LABORATORY MEASUREMENTS OF ICE HOCKEY STICK PERFORMANCE

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In spite of the broad popularity of ice hockey, little has been done to characterize the performance of sticks used in play. Data representative of play conditions is particularly lacking. A high speed impact test was developed to measure the performance of hockey sticks. The performance of six wood and 11 composite sticks (including different shaft tapers for each group) were compared to evaluate the effect of modern materials on the game. Stick performance was expressed in terms of the maximum puck speed from an idealized slap shot. The average performance of the wood sticks was found to be 10% higher than the composite sticks. Shaft loading was found to increase the puck speed, but did not significantly change the relative performance of the sticks. In contrast to balls in golf and baseball, puck hardness was shown to have a negligible effect on stick performance.

1 Introduction

Players use several different methods to propel the puck with the stick, of which the slap shot is fastest (Villasenor, et al., 2006). Many studies of the slap shot are concerned with the technical aspects of shooting (Hoerner, 1989). The effect of stick stiffness on slap shot performance has been considered where a high variation between subjects and no significant trend between stick stiffness and puck speed was observed (Pearsall, et al., 1999). Stick stiffness for elite and recreational players was found to contribute to increased puck speed with increasing shaft deflection (Villasenor, et al., 2006).

Hardness, flexibility, and wear resistance are important properties for hockey sticks, accordingly wood sticks are often made from hardwoods such as elm, birch, aspen, or ash (Hache, 2002). 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.

Composite hockey sticks can be made from a combination of fiberglass, Kevlar, or carbon fibers in a polymeric resin. These materials can reduce stick weight, improve strength and are more uniform than natural wood (Hache, 2002). The weight, stiffness, and geometry of composite sticks can be manipulated in ways not possible with natural materials. The cross-section of the shaft can be designed to have a concave, straight wall, or convex shape. The shaft can also be tapered along its length to control its deflected shape.

The effect of modern stick designs on performance is not well understood (Pearsall, et al., 1999; Sim, et al., 1978). In the following, a test apparatus is proposed to measure the response of sticks at speeds representative of play. The apparatus is used to compare wood and composite stick performance.

2 THE SLAP SHOT

During a slap shot, the stick contacts the ice slightly before the puck, deflecting, or loading the shaft. The stick may be viewed as a beam under a three-point-bending load. The upper hand and ice act as the outside constraints, while the lower hand applies the central load. As the stick travels forward it contacts the puck which further loads the stick. The loaded shaft recoils, propelling the puck at a speed greater than the initial 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.

Stick motion during the slap shot of an upper level recreational player was measured by tracking visual markers on the stick with high-speed video (1000 fps). Figure 1 shows the speed of a marker 10 cm from the blade as a function of time. The puck and stick were in contact for 32 ms. Two distinct regions of contact are apparent. During the first 10 ms of puck-stick contact, the stick shows a sharp decrease followed by a sharp increase in speed. The puck-stick forces are largest during the first 10 ms of contact as the puck accelerates to the stick speed. During the remaining 22 ms, the stick “unloads” imparting further speed to the puck, which is not entirely apparent from the stick location (10 cm from the puck) tracked in the video.

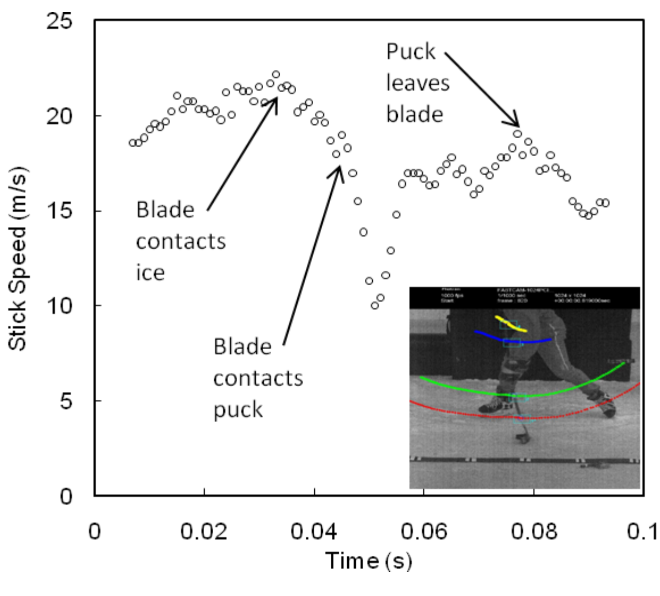

Figure 1. Stick speed measured 10 cm from the blade (red markers) during a slap shot.

3 STICK LOADING

To measure the stick performance in the laboratory, the effect of stick loading should be considered. It is not apparent, however, how stick stiffness and loading should interact. Consider the following ideal models of a player swinging sticks of different stiffness. If a player provides a constant force, F_p, as the stick strikes the ice, the loaded stick with stiffness k_s, would have a potential energy of

$$\frac{1}{2}\frac{F_p^2}{k_s} \quad (1)$$

A constant player force suggests the effect of stick loading is lower for sticks with high stiffness. If, however, the sticks are sufficiently compliant, the player could impart a constant displacement, x_p. Under this circumstance, the loaded stick would have a potential energy of

$$\frac{1}{2}k_s x_p^2 \quad (2)$$

A player constant displacement suggests that the effect of stick loading increases for sticks of higher stiffness. Since it is not clear which model is correct, we chose to decouple the initial stick-puck impact from the ensuing effect of stick loading.

4 TEST APPARATUS

The stick performance test setup consisted of an air cannon that oriented and propelled the puck toward an initially stationary, pivoted stick. The pivot was about an axis perpendicular to the length of the stick that was located Q=0.9 m from the blade of the stick. The pivot was close to the location where the lower hand would load the stick during a slap shot, which provided a shaft flexural stiffness comparable to that occurring in play.

Six wood sticks and 11 composite sticks were compared, including different shaft tapers for both groups. The sticks are commercially available, and comprise four different manufacturers. Flexural stiffness was measured in a three-point-bend fixture with a 1.27 m span and a centrally applied load for each stick. The mass moment of inertia (*MOI*) was measured by pivoting the stick 0.9 m (35 in) from the blade as described in ASTM F2398. Comparing the average wood and composite stick properties, the wood sticks had an *MOI* that was 7% higher and a stiffness that was 4% higher than the composite sticks.

5 STICK PERFORMANCE

The collision efficiency, e_a, from a puck-stick impact with initial puck speed v_i and post-impact puck speed v_r may be found from (Nathan, 2003)

$$e_a = \frac{v_r}{v_i} \tag{3}$$

The collision efficiency may be used to describe the puck speed in play conditions, v_p. For an initially stationary puck the puck speed in play is (Nathan, 2003)

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

where v_s is the stick speed. The stick speed has been shown to reach 27 m/s (60 mph) for elite-level slap shots in play (Lomond, et al., 2007). Studies of baseball bats, tennis rackets and golf clubs have found the swing speed to depend on the impact location, Q, and *MOI* according to (Nathan, 2003; Cross & Bower, 2006)

$$v_s = v_s\left(\frac{Q}{Q_n}\right)\left(\frac{I_n}{I}\right)^n \tag{5}$$

where the subscript, n, indicates the nominal or reference condition. The linear dependence of the impact location comes from rigid body motion about an instantaneous center. The non-linear dependence of *MOI* is a complex human factors problem. The strength of the non-linearity, n, varies among and between players. On average, n is close to 0.25 (Cross & Bower, 2006). In evaluating Eq. (4) the following values for Eq. (5) were used: v_n=27m/s, Q_n=0.9 m, I_n=882 g m^2, and n=0.25.

Pucks were fired on the lower 25 mm of the blade. The stick was impacted at eight locations, starting with the heel and moving across the blade in 25 mm intervals. The performance at each location was taken from the average of six impacts. The impact location providing the highest performance was used for each stick. Light gates measured the inbound speed of the puck and an optical encoder measured the angular velocity of the stick after impact. Angular momentum about the pivot was used to obtain the unmeasured rebound puck speed. High speed video and powder spray on the blade were both used to verify valid impacts. Valid impacts had an inbound speed of 23 $\pm$ 0.5 m/s (50 $\pm$ 1 mph), did not wobble or spin, and the round edge of the puck impacting the blade. The incoming test puck speed was selected to ensure each stick could undergo a complete scan without damage and should not be confused with the stick speed used in Eq. (4) to obtain the stick performance. Three sticks were tested three times each to determine the test repeatability. The peak performance was repeatable within 3% for each stick.

The peak performance of each stick, based on the initial collision with no shaft loading, is given in Figure 2. The average performance of the six wood sticks was 10%

greater than the 11 composite sticks. Shaft taper appears to have a detrimental effect on performance. The average performance of the tapered sticks was 7% lower than the straight sticks. Two of the six wood sticks were tapered, while nine of the 11 composite sticks were tapered. While, the apparent effect of taper and material is not entirely decoupled, the taper is representative of sticks commonly used in play (i.e. wood shafts tend to be straight, and composite shafts are often tapered).

One could argue that the weight of the protective equipment used in hockey reduces the effect of stick *MOI* on the swing speed in Eq. (5) (Hache, 2002). For comparison, stick performance is included in Figure 2 for n=0 in Eq. (5). The average performance of the wood sticks compared to the composite sticks increased slightly to 12% for this case. Thus, for the sticks considered here, the effect of stick *MOI* on performance was small.

In recreational play, puck speeds of 31 m/s (70 mph) are common. Because of the nature of the test used to measure stick performance, the no-load results presented in Figure 2 do not include the contribution of the stick unloading. It was observed that a stick loading of 450 N (100 lbs) or 60 mm (2.3 in) increased the average puck speed to 31 m/s. With stick loading included (and n=0.25), the wood sticks maintained their advantage over the composite sticks, although the margin narrowed. For the cases of constant force and displacement, the average wood performance was 5% and 7% higher, respectively than the average composite stick performance. The two cases of shaft loading are included in Figure 2. Excluding stick C7 (that had an unusually low stiffness) the effect of stick unloading had a small effect on the relative stick performance.

The performance of golf clubs and baseball bats is strongly influenced by the hardness of the ball (Nathan, et al., 2004). The effect of puck hardness was considered in the current study by comparing stick performance with pucks at 22 and -4°C. No measurable difference in stick performance with puck hardness was observed. The relatively long contact duration with puck-stick impacts apparently minimized the trampoline effect that is dominant with shorter duration impacts in golf and baseball. Puck hardness is, nevertheless, important when considering player injury.

6 Summary

Measurements of recreational level players showed the slap could be divided into three parts: loading, puck contact, and unloading. A test apparatus to model the puck contact portion of the slap shot was proposed. Stick performance was expressed in terms of the maximum puck speed from an idealized slap shot. Factors affecting the player swing speed and stick loading were also considered and shown to have a secondary effect on the relative performance of hockey sticks. The performance of wood sticks was shown to be measurably higher than composite sticks. Shaft loading increased stick performance, but had little effect on the relative performance. Puck hardness did not have a measurable effect on stick performance.

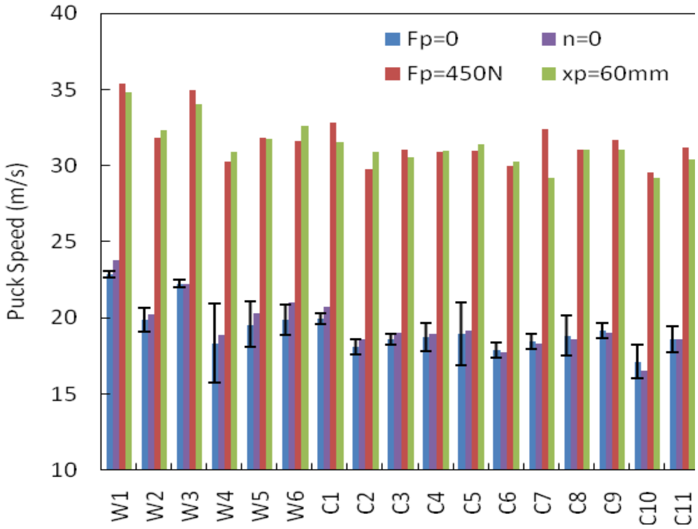

Figure 2: Stick performance for the cases of: no stick loading (F_p=0), constant swing speed (n=0), constant stick force (F_p=450N), and constant stick displacement (x_p=60 mm).

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