength of composite materials allows increased stick compliance.

These developments in composite hockey stick manufacturing have led to changes in stick construction and design. The cross-section of the shaft can be designed to have a concave, straight wall, or convex shape. Shafts can also be tapered to control the location of the kick point of the stick [1]. The effect of these changes on stick performance is not well understood and the direct relationship between shot performance and stick dynamics has not been determined [4, 6]. Vibration of hockey sticks has also become more important with the introduction of composite materials, which players often claim provide a poor feel for the puck on the stick compared to wood [1].

Manufacturers are using new materials and geometric features of sticks that claim to allow the puck to release from the stick faster, but little independent research has been done to confirm or deny these claims. In this study, hockey pucks were characterized by their elasticity and hardness. A test apparatus was developed to measure the response of pucks and sticks at speeds representative of play. The effect of stick vibration was considered using modal analysis. A measure was derived to compare stick performance under realistic play conditions

2.0 Experimental Methods

2.1 Puck Testing

The pucks considered here consisted of two different brands that are commonly used in recreational play, referred to as PA and PB. Two dozen pucks of brand PA were tested and 12 pucks of brand PB were tested. Pucks were characterized in terms of their COR and hardness. The effects of temperature and speed on puck impact properties were also investigated.

All pucks were tested at 55 ± 1 mph at room temperature (72° F). Furthermore, 12 PA pucks were tested at 25 ± 3° F. Temperature related tests required a two hour wait period between impacts to achieve uniform temperature. A non-contact infrared temperature sensor was used to verify the puck temperature prior to firing. To investigate the effect of speed on puck impact properties, pucks were tested at intervals of 10 mph from 55 mph up to 85 mph at room temperature (72° F).

The hockey puck COR was measured in a manner analogous to that described in ASTM 1888-02 [7]. A high speed air cannon fired pucks at a rigid strike plate mounted on an array of load cells (Figure 1). Light gates were used to measure the inbound and rebound speeds of the puck. The COR was then calculated as

$$COR = \frac{-v_p'}{v_p} \tag{1}$$

where $-v_p'$ and v_p are the outgoing and incoming puck speeds, respectively. A valid impact was defined as one in which the inbound speed was within ± 1 mph of the target speed, the round edge of the puck impacted the strike plate, and the rebound was parallel to the inbound path within 5 degrees with no wobbling or spinning.

The hardness of the puck was described by its peak impact force, found by impacting a rigidly mounted load cell as depicted in Fig. 1. The impact force was combined with the incoming puck speed to obtain a puck dynamic stiffness, DS, as

$$DS = \frac{1}{m_p}\left(\frac{F_i}{v_p}\right)^2 \tag{2}$$

where m_p is the mass of the puck and F_i is the peak impact force [8].

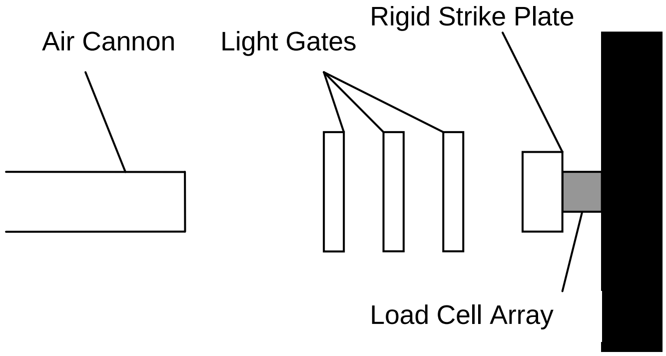

Figure 1: Puck testing setup

2.2 Stick Testing

2.2.1 **Modal Analysis**

Modal analysis was performed on a variety of straight shaft wood sticks, straight shaft composite sticks, and tapered shaft composite sticks as summarized in Table 1. The prefix W or C corresponds to a wood or composite stick.

Table 1: Summary of Sticks Tested and the Mode 1 Bending Lower Node Location

Stick Number	Material	Geometry	MOI (oz- in^2)	Mode 1 Node (in)
W1	Wood	Straight shaft	11000	11
W2	Wood	Straight shaft	9370	11
W3	Wood	Straight shaft	9701	11
W4	Wood	Straight shaft	9984	10
C2	Composite	Straight shaft	10445	10
C3	Composite	Tapered shaft high end	9491	10
C4	Composite	Tapered shaft high end	11658	9
C5	Composite	Tapered shaft	11051	9
C6	Composite	Tapered shaft high end	9830	7
C7	Composite	Tapered shaft	9752	9
C8	Composite	Tapered shaft	8753	9
C9	Composite	Tapered shaft	10485	9

A roving hammer test was performed with an impact hammer (PCB Piezotronics, Model # 350B23, Depew, NY). A 0.5 g uniaxial accelerometer was fixed in the middle of the top of the shaft (PCB Piezotronics, Model # 352C22, Depew, NY). The shaft of the stick was impacted at one inch intervals along its entire length on the top of the stick (Figure 2). The imaginary part of the FRF was plotted along the length of the stick to obtain a waterfall plot of mode shapes.


Figure 2: Modal analysis setup

2.2.2 **Stick Performance**

The stick performance test setup was similar to that used for puck DS testing. For this test, the rigid array of load cells was replaced with a pivoted stick to model a puck impacting the blade (Figure 3). The stick was pivoted about an axis perpendicular to the length of the stick, and located 35 inches from the bottom of the stick. For an actual slap shot, the instantaneous center of rotation of the stick is much closer to the top of the stick. The stick was relatively flexible, and therefore the exact center of rotation or pivot distance, PD, was not important in determining the dynamic behavior of the stick.

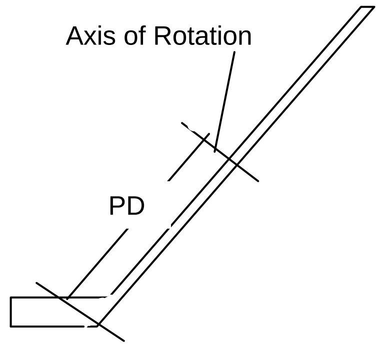

Figure 3: Performance testing stick schematic

In an actual slap shot, the resulting puck speed is due to a combination of shaft loading and swing speed of the stick. The small effect of stick stiffness on puck velocity [4] suggests that stick speed and deflection increase with player ability [2]. Thus, shaft loading may be viewed as a constant increase in stick speed (independent of shaft stiffness) that may be accounted for in the stick swing speed.

The performance of a wood (W2), a straight shaft composite (C2), a mid-range tapered composite (C9), and a top of the line tapered composite (C3) stick were compared. Each stick was impacted at seven different locations along the blade. The impact locations were on the bottom inch of the blade in one inch horizontal intervals, beginning at the heel of the blade. Reported values are the averages from six pucks at each impact location.

For performance testing, pucks were fired at a known location on the blade of the pivoted stick. Light gates measured the inbound speed of the puck and a potentiometer measured the angular velocity of the stick after impact. High speed video and powder spray on the blade were both used to verify each impact. A valid impact was defined as one that had an inbound speed of 50 ± 1 mph, did not wobble or spin, and the round edge impacted the lower inch of the blade. A polyethylene sabot supported the puck as it was fired from the cannon to ensure a flat puck trajectory with no spinning or wobbling.

The collision efficiency, e_a, from a puck-stick impact may be found from [9]

$$e_a = \frac{v_p'}{v_p} \tag{3}$$

The collision efficiency may be used to describe the puck speed in play conditions according to

$$PS = v_p e_a + v_s(1 + e_a) \tag{4}$$

where v_s is the stick swing speed [9]. For the case of a swinging stick impacting an initially stationary puck, Equation (4) reduces to

$$PS = v_s(1 + e_a) \tag{5}$$

The stick swing speed was calculated in miles per hour from a nominal average swing speed, in this case 60 mph for a stick with I = 10,000 oz in^2 at a 35 inch impact location. The stick moment of inertia about the axis of rotation was found in a manner analogous to that described in ASTM F2398 [11]. Speed has been shown to depend on inertia for a variety of sports [9, 10]. It was scaled according to impact location, Q (measured from the pivot point), and the stick moment of inertia, I, according to

$$v_s = 60\left(\frac{Q}{35}\right)\left(\frac{10{,}000}{I}\right)^{1/4} \tag{6}$$

3.0 Results and Discussion

3.1 Puck Testing

The 55 mph DS and COR results for the pucks tested at room temperature (72 °F) show significant difference between different brands. On average, the PB pucks were lower than the PA pucks in COR by 10.1% and in DS by 33.2%. Results are summarized in Figure 4.

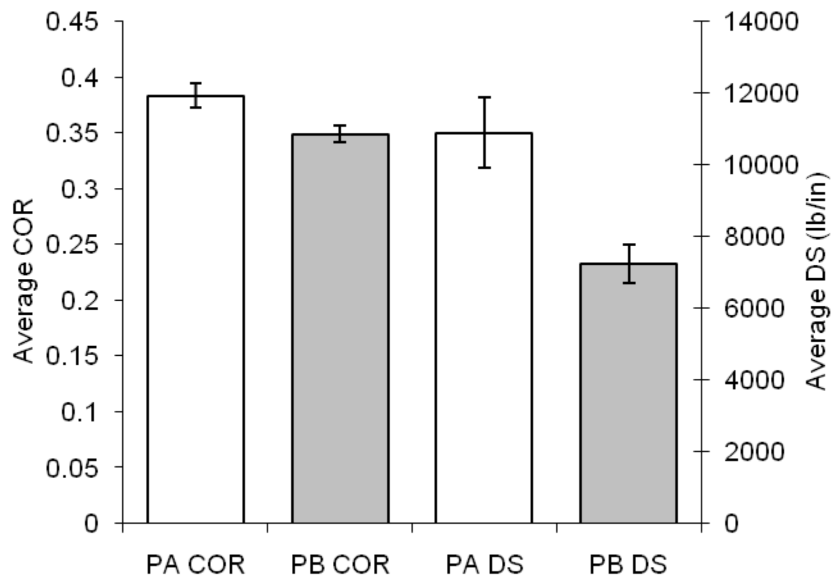

Figure 4: Average 55 mph COR and DS for Pucks Tested at Room Temperature

Puck COR and DS at room temperature are presented as a function of speed in Fig. 5. The COR decreased linearly with increasing speed. (Drop COR results [1] have been included for comparison, with a linear trend line between the high speed and drop test results.) The DS appears to increase with speed, suggesting the puck behaves as a non-linear spring.

The puck COR and DS is presented in Fig. 6 as a function of temperature. Both COR and DS show a non-linear dependence on temperature, where COR plateaus at low temperature and DS plateaus at higher temperatures. The low temperature COR was within the range found from vertical drop tests [1]. This suggests that the plateau shown in Fig. 6 may also occur with speed at low temperature.

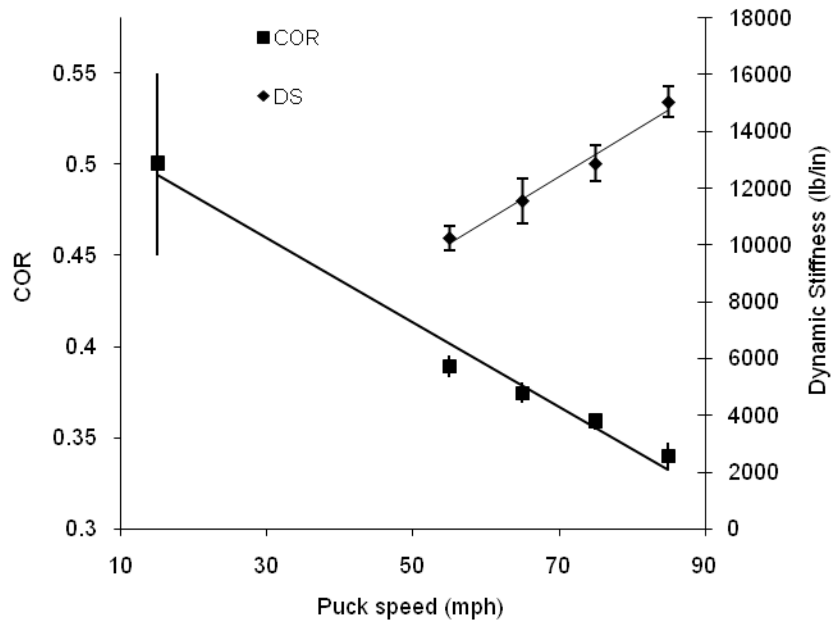

Figure 5: Effect of Speed on Puck COR and DS at Room Temperature

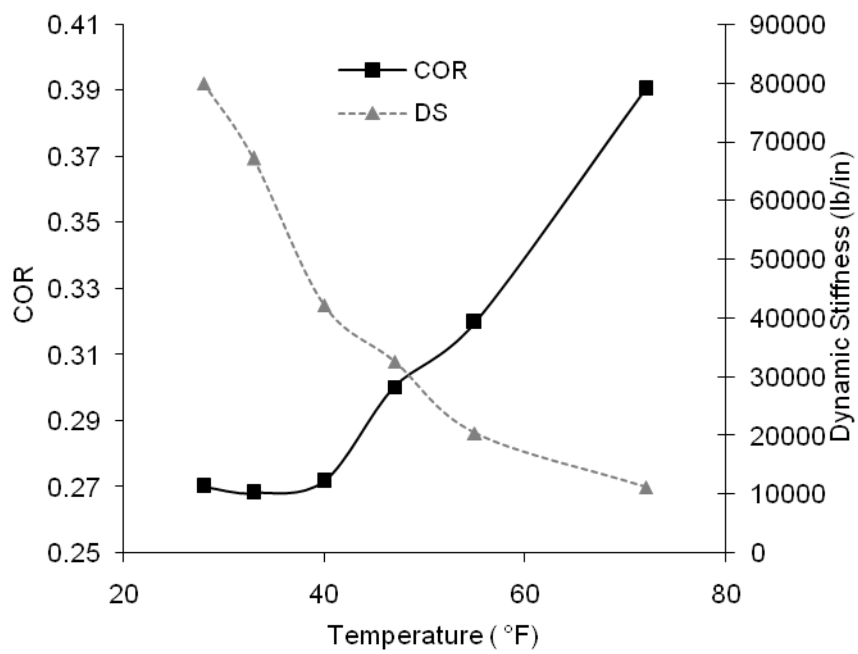

Figure 6: Effect of Puck Temperature on COR and DS

3.2 Stick Testing

3.2.1 Modal Analysis

Natural frequencies were obtained for the first and second bending modes of each stick in Table 1. Frequencies for the first bending mode were fairly close for all of the sticks. The lowest mode one frequency was stick W1 at 47 Hz and the highest was stick C8 at 60 Hz. Mode two frequencies showed a greater spread, between 116 – 161 Hz. Bending mode frequencies are summarized in Figure 7.

It is difficult to extrapolate frequency information to stick performance. It is, nevertheless, noteworthy that the wood sticks have lowest frequencies and are reported to provide the best feel for the puck. These are followed by the high end tapered shaft composite sticks, which are said to provide a better feel for the puck than mid to lower end composite sticks. The frequencies are all relatively close together, however, and a direct correlation between first bending mode frequencies and perceived player feel is difficult to quantify.

Some insight into the location of the kick point was provided by the location of the first bending node, summarized in Table 1. A lower node location on the shaft would tend to lower the kick point. The node locations were measured from the bottom of the shaft. The highest node locations occured in the wood sticks. Wood sticks are generally stiffer than composite sticks and have no taper throughout the shaft and shaft/blade junction, or hosel, so it is reasonable to expect that they would have the highest kick point. The lowest node location belonged to stick C6. Stick C6 is a high end tapered stick that is made by true one piece construction. (True one piece sticks are molded from a continuous composite piece that does not have a material bond in the hosel.) This stick would have a more continuous shaft, lowering the stiffness of the shaft in the hosel area.

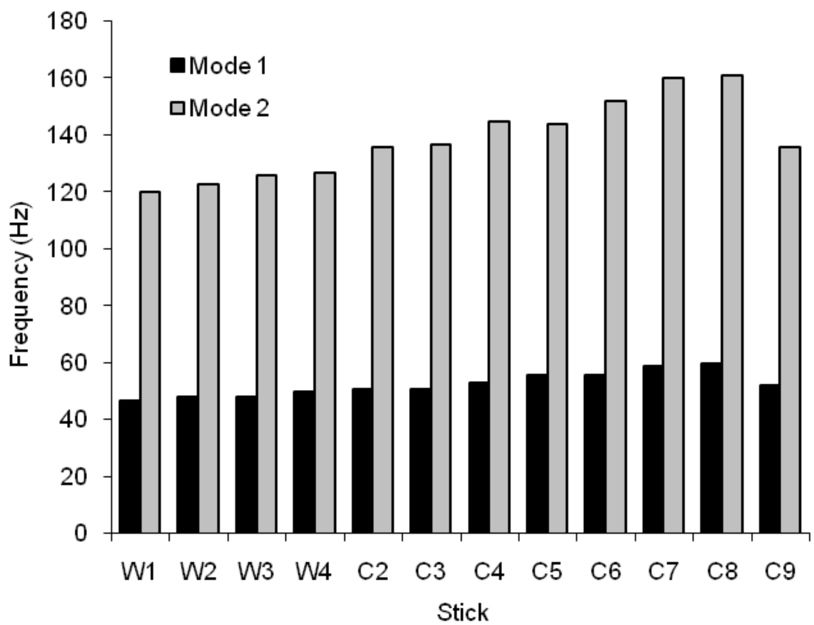

Figure 7: Summary of Bending Mode 1 and 2 Frequencies

3.2.2 **Stick Performance Testing**

Performance curves of PS as a function of impact location were generated for four different sticks. The highest performing stick was the straight shaft composite stick, C2, with a peak PS of 95.6 mph. The lowest performing stick was the wood stick, W2, with a peak PS of 75.6 mph. The two tapered shaft composite sticks lie in the middle. The higher performance of composite sticks suggests that new materials do result in higher performing sticks than wood. Peak PS values are reported in Figure 8.

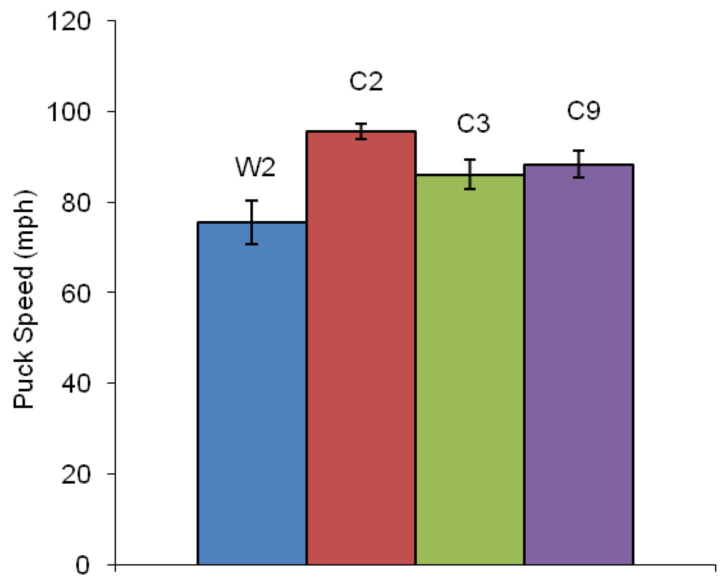

Figure 8: Stick Performance Results for Four Sticks

4.0 Conclusion

In this study, a test fixture was developed to characterize ice hockey pucks in terms of COR and DS and hockey sticks in terms of vibration and performance. Puck response had a measurable dependence on speed, temperature and brand. Hockey sticks were compared by their first and second bending mode frequencies as well as the location of the first bending node. A strong correlation between the measured vibrational response and player perception of feel was not observed. A measure to compare the performance of hockey sticks was proposed, based on an idealized puck speed. Using this measure, composite stick performance was shown to be significantly greater than wood sticks.

5.0 References

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