

Recoil Effect of the Ice Hockey Stick During a Slap Shot

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The purpose of this study was to examine the “recoil” effect of the ice hockey stick shaft during a stationary slap shot. Nine male adult subjects (four elite and five recreational) were tested. Their performances were evaluated by simultaneously recording stick movement and internal bending from high-speed digital video (1,000 Hz) and puck acceleration from a triaxial accelerometer positioned inside the puck. In addition, an electrical circuit measured blade–puck contact time. Data were analyzed with a one-way MANOVA for several dependent variables, including final puck velocity, puck acceleration, maximum stick shaft bending (angle and distance deflection), stick shaft angular velocities, blade–puck contact time, and corresponding time events. The results indicate the following. First, blade–puck contact time was greater for the elite than for recreational players (38 ± 9 ms and 27 ± 5 ms); however, measures for puck acceleration were essentially the same ($63.8 g \pm 9.9$ and $61.8 g \pm 19.5$). Two, the elite players were able to generate greater puck velocities (120 ± 18 km/h and 80.3 ± 11.6 km/h). Three, the recoil timing was found to be greater for elite players (59.8% of blade–puck contact).

Key Words: blade–puck contact, ice hockey, stick, recoil, slap shot, skill

The ice hockey stick is used as an extension of the arms in order to control puck movement as well as to project the puck in passing and shooting. There

are numerous techniques for projecting the puck; the fastest is the slap shot. The slap shot is executed by grasping the stick with both hands spaced approximately 40 to 60 cm apart. The skill may be broken into six distinct phases: backswing, downswing, preloading, loading, release, and follow-through (Hoerner, 1989; Pearsall, Montgomery, Rothschild, & Turcotte, 1999; Wu, Pearsall, Hodges, Turcotte, & Lefebvre, 2003). During the preloading phase, the blade of the stick makes contact with the ice surface (creating the slap sound) and precedes puck contact (by approximately 0.15 m to 0.30 m), and stick shaft bending is initiated by the coupled loading from the ice (ground) reaction force and the downward pressing of the lower hand on the shaft. Subsequently, the puck is impacted by the blade (loading phase) and then propelled (released phase) toward the goal or net. The resultant trajectory and speed of the puck are determined by several mechanical factors (Hoerner, 1989; Marino, 1998; Pearsall, Turcotte, & Murphy, 2000), such as impulse on the puck, acceleration of the puck, contact time with the puck, forces exerted by the player, and stiffness of the stick, among others. Various methods have been used to calculate puck velocities in a slap shot, for instance, cinematographic analysis for calculation of instantaneous velocity (Chau, Sim, Stauffer, & Johannson, 1973) and radar guns for estimation of maximal velocity (Pearsall et al., 1999). However, alternative technologies, such as accelerometers and various optoelectronic tracking devices that permit high sampling rates (i.e., >1,000 Hz) can be used to directly measure puck responses in a slap shot.

Several studies of shooting performance have been conducted (e.g., Marino, 1998; Pearsall et al. 1999; Murphy, 2001; Wu et al., 2003; Woo, Loh,

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Turcotte, & Pearsall, 2004). The stick parameters examined have included bending and torsion stiffness, with a variety of construction materials. From these studies, the authors suggested that movement patterns of elite players were predominant factors in determining critical outcomes, such as puck velocity, despite the variation of stick stiffness. However, the effect of the different mechanical factors (e.g., stick bend, puck velocity, and puck contact time) on shooting performance is not completely understood (e.g., puck velocity, net target). For instance, how do these parameters affect the catapult or recoil effect of the stick during a shot? What mechanical differences in stick dynamics are advantageous? Hence, the purpose of this study was to examine the recoil effect of the ice hockey stick shaft during a stationary slap shot; more specifically, the relationship between puck velocity and stick bending will be examined in conjunction with skill level.

Materials and Methods

Hockey sticks of wood and laminate shaft construction (Bauer Supreme 3030) with left- and right-handed blades were used in the experiment. The stick shaft dimensions were length, 1.35 m; major axis length, 0.02 m; and mass, 0.6 kg. The puck physical parameters were mass (accelerometer + puck), 0.260 kg; diameter, 7.62 cm; and thickness, 2.54 cm.

Nine male subjects volunteered for this study. Four were classified as the elite group (mean height, 181.4 ± 8.7 cm; mean mass, 85.2 ± 7.5 kg; mean age, 31 ± 13.3 years) and the remaining five as the recreational group (mean height, 171.9 ± 8 cm; mean mass, 74.5 ± 9.5 kg; mean age, 28.8 ± 7.6 years). Elite subjects had at least three years of competitive playing experience at junior or senior levels. Recreational subjects were those with only intramural playing experience. Two subjects from the elite group were right-handed shooters, and the rest, including the recreational group, were left-handed shooters. Ethics approval for this research was obtained from the Research Ethics Board of the Faculty of Education, McGill University.

Data collection consisted of the simultaneous recording of high-speed video and puck acceleration. Analog signals were collected by a data acquisition card (DAQ, AT-MIO-16X, National Instruments). To synchronize the above systems, a blade-to-puck

contact circuit was employed in a method similar to that used by Roberts, Jones, and Rothberg (2001); that is, both the stick's blade and the puck were wrapped in metal foil and connected by a 10-m cable in series with a 9-V DC battery. Thus, during puck and blade contact, a voltage signal would be simultaneously recorded on the video image and analog-to-digital files.

A high-speed video system (Motion Scope, RedLake Imaging, Model PCI 1000; sample rate of 1,000 Hz) was used to record the stick movements. The camera was positioned 4 m laterally to the puck direction of motion and 1.10 m vertically above the plane of the surface. The camera was oriented horizontally and perpendicular to the global sagittal plane of motion. Five adhesive spherical reflective markers were placed along the shaft of the stick at 0.10-m intervals to a distance of 0.20 m from the blade's heel. From the projection onto the camera plane, the marker locations were digitized using the Ariel Performance Analysis System (Ariel Dynamics, San Diego, CA) and could be located to within 3 mm per pixel (picture element) from the video recording of a 1.5×1.5 -m field of view. Angular deflections, velocities, and respective times of occurrence from the four distal segments (i.e., four, five, six, and seven; below the bottom hand on the stick) were the three dependent variables obtained from this analysis (Figure 1). The total angle of deflection ($\theta_{\text{total}} = \theta_{4-5} + \theta_{5-6} + \theta_{6-7}$) of bending was calculated as the intercept angle between projection lines from segments 4 and 7 of the stick (Figure 1).

The "recoil effect" (minimum stick joint angle displacement), was estimated from the spatio-temporal measurements acquired through the high-speed video system and the blade-to-puck contact circuit; that is, the *recoil angle*, which refers to the stick shaft deformation in the minor axis that follows the bending angle during the slap shot (unbending) and the *recoil phase*, which refers to the period of time in which the recoil angle was occurring (unbending period). See Figures 2 and 5.

A piezoelectric triaxial accelerometer (Model 8792A500, Kistler Instrumentation Co., Amherst, NY) measured puck accelerations for each trial. The accelerometer had a linear acceleration range of ± 500 g, 10 mV/g sensitivity, and 1,000-g shock tolerance (note that although exceeded briefly at impact, only values up to 500 g were used in subsequent calculations, Figure 2). The accelerometer

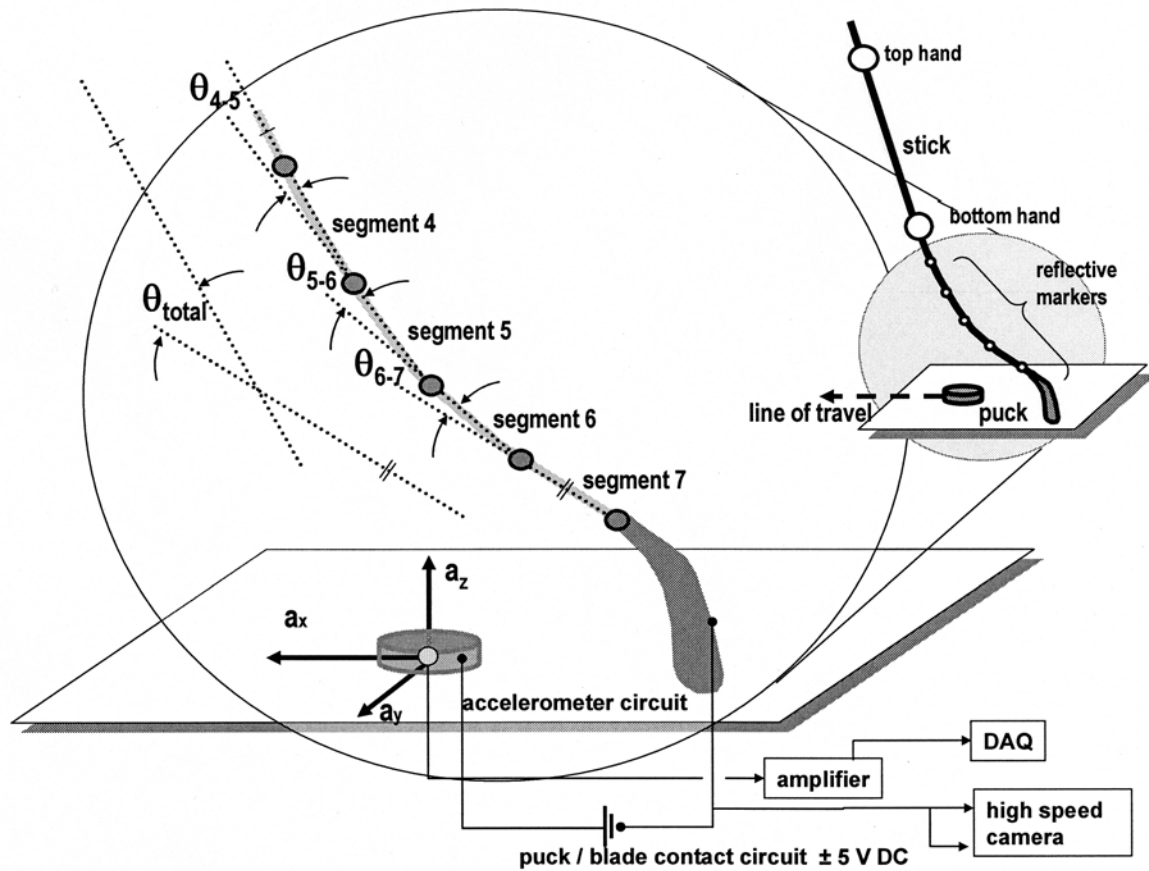


Figure 1 — Setup of the experiment. Stick angle deflections (θ_{4-5} , θ_{5-6} , θ_{6-7} , θ_{total}), accelerometer's axes, and data acquisition synchronization.

was embedded in the center of a modified puck (i.e., the core had been drilled out) and attached to a cable leading to a charge amplifier (Type 5134, Kistler, Amherst, NY). An analog-to-digital board (AT-MIO-16X, National Instruments) recorded the signals at 10 kHz using LabView 6.1 software on a PC Pentium III. To prevent cable damage during the shot, the cable was extended from the net out to the shot location. In this manner, rapid distension of the cable was avoided. Preliminary testing indicated that the cable did decrease shot velocity by approximately 10% compared to a puck propelled free of cable connection.

The subjects wore ice hockey gloves and stood on a 3-m square piece of 0.004-m thick polyethylene (artificial ice) to execute the slap shots. As in a previous study, the surface friction of the polyethylene sheet was reduced by preapplication of a silicon lubricant (Pearsall et al., 1999) to mimic ice surface

reology. Subjects were not given instructions on shooting technique other than the requirement to maintain a constant foot placement. They performed a minimum of three practice trials. Subjects performed approximately 8–10 slap shots. A shot was considered a good trial if (1) the puck went into the target area (0.60 m \times 0.60 m) approximately 3.3 m from shot to goal, (2) the blade–puck contact circuit was working properly, (3) the puck acceleration was successfully captured, and (4) the subject was satisfied that the trial was a maximal effort.

Table 1 summarizes the independent and dependent variables of this study. The two main phases distinguished were the stick bend and stick recoil, which corresponded to the maximum and minimum intersegment angles of deflection. The blade-to-puck contact time ($T_{contact}$) was broken down into the following events: initial contact (t_1), final contact (t_6), and for the times of intersegment estimates of maxi-

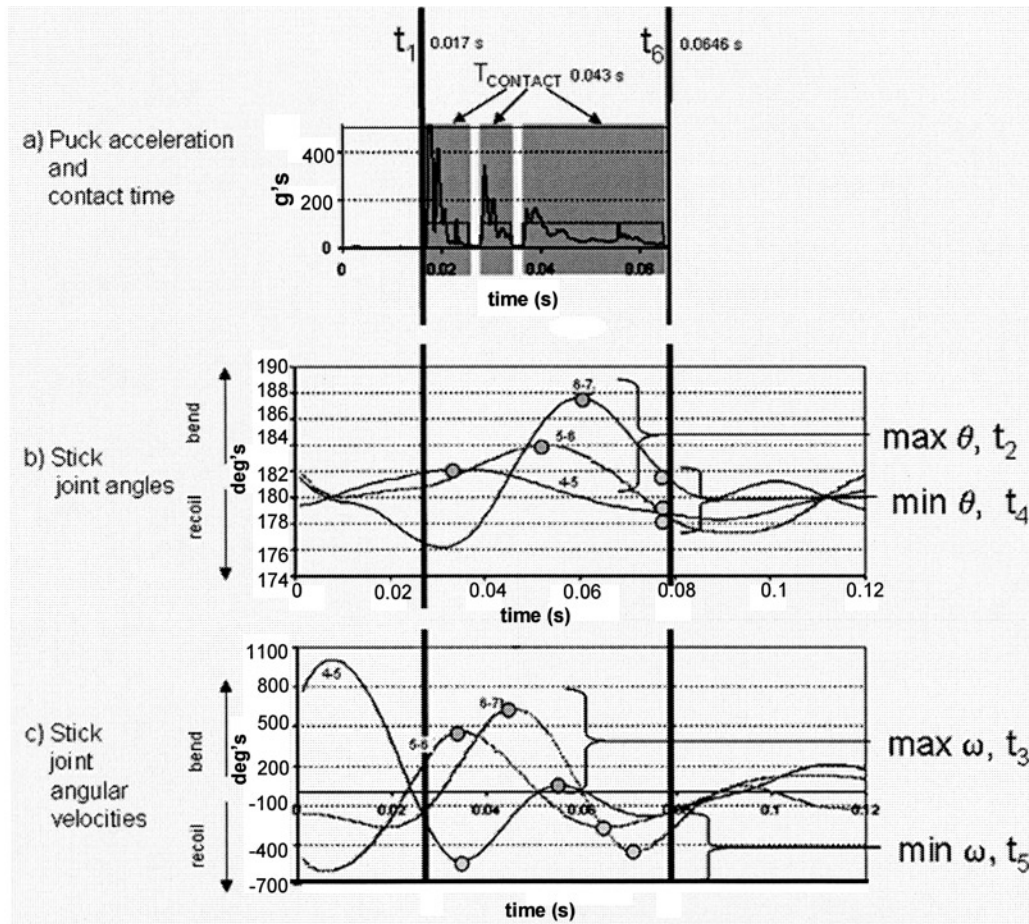


Figure 2 — Synchronization of stick kinematics and puck acceleration (g 's) through the puck circuit contact. Example data shows initial to final contact (t_1 – t_6) and total contact (i.e., $T_{\text{contact}} = \sum \Delta t$, where puck acceleration $> 10 g$'s = shaded area) (a), as well as corresponding stick angle deflections (θ) and stick angular velocities (ω) are shown (b, c).

imum and minimum angles (t_2 and t_4 , respectively) and angular velocities (t_3 and t_5 respectively), during contact (t_1 to t_6) for the maximum and minimum intersegment estimates of angle and angular velocity (Figure 2).

The statistical analyses were performed using SPSS v. 13.0 statistical software. Significant differences were considered at $p < 0.05$. These included (1) a multivariate analysis (Hotelling's T) between groups and (2) multiple linear regressions to predict puck velocity.

Contact time was identified by the accelerometer's positive impulse time phase ($T_{\text{contact}} = \sum \Delta t$, where puck acceleration exceeded $10 g$'s) and corroborated with the blade–puck circuit. Peak puck velocity (V_p) was identified as the maximum velocity achieved from the integrated accelerometer measures using the trapezoidal rule (Irvine, 2004).

Table 1 Summary of Independent and Dependent Variables

Independent variable	Dependent variables
Skill level:	Peak puck velocity (V_p)
Elite	Average puck acceleration (A_p)
Recreational	Blade–puck contact time (T_{contact})
	Stick distance deflection (D_{stick})
	Maximum and minimum intersegment angles of deflection (θ_{4-5} , θ_{5-6} , θ_{6-7})
	Stick deflection angle ($\theta_{\text{stick}} = \theta_{4-7}$)
	Maximum and minimum intersegment angular velocities (ω_{4-5} , ω_{5-6} , ω_{6-7})
	Stick deflection angular velocity ($\omega_{\text{stick}} = \omega_{4-7}$)
	Time to maximum stick recoil (t_4 : time of minimum intersegment angle)

Results


Main results are summarized in Table 2. Multivariate analysis indicated differences between elite and recreational players considering multiple comparisons of dependent variables ($p = 0.009$). Specifically, the elite group showed greater average puck velocity than the recreational group; 120.8 ± 18 km/h (33.6 ± 5 m/s) and 80.3 ± 11.6 km/h (22.3 ± 3.2 m/s), respectively ($p = 0.004$). Conversely, with regards to average puck acceleration A_p , no significant differences between groups were found ($F = 0.03, p = 0.86$), where values of 63.8 ± 9.9 g and 61.8 ± 19.5 g were observed for the elite and the recreational participants, respectively.

Table 2 Main Results in Puck Acceleration, Puck Velocity, Blade–Puck Contact Time, and Stick Deflection

Level	Elite		Recreational	
	M	SD	M	SD
A_p (g)	63.8	9.9	61.8	19.5
V_p (m/s)	33.6	5	22.3	3.2*
T_{contact} (ms)	38	9	27	5*
D_{stick} (m)	0.04	0.022	0.012	0.008*
θ_{stick} (deg)	7.6	4.0	2.2	1.5*

* $p < 0.05$.

Concerning blade-to-puck contact times (T_{contact}), significant differences were found ($F = 6.79, p = 0.04$), with the elite group having 38 ± 9 ms and the recreational group 27 ± 5 ms. During the shots, the blade and puck were typically not in continuous contact; one to three transient separations occurred. In general, T_{contact} represented approximately 80 to 85% of the time between initial (t_i) and final (t_f) contact. Time events for stick recoil phase (recoil timing t_4) were found with significant differences ($F_{4-5} = 21.67, p_{4-5} = 0.002$; $F_{5-6} = 15.06, p_{5-6} = 0.006$; $F_{6-7} = 7.08, p_{6-7} = 0.032$) for the three intersegment angles examined (4-5, 5-6, 6-7); see Figure 3. Regression analysis indicated a strong relationship between V_p and T_{contact} ($V_p = 864.73 * T_{\text{contact}} + 8.0556, r = 0.91$).

With reference to the stick bend phase, for the most proximal intersegment angle θ_{45} , a significant difference was found ($F = 6.23, p = 0.041$) between groups. Furthermore, the amount of angular deflection varied between stick segments. For instance, during the stick recoil phase, significant differences were shown in maximum stick bending between intersegment angles θ_{56} and θ_{78} ($t = 2.83, p = 0.02$), and between θ_{67} and θ_{78} ($t = 4.17, p = 0.003$). For the elite group, the bending occurred shortly before or at the instant of first contact (t_1) until 28.8% of blade–puck contact window followed by the recoil-phase, which lasted until 59.8% after bend phase or 88.6% after first touch  (Figure 5). Conversely, the recreational group showed a different sequence,

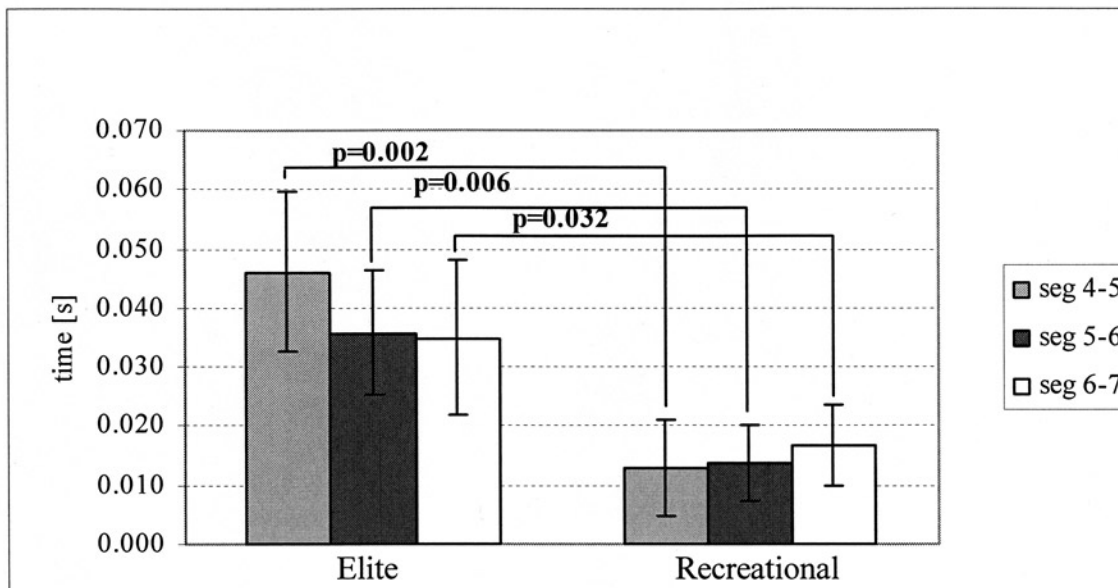


Figure 3 — Average time to maximum stick recoil for each segment.

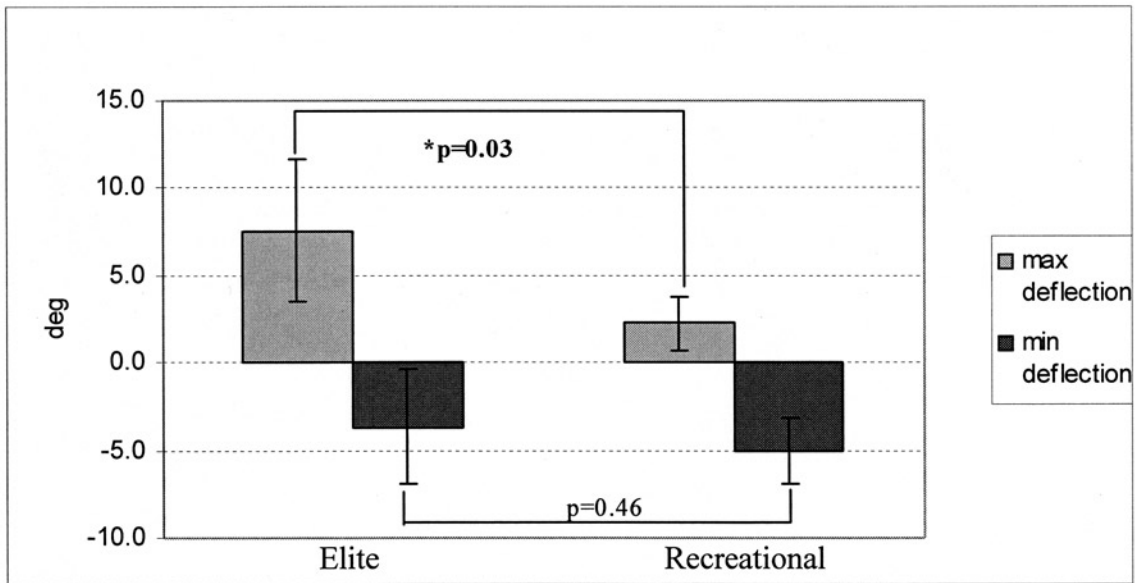


Figure 4 — Average maximum and minimum angular deflections (degrees).

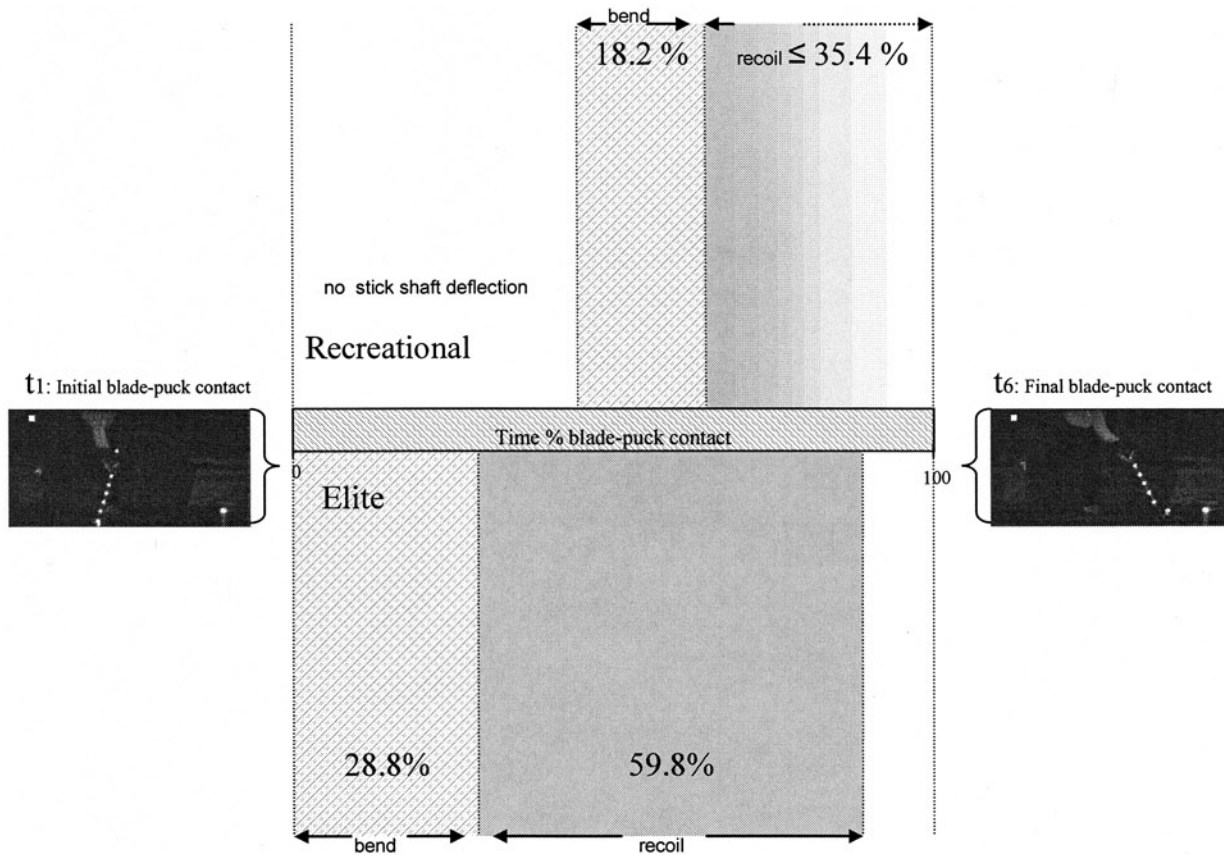


Figure 5 — Average percentage of time spent in bend and recoil during puck-blade contact.

such that the bend phase began only after halfway through the contact window (44.4%), and then lasting for only 18.2% of T_{contact} before initiating the stick recoil (up to 35.4% of contact time remaining) (Figure 5).

As a whole, significant differences in the maximum deflection angle (θ_{stick}) were observed between groups ($F = 7.51$, $p = 0.03$). These differences corresponded to maximum stick deflections (D_{stick}) of 0.040 ± 0.022 m and 0.012 ± 0.008 m, for elite and recreational, respectively (Fig. 4). Regression analysis indicated strong relationship between final puck velocity and maximum angle deflection ($V_p = 1.6432 * \theta_{\text{stick}} + 19.733$, $r = 0.91$).

Discussion

The above research protocol quantified similarities and differences in technique that may explain the ability of elite players to achieve greater puck velocity (V_p) during the slap shot than recreational players as well as give insight into the mechanics of the stick recoil phenomenon. Contrary to expectation, it is not simply a case that elites hit the puck harder; in fact, both groups applied the same magnitude of force to the puck during the shot (as evident from similar average puck accelerations). The elite and recreational groups differed in the puck-to-blade contact time achieved, the peak puck velocity, and the blade-puck contact time. However, no significant differences were found in puck acceleration (A_p) between groups. Further, A_p did not correlate highly with V_p .

The V_p obtained in the current study were within the range of previous studies (Alexander, Haddow, & Schultz, 1963; Chau et al., 1973, Doré & Roy, 1976; Sim & Chau, 1978; Marino, 1998; Pearsall et al., 1999 & 2001; Wu et al., 2003). For instance, Wu et al. (2003) found V_p of 108 ± 9.36 km/h (30.0 ± 2.6 m/s) for elite players in comparison to 120.6 ± 18 km/h (33.5 ± 5 m/s) for the current study. Similarly, for the recreational group, velocities of 83.88 ± 14.04 km/h (23.3 ± 3.9 m/s) were reported by Wu et al. (2003), whereas, in this research project, the recreational group performed slap shots at 80.28 ± 11.52 km/h (22.3 ± 3.2 m/s). However, small discrepancies in reported speeds with some earlier studies do exist (Alexander et al., 1963; Cotton, 1966; Roy, 1976), in which lower values for standing slap shots were reported. These differences

might be related to the various measuring techniques used (stopwatch, cine) for recording puck velocities, among other factors (e.g., mechanical properties of the stick and the environment; subject sample groups; variations in skill, mass, and strength). In the present study, the puck velocity was obtained directly, by integrating the magnitude of acceleration measures.

Concerning the temporal events of the slap shot (T_{contact} , t_1-t_6) during blade-puck contact, differences in both the magnitude and sequence of the two main phases (stick shaft bend and recoil) were observed between groups. For instance, a consistent bend-recoil sequence of the three stick shaft segments examined for the elite group was observed in contrast to the recreational group, where a recoil phase was relatively nonexistent. The results also suggest that differences in blade-puck contact time and not differences in puck acceleration had a major influence on V_p . A strong linear relationship between T_{contact} and V_p was indicated. Stated simply, the longer the blade was in contact with the puck during the slap shot, the greater the final puck velocity. The significant differences found between groups in blade-puck contact time are congruent with the findings of 3-D global kinematics (Woo et al., 2004), wherein the elite players performed the typical shot motion with greater horizontal translation toward the target than the recreational players. Thus, elite players have the opportunity for a longer blade-puck contact time during the slap shot.

With regards to the maximum and minimum stick joint angle displacements (bend and recoil phases, respectively), during the contact window significant differences were found between groups for the most proximal intersegment angle examined $\theta_{4,5}$ (Figure 6). During the bend phase for both groups, shaft deflection angles increased toward the distal intersegment $\theta_{6,7}$. Differences were observed during the recoil phase, with greater joint angle differences observed between $\theta_{4,5}$, $\theta_{5,6}$, and $\theta_{6,7}$ for the elite group. These cumulative differences corresponded in greater maximum angle deflection (θ_{stick}), and the maximum stick distance deflection (D_{stick}) for the elites. In other words, the findings suggest that there is a lower "kick point" on the stick shaft for the more skilled group (i.e., the point along the shaft where the predominant bending begins). These differences in stick shaft deflections between groups might be related to the different load distribution

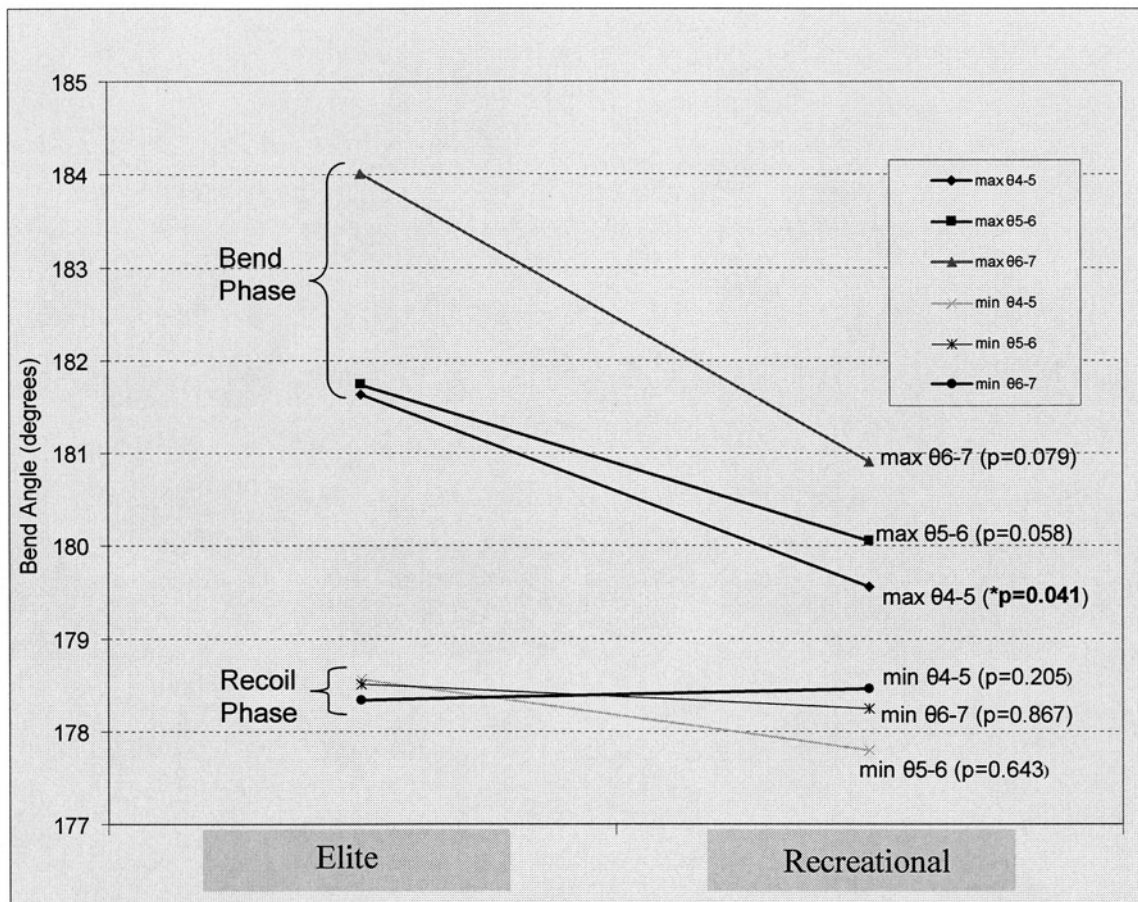


Figure 6 — Average maximum and minimum joint angle displacements.

applied to the stick shaft between the top and bottom hands as well as tapering shaft thickness toward the distal end. Given the previous discussion and as was expected, significant differences in maximum stick distance deflection were found between groups. Furthermore, a strong relationship between maximum deflection distance and the V_p was found. Together these results suggest that stick bending behaviors were strongly related to peak puck velocity, corroborating the observations of Pearsall et al. (1999) and Wu et al. (2003).

It is possible to make some inferences about the stick recoil behavior observed and energy exchange between the stick and puck. In order of events, the possible energy conversions occurred as follows. During the preloading and loading phases, the stick's kinetic (swing) energy is converted in part into (1) elastic strain energy within the stick's lower shaft as evident from the increasing bend deformation toward the distal end of the stick and

(2) puck kinetic energy due to impact momentum transfer. Then, as the stick shaft unbends (recoil), the stored elastic strain energy is released, which in turn is transmitted, in part or in whole, to the puck. Impulse can be completely transmitted to the puck only if optimally timed to permit blade-to-puck contact up to the release phase (as observed in the elite subjects). In this instance, elastic (bend) energy can contribute more to the net puck velocity. Of course, the impact scenario for the slap shot is more complex because it was not instantaneous but instead occurred over 30 to 40 ms, and, furthermore, energy gains and losses could have occurred at other interfaces. For instance, other unknown energy exchanges occur due to forces at the hands, surface-blade friction, puck surface friction, blade vibration, and puck deformation.

This study provides estimates of the dynamic response of the stick shaft. For instance, despite evidence that the performance of the slap shot is

affected by using either composite or wooden sticks (Pearsall et al. 1999; Wu et al., 2003), by investigating the recoil effect with different stick materials, some insights yet could be provided leading to product development, such as optimization of design (blade geometry, the recoil kick point), construction, and materials. Thus, development of stronger, lighter, and/or more flexible ice hockey sticks could have a great effect on puck velocities. As well, the precise knowledge of the biomechanics of the stick shaft loading and bending could provide relevant information to understand the injury mechanisms implicated in the execution of the slap shot (Lacroix et al., 1998).

Some experimental limitations should be noted. The polyethylene ice surface was not the same as real ice. The subjects performed stationary slap shots, and the only equipment used was their gloves. The sample size consisted only of nine adult male subjects and 2-D analysis rather than 3-D analysis was performed. Several improvements could be made in future studies. For instance, with a larger sample size the variability of the sampling distribution could be decreased and consequently the statistical power and confidence of the study could be improved. By using smaller reflective markers, a better resolution in the digitizing process could be achieved. In addition, with a 3-D analysis by using alternative motion-tracking systems with higher sample rates (i.e., >1,000 Hz), a better resolution would be achieved, thereby allowing at the same time the observation of torsion responses in the stick shaft during the slap shot. Moreover, the integration of kinematics along with additional kinetic measurement techniques, such as hand grip dynamometers (top- and bottom-hand forces measures), force plate (stick-ground reaction force), multiple accelerometers on the stick (one per reflective marker), and EMG may provide further insights regarding this crucial skill (slap shot).

In summary, the present study was designed to examine the recoil effect of the ice hockey stick shaft during a stationary slap shot. With regard to puck velocities, the findings were in agreement with previous studies (Alexander et al., 1963; Chau et al., 1973; Doré & Roy, 1976; Sim & Chau, 1978; Marino, 1991; Pearsall et al., 1999, 2001; Wu et al., 2003). Blade-puck contact time (T_{contact}) was identified as the main factor highly related to peak

puck velocity (V_p). From these results, a better understanding of the impact blade-puck event during a stationary slap shot was obtained. This provides more insight into mechanical parameters that influence the performance of the ice hockey slap shot. Further, these findings provide guidance for future ice hockey stick development (e.g., construction materials and design).

Acknowledgments

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