Three-dimensional analysis of blade contact in an ice hockey slap shot, in relation to player skill

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Abstract

The purpose of this study was to examine the three-dimensional movement profile of the blade during a stationary slap shot, as a function of player skill level. A total of 15 subjects participated; eight were classified as elite and the remaining seven were recreational. Performances were evaluated by simultaneously recording the movements of the stick's lower shaft and blade with high-speed video (1000 Hz), the time of stick–ground contact with two uniaxial forceplates and time of blade–puck contact with a uniaxial accelerometer mounted within the puck. Data were analysed with a two-way MANOVA for several dependent variables including linear kinematics, temporal phase data and global angles. The results indicated that skill level affected blade kinematics, with elite shooters tending to alter timing parameters (i.e. phase length), magnitude of linear variables (i.e. displacement, etc.) and the overall blade orientation to achieve a higher velocity slap shot. These analyses identified a unique 'rocker' phase within the execution of the slap shot in both groups.

Keywords: ice hockey, blade, slap shot, skill, rocker, kinematics, orientation

Introduction

The game of ice hockey is multi-faceted and requires a complex combination of skill sets from its players. Hockey skills can be divided into three general categories – skating, shooting and checking – which can be further subdivided into more specific skills (Pearsall *et al.*, 2000). Of these skills, the most spectacular is shooting, which is influenced by a wide variety of factors including puck impulse, puck acceleration, puck, mass, blade–puck contact time, initial puck velocity, initial/final stick velocity, stick mass, forces exerted by the player, stick stiffness and stick bending (Pearsall *et al.*, 2000). Hockey's most prolific shot – the slap shot – is employed 26% of the time by forwards and 54% of the time by defence players (Montgomery *et al.*, 2004) and is distinguished by its increased puck velocity, as compared to other shots (i.e. wrist, snap, sweep) (Pearsall *et al.*, 1999).

The primary objective of the slap shot is projecting the puck with maximal velocity and accuracy as a means to out-manoeuvre the opposing goalie and, ultimately, score. There is constant pressure from athletes, coaches and stick manufacturers to better understand

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how slap shot velocity can be increased. Previous works have made great strides in defining the overall role of the hockey stick shaft, including the effects of various shaft properties (e.g. stiffness and construction materials) (Marino, 1998; Marino & VanNeck, 1998; Pearsall *et al.*, 1999; Roy & Delisle, 1984; Roy & Doré, 1975; Simard *et al.*, 2004; Villaseñor-Herrera, 2004; Worobets *et al.*, 2006; Wu *et al.*, 2003). Similarly, several authors have provided descriptions of whole-body kinematics during the stationary slap shot using both two- and three-dimensional methods (Hayes, 1965; Polano, 2003; Roy & Doré, 1976; Woo, 2004). While the movement characteristics of the blade during the slap shot remain largely unknown, similar work in golf suggests that the final direction of the puck once it leaves the blade are determined by 1) the direction of the blade prior to, during and immediately following impact; 2) the orientation of the blade relative to this direction; and 3) frictional interactions between the surface of the blade and puck during impact (adapted from Williams & Sih, 2002).

Proper timing and sequencing of movements has also been long recognised as an essential component in successful striking tasks (Caljouw *et al.*, 2005). Yet, the overall joint sequencing patterns and the exact timing parameters between the stick and puck within the ice hockey slap shot have remained largely unstudied until recently. Woo (2004) provided a preliminary investigation into the sequencing of joint movements during a stationary slap shot and was able to quantify an apparent proximal-to-distal joint sequence that had previously only been eluded to in qualitative descriptions (Hayes, 1965). Similarly, recent investigations have begun to examine timing parameters between the stick and puck. These include time to peak force (Pearsall *et al.*, 1999), time from initial ground contact to puck contact (Polano, 2003) and duration of puck–blade contact (Polano, 2003; Villaseñor-Herrera, 2004). However, the present study is the first attempt to provide a detailed temporal analysis of all the impact events associated with the blade during the stationary slap shot. As such, the purpose of this study is to quantify the influence of player skill on stationary slap shot performance during the critical period of blade–ground contact.

Materials and methods

Sticks and puck

Six models of carbon-fibre composite hockey sticks, with both right- and left-handed blade curvatures, from three industry-leading manufacturers, were subjected to the testing protocol. All sticks possessed an identical lie angle (that is, the shaft projects 40º from the vertical with respect to the blade). The unique make, model and individual blade parameters of each stick model are listed in Table 1. Reflective markers (6 mm in diameter) were glued to the back of the blade surface. Markers were then wrapped with two layers of transparent, heat-shrinkable, plastic wrap and covered with black hockey tape, to reduce excess glare and assure all the markers remained fixed during impact. For reference, the blade markers were numbered according to their spatial location with marker 1-1 being the top row in the column closest to the heel of the blade, while the shaft markers were numbered S1 and S2, with S1 located on the top edge of the shaft (Fig. 1). The front face of the blade (which contacts the puck) was divided into six vertical contact zones from the blade's heel to toe. The locations of these zones were determined with respect to marker locations.

Table 1 Blade construction properties for each test stick (adapted from Pearsall *et al.*, 1999)

Model	Abbreviation	Structure type	Materials	Curve
CCM Vector 120	CCM	Sandwich structure	Fibreglass, carbon, ABS plastic	Heel
Bauer Vapor XX	VXX	Full wrap RTM blade	100% carbon, low density foam	Mid
Easton Stealth	EAST	Full wrap prepreg blade	100% carbon, low density foam	Mid-heel
Easton Si-Core	SIC	Full wrap prepreg blade with silicon inserts	100% carbon, low density foam, silicon inserts	Mid-heel
Bauer Vapor XXX	VXXX	Full wrap prepreg blade	100% carbon, high density foam	Mid
Bauer Vapor I CTC	CTC	Full wrap prepreg blade	80% fibreglass, 20% carbon	Mid

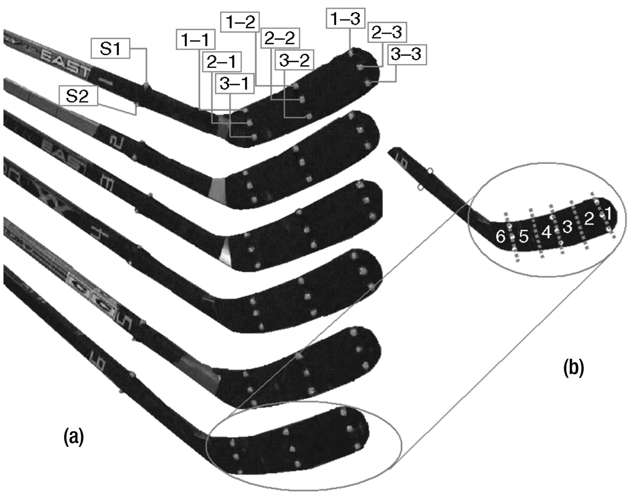

Figure 1 Sample of test sticks
(a) with marker locations
(b) with puck contact zones indicated.

Subjects

Fifteen male subjects volunteered for this study and were divided into two groups, based on skill level. Eight were classified as elite subjects (i.e. ELITE), as they were collegiate hockey players from the McGill varsity ice hockey team, while the remaining seven – university students who played ice hockey less than two times per week – represented the recreational group (i.e. REC). Both skill groups had a variety of both left- and right-handed shooters. There were no significant differences in height or weight between the groups, with mean heights of 180.6 cm (± 8.9) and 175.6 cm (± 7.4) and mean weights of 88.3 kg (± 8.1) and 75.2 kg (± 17.8) for the ELITE and REC groups, respectively. Ethics approval for this study was obtained from the Research Ethics board of the Faculty of Education of McGill University.

Testing apparatus

Data collection consisted of the simultaneous recording of high-speed video, puck acceleration and stick impact Z force. Two high-speed video cameras (PCI 100 HSC Motionscope, Redlake Imaging Inc., USA and EKTAPRO, Kodak Inc., USA), sampling at 1000 Hz, were used to record the movements of the blade and lower shaft. Cameras were placed on opposite sides of the subject, approximately 4.7 m from the puck and 0.6 m above the puck, with an angle of 65° between them for optimal post-three-dimensional reconstruction (Nigg & Herzog, 1999) (Fig. 2).

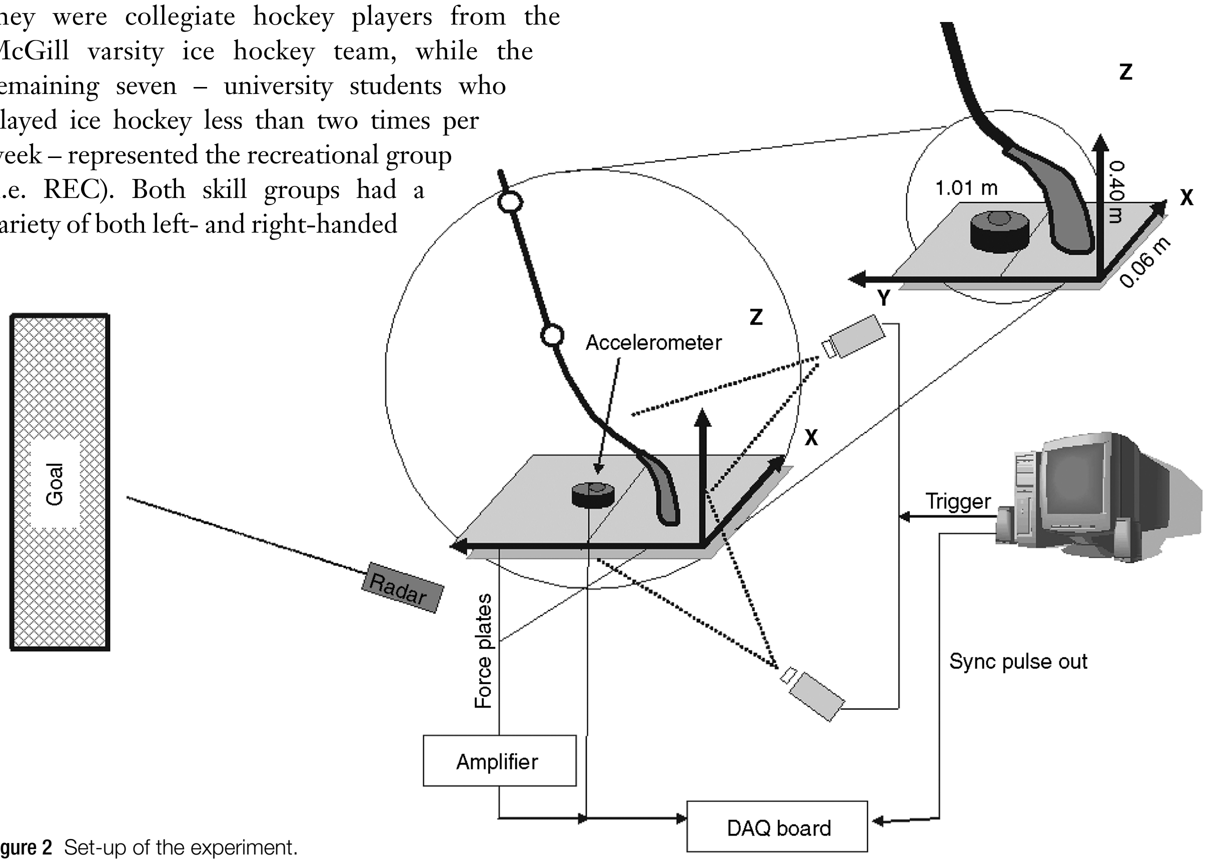

Figure 2 Set-up of the experiment.

Marker locations were digitised using MatLab® (version 6.0.0.88 release 12.0) (MathWorks Inc., USA) modules and could be located within 0.23 cm per pixel from a video recording of a 40 cm wide, 101.5 cm long, and 35 cm high field of view. Trial video data were synchronised at the instant of initial blade-to-ground contact. Each trial's video data and the corresponding calibration files were then combined in a DLT reconstruction and the resulting data were filtered with a fourth order Butterworth filter with a cut-off frequency of 75 Hz.

After reconstruction, several markers were selected for analysis, based on their ability to approximate the position of key areas of the hockey stick. These markers include 2-2 (indicating gross blade position), 3-1 (indicating heel position), and 3-3 (indicating toe position). In addition to displacement measures, the linear velocity was also calculated in the sagittal plane by differentiating the displacement data.

Three global angles were calculated in order to represent the general orientation of the blade throughout the shot. First, face angle ($\theta_{bt\text{-}f}$) – the angle between a segment along the length of the blade (from heel to toe) with respect to the frontal (XZ) plane – was calculated (Fig. 3a). When the blade was ahead of the shaft (or in front of the projected global frontal plane) the angle was termed positive; and when the blade was positioned behind the shaft (or behind the projected global frontal plane) the angle was termed negative. Second, loft angle ($\theta_{bt\text{-}t}$) – the angle of the same heel-to-toe segment with respect to the global transverse plane – was also calculated (Fig. 3b), such that when the heel portion of the blade was higher than the toe, the angle was termed positive and when the toe portion was higher than the heel, the angle was termed negative (Fig. 3b). Finally, tilt angle ($\theta_{tb\text{-}t}$) – the angle of a segment defined across the width of the blade (from 1-2 to 3-2) with respect to the global transverse plane – was measured (Fig. 3c). An increase in tilt angle was termed 'opening' of the blade, while a decreasing angle was termed 'closing' of the blade.

A uniaxial accelerometer (ACH-01, Measurement Specialties Inc., USA) mounted within a standard ice hockey puck identified initial puck–blade contact with respect to blade kinematic data. The centre of the puck was drilled out to accommodate the sensor and a thin metal cover was attached. The resulting puck weighed approximately 0.160 kg. The wire from the accelerometer was routed through a small trough in the edge of the puck and fed through the goal to a PC data acquisition card (AT-MIO-16X PC DAQ board, National Instruments Inc, USA). The resulting signals were recorded at 10 kHz using LabView 6.1© software (National Instruments Corp., USA).

In order to capture the entire loading phase of the slap shot, two uniaxial force plates (6400 series, Pennsylvania Scale Company, USA) were placed together in the centre of the testing platform. The force plates identified the blade-to-surface contact with respect to blade kinematics. Each device measured 46 × 61 cm and was located within the testing platform beneath the puck. Each force plate was connected to an individual power supply, a common amplifier and then to the above-mentioned PC data acquisition card. The trigger output channel of the high-speed camera system was connected to this DAQ card, thus synchronising the high-speed video, accelerometer and force plate data (see Fig. 2 for full experimental layout).

Events were formally defined using both video (for toe–ground contact (TC), heel–ground contact (HC), and stick off ground (S-OFF)) and accelerometer (for stick–puck contact (PC)) data. For the initial blade–ground contact event, video data were compared with force plate data to confirm accuracy. These events were used to define phases of interest which included blade–ground contact (Δt_1), stick loading (Δt_2) and toe-to-heel contact (Δt_3).

Testing protocol

Testing was performed on a wooden platform 46 cm high, 240 cm wide and 720 cm long. The shooting surface was covered with 1 mm thick polyethylene sheets and sprayed with a silicon lubricant to simulate low friction ice surfaces (Pearsall *et al.*, 1999; Wu *et al.*, 2003). During each slap shot, all participants wore a standardised pair of Bauer Vapor XXX Pro gloves (Nike Bauer Hockey Inc., USA). Each subject took five practice shots with a standard hockey puck. The average puck velocity (P_v) of these practice shots was recorded from the radar gun (SR3600, Sports Radar Ltd., USA) placed beside the testing platform, opposite the subject (Fig. 2).

A total of three shots with each of the six test sticks was recorded for each subject, using the instrumented hockey puck described earlier. For the purposes of this paper, a trial consisted of a stationary slap shot analysed from the HC to S-OFF event, into a designated target (located ~4.4 m in front of them) and involved the simultaneous recording with high-speed video cameras, the accelerometer, force plates and radar gun. Successful completion of a trial was determined by verbal confirmation from the participant approving the slap shot and hitting the target (approximately 0.85 m wide × 1.13 m high and 4.4 m away).

Prior to each trial, the edge of the instrumented puck was covered with coloured chalk, so that upon contact with the blade the chalk illustrated the exact point of contact (P_c) and the path of the puck across the blade. After each trial, the contact zone where the puck first contacted the blade was recorded and the blade was wiped clean of all chalk residue for the subsequent trial (Simard *et al.*, 2004).

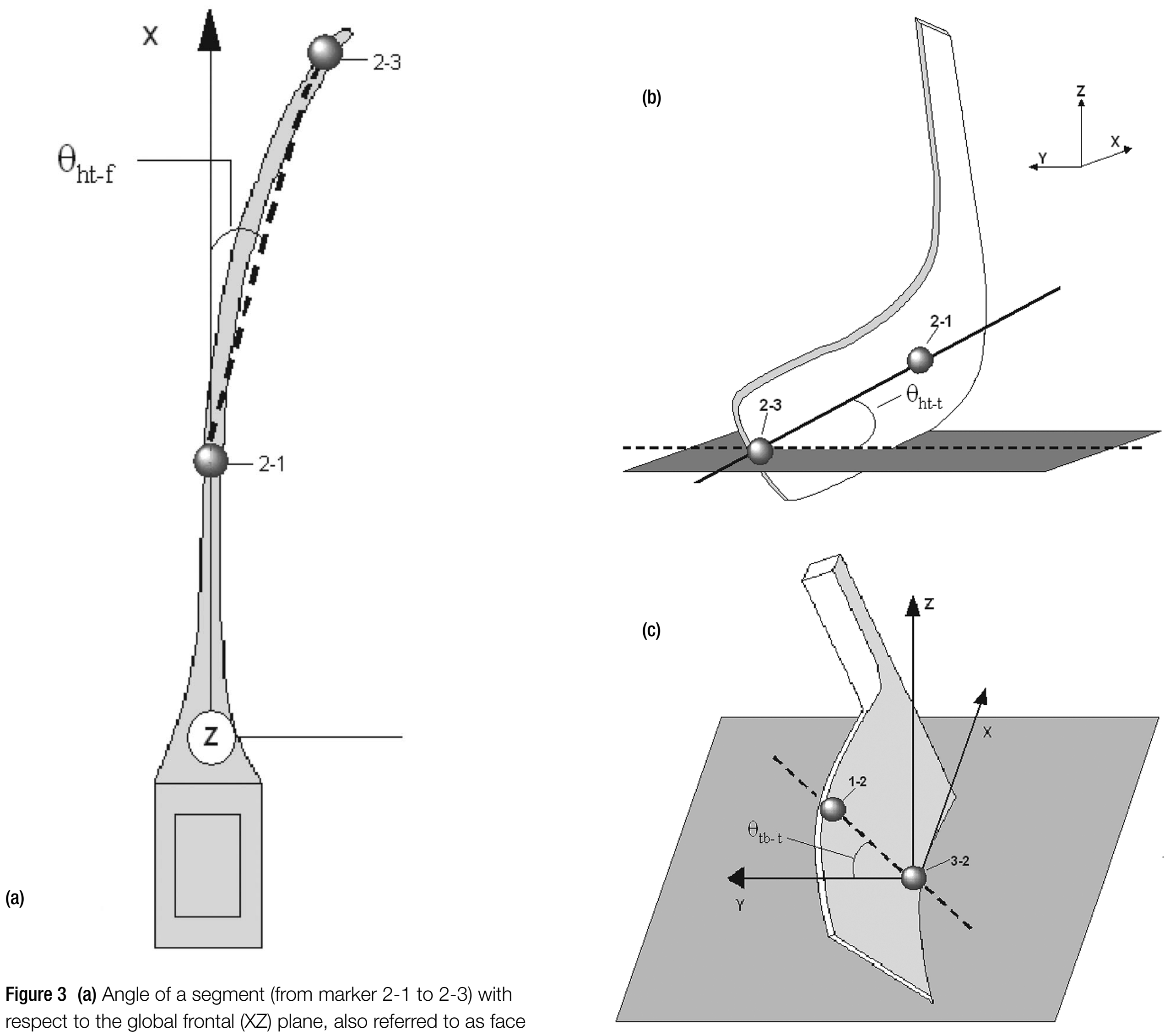

Figure 3 **(a)** Angle of a segment (from marker 2-1 to 2-3) with respect to the global frontal (XZ) plane, also referred to as face angle;
(b) An example of the tilt angle measured between a segment across the length of the blade (from 2-1 to 2-3) and the global transverse (XY) plane;
(c) An example of the loft angle measured between a segment across the width of the blade (from 1-2 to 3-2) and the global transverse (XY) plane.

Data analysis

Trials were time-normalised, such that the events of TC on and S-OFF represent 0 and 100%, respectively. Means of each dependent variable at each event were compared within and between independent variables of skill level (ELITE and REC) and stick model (i.e. CCM, EAST, SIC, VXX, VXXX and CTC). Complete lists of dependent variables are listed in Table 2.

Table 2 List of dependent variables (DV)

Abbreviation	Variable definition
P_v	Puck velocity
P_c	Puck contact zone
Δt_1	Time from initial toe contact (TC) to initial heel contact (HC)
Δt_2	Loading phase (initial toe contact (TC) to initial blade–puck contact (PC))
Δt_3	Total blade–ground contact time (from initial toe contact (TC) to final stick–ground contact (S-OFF)
Face angle	Global blade angle (2-1 to 2-3) with respect to the frontal plane
Loft angle	Global blade angle (2-1 to 2-3) with respect to the transverse plane
Tilt angle	Global blade angle (1-2 to 3-2) with respect to the transverse plane
d_b	Linear displacement of blade in the sagittal plane
v_b	Linear velocity of blade in the sagittal plane

Statistical analysis included a two-way MANOVA ($p < 0.05$), with a Tukey HSD post-hoc, where appropriate. All statistical analyses were performed with Statistica© 5.0 (StatSoft Inc., OK, USA) and MatLab® (version 6.0.0.88 release 12.0) (MathWorks Inc., Natick, MA, USA) software.

Results

Temporal events and phasing

The slap shot trials were divided into three phases that included 1) toe-to-heel contact; 2) stick loading; and 3) blade–ground contact. Toe-to-heel (Δt_1) contact was defined as the period of time from TC to HC; blade–puck contact (Δt_2) was defined as the period of time from TC to PC; and blade–ground contact (Δt_3) was defined as the period of time from TC to S-OFF. The backswing and follow-through phases previously described in the literature are ignored here as they are less likely to contribute to blade deformation.

The initial two phases of the slap shot were significantly shorter ($p < 0.05$ and $p < 0.01$, respectively) in the ELITE group than in the REC group (Table 3). However, the mean duration of the final phase, Δt_3, was significantly higher ($p < 0.01$) in the ELITE group than in the REC group.

Table 3 Mean duration of time (s) spent in each phase of the slap shot for each skill group. Significance is denoted by * ($p < 0.05$) and ** ($p < 0.01$)

Phase	Skill group	Mean absolute time (s)	SD
Δt_1*	ELITE	0.006	0.006
	REC	0.009	0.005
Δt_2**	ELITE	0.014	0.005
	REC	0.017	0.005
Δt_3**	ELITE	0.027	0.005
	REC	0.024	0.005

Blade orientation

Fig. 4 shows the mean overall global angles (i.e. face angle, loft angle and tilt angle) of the blade throughout the slap shot, the mean maximum and minimum values of each displacement graph and the overall range of displacement. Significant differences between skill groups occurred in maximum loft angle ($p < 0.01$), minimum tilt angle and loft angle ($p < 0.01$) and the overall range of all global angles ($p < 0.01$ to $p < 0.05$).

There was no significant difference in face angle between skill groups at TC, HC and PC, averaging 1º, –3º and 9º, respectively. However, at the final S-OFF event the ELITE group displayed significantly greater ($p < 0.01$) face angles (18º ± 13º) than the REC group (–2º ± 10º).

Significant differences occurred between groups ($p < 0.01$) in loft angle at TC, PC and S-OFF. For instance at TC, the ELITE group demonstrated a mean loft of 5º (± 4º), as compared to only 1º (± 3º) in the REC group. At HC, both groups positioned the blade at –3º (± 3º). The ELITE group maintained this position through PC, while the REC group shifted the blade's orientation to –5º (± 3º). Final stick orientation at S-OFF was significantly more positive ($p < 0.01$) in the ELITE group (5º ± 5º) than in the REC group (2º ± 4º).

The REC group demonstrated a significantly greater ($p < 0.01$) tilt angle (72º ± 10º) than the ELITE group (i.e. 66º ± 6º) at TC. However, both groups

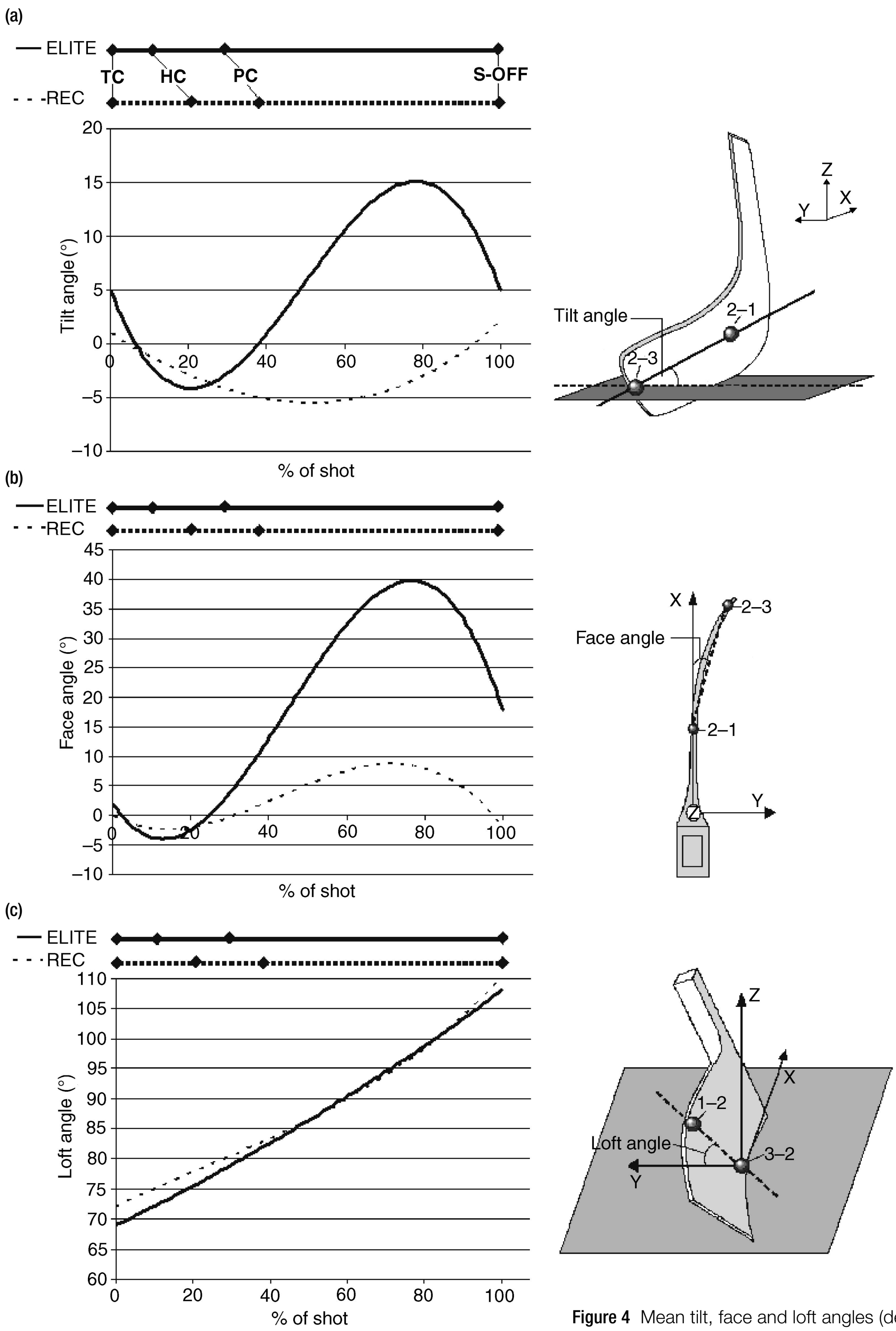

Figure 4 Mean tilt, face and loft angles (deg) of the blade over time for each skill group are presented in graphs **(a)**, **(b)** and **(c)**, respectively. Events of TC, HC, PC and S-OFF are indicated for each group.

possessed similar angles at HC (mean of 79º ± 8º). Yet at PC, the REC group again displayed a greater tilt angle (83º ± 10º) than the ELITE group (76º ± 6º). There were no significant differences in tilt angles between skill groups at S-OFF, with a mean angle of 109º (± 11º).

Puck velocity and contact location (P_v and P_c)

The ELITE group demonstrated a significantly higher ($p < 0.01$) mean puck velocity (73.7 ± 13.6 m s^{-1}) than the REC group (66.9 ± 14.9 m s^{-1}). With regard to puck contact location, as measured by chalk outlines on the blade's contact surface, there were no significant differences found between the locations of initial puck contact for either skill level or stick model. Subjects tended to contact the puck within zone five (Fig. 1).

Blade linear kinematics (d_b and v_b)

The global position of the blade (i.e. d_b) was measured in the sagittal plane at each of the temporal events. From TC to S-OFF, d_b tended to increase linearly, with no significant difference between skill groups at TC, HC or PC. However, d_b at the final, S-OFF, event was significantly higher ($p < 0.01$) in the ELITE group (1.41 ± 0.21 m) than in the REC group (1.26 ± 0.17 m) (Table 4). Similarly, the total range of blade excursion in the sagittal plane was significantly greater ($p < 0.05$) in the ELITE group (1.18 ± 0.39 m) than in the REC group (0.99 ± 0.27 m).

Table 4 also shows the mean sagittal plane blade velocity (v_b) for each skill group at each temporal event. Significant differences occurred only at HC and S-OFF, $p < 0.05$ and $p < 0.01$, respectively. ELITE groups also generated a significantly higher ($p < 0.01$) maximum v_b (28.0 ± 3.65 m s^{-1}) than the REC group (21.48 ± 2.74 m s^{-1}).

Blade displacement was investigated further by examining the vertical displacement of the heel and toe markers (i.e. 3-1 and 3-3, respectively). During Δt_1, the ELITE group demonstrated significantly more vertical displacement at both the heel (–1.3 cm) and toe (0.7 cm) of the blade than the REC group (0.1 and 0 cm for the heel and toe, respectively). Similarly during Δt_2, the ELITE group again displayed a greater vertical change in heel displacement, –1.3 cm, as compared to only 0.1 cm in the REC group.

Discussion

The above testing protocol quantified differences in shooting technique that may contribute to ELITE players' ability to achieve a greater puck velocity during a stationary slap shot than their REC counterparts, as well as providing further insight into the blade mechanics. Slap shot performance is primarily classified on the basis of puck velocity. In this study, mean puck velocity during test trials was measured with a radar gun to be 73.7 km h^{-1} and 66.9 km h^{-1} for the ELITE and REC groups, respectively. These values are substantially lower than those previously reported for similar skill groups performing the stationary slap shot, which ranged from 80 to 121 km h^{-1} (Pearsall *et al.*, 2000). However, the additional weight of the wire in combination with the effective tethering of the test puck served to dramatically reduce puck velocity.

The literature suggests that highly skilled players use a variety of techniques to achieve higher slap shot velocities. Primarily, ELITE shooters are thought to better utilise the loading phase of the slap shot, causing increased shaft deflection, a longer period of

Table 4 Mean forward (Y) component of displacement and velocity (cm s^{-1}) of the blade (marker 2-2) at each event. Statistical significance is denoted by ** ($p < 0.01$) and * ($p < 0.05$).

		TC		HC		PC		S-OFF	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
d_b (m)	ELITE	0.47	0.18	0.59	0.19	0.74	0.15	**1.41	0.21
	REC	0.53	0.13	0.60	0.15	0.75	0.16	1.26	0.17
v_b (m s^{-1})	ELITE	20.73	1.66	*18.82	1.77	17.68	2.00	**27.51	4.31
	REC	20.43	2.58	19.88	2.43	18.31	3.31	15.14	6.27

stick–ground contact and higher vertical ground reaction forces which combine to generate higher stick elastic (or bend) energy, thus imparting a greater impulse on the puck (Pearsall *et al.*, 1999; Roy & Doré, 1976; Villaseñor-Herrera, 2004). Woo (2004) also attributed ELITE shooters' increased shot velocity to increased translational acceleration of the stick; as compared to REC shooters who utilised greater rotational acceleration.

The current study is the most detailed report to date, providing substantive information about blade-to-ground and blade-to-puck kinematics. The following passages will attempt to describe how each kinematic parameter relates to the overall skill execution.

Temporal events and phasing

Significant differences between skill groups in the duration of each of the three phases of the slap shot were apparent. The ELITE group demonstrated significantly shorter Δt_1 and Δt_2 than the REC group, which appeared to be the result of increased v_b during these phases (Table 3). In particular, the duration of Δt_2 found in the present study are comparable to those reported by Polano (2003), who reported a mean of three skilled shooters of 19 ms (or 0.019 s) for the same phase of a stationary slap shot performed on ice.

The final phase, Δt_3, was significantly longer in the ELITE group (e.g. 27 ms or 58% of shot) than in the REC group (e.g. 24 ms or 53% of shot) (Table 3). Doré & Roy (1976) reported a longer duration of stick–ground contact (40 ms) during a slap shot; however, this study may have been somewhat limited by its use of two-dimensional kinematic data to identify some temporal events.

Overview of blade function

Figs. 5a–d show an over-trace of the movement path of the blade during a typical trial from several different angles. Figs. 5a and b appear to confirm earlier observations that the path of the stick from the top of the backswing to initial ground contact (TC) is primarily pendular in nature (Polano, 2003; Woo, 2004), similar to a golf swing (Mason *et al.*, 1992; Neal, 1983; Whittaker, 1999). However, once the toe makes contact with the ground, the blade's movement path shifts dramatically in all directions. The blade's sagittal (YZ) plane movement demonstrates a primarily linear (or translational) movement path (Figs 5c and d) and it shifts away from the base of support in the X direction (Fig. 5a), thus confirming earlier observations (Woo, 2004) and further suggesting that an important transition phase between the primarily rotational acceleration of the stick in downswing and the primarily linear acceleration of the stick during loading exists.

Figs. 5a, b and d also demonstrate that during this phase (from TC to HC) there is a clear tendency to load the blade from toe to heel in a 'rocker'-like fashion. It appears that this 'rocker phase' is at least partially a function of the stick's geometry (particularly the lie angle). That is, with all other variables being equal, increasing the lie stick's lie angle should result in an earlier TC event and longer Δt_1, Δt_2 and Δt_3, thereby potentially increasing puck–blade contact time and, consequently, puck velocity (Villaseñor-Herrera, 2004).

Conversely under the same conditions, decreasing the lie angle would theoretically result in a later TC event and shorter Δt_1, Δt_2 and Δt_3 phases; potentially decreasing puck–blade contact time and puck velocity. However, since lie angle was not a dependent variable in this study, these hypotheses remain a subject for future investigation.

Additionally, the exact purpose of this blade loading pattern remains unknown. To date, this pattern has been documented only in one other study (Polano, 2003) where lie angle was not reported. Since the lie angle was kept constant in the present study, it is impossible to determine if this pattern holds for other stick geometries. One might expect that as the lie angle decreased (i.e. approached 90º), the point of initial blade–ground contact would shift towards mid-blade, possibly eliminating the rocker phase in extreme cases.

Conversely, the TC event may also be an intentional technique employed by players to help dampen vibration harmonics upon stick–ground contact (Merkel & Blough, 1999; Roberts *et al.*, 2005) or to improve shot accuracy by providing players with some proprioceptive feedback (Falconer, 1994). The remainder of the text will attempt to quantify and define the blade's kinematic response to the events of ground contact in both ELITE and REC slap shots,

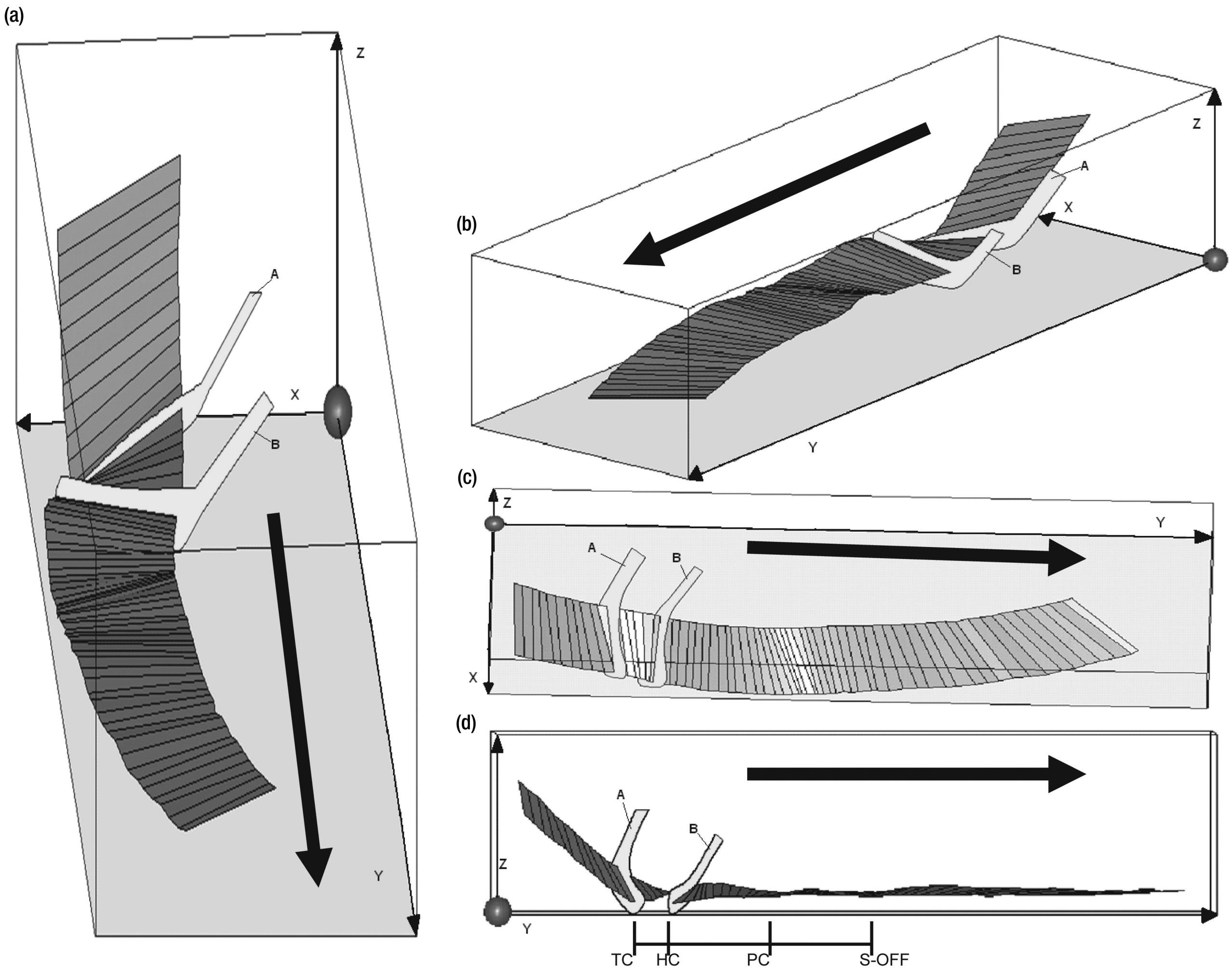

Figure 5 Over-trace of blade displacement from several views including **(a)** oblique frontal, **(b)** oblique sagittal, **(c)** transverse, and **(d)** sagittal plane. Axes are marked X, Y and Z as indicated, arrows indicate the direction to the goal and **(a)** and **(b)** represent TC and HC, respectively.

within the context of current slap shot literature. Particular attention will be paid to the previously unexplored characteristics of the rocker phase.

Blade orientation

Of the previously described factors thought to affect final puck trajectory (Williams & Sih, 2002), thus far the linear kinematics has described the direction of the blade in great detail from initial TC to S-OFF; while frictional interactions were beyond the scope of the present study and will not be discussed. The third and final factor, blade orientation, will be addressed with reference to the tilt, face and loft angles described previously.

With regard to tilt, at TC, the ELITE group maintained a significantly more closed blade position than the REC group. From TC to HC the blade opens until it reaches its maximum tilt angle approximately midway between HC and PC. This trend was consistent between groups; however, the ELITE group utilised a greater range of tilt (13º) than the REC group (6º), which suggests an increased rolling of the wrists (i.e. combination of flexion/extension and pronation/supination) to open the face of the blade (Fig. 4). This coincides with early, and primarily qualitative, descriptions of the slap shot that highlight the importance of the wrist snap, where as the stick moves from backswing to downswing the top wrist shifts from supination to extension and the lower wrist shifts from pronation to flexion (Alexander *et al.*, 1963; Hayes, 1965). The wrist snap is thought to help increase puck acceleration by maintaining blade–puck contact and allowing the frictional force that develops between the blade and the puck to accelerate the puck into rotation (Therrian & Bourassa, 1982).

From its maximum tilt, both groups began to close the blade as it approached PC; however, the ELITE group displayed a significantly smaller angle than the REC group at PC. This seems to suggest that the ELITE group was able to accomplish a much greater wrist snap than the REC group (Fig. 4). Once the wrist snap was completed, the blade began to open again. This opening continued through to S-OFF as the puck rolled along the length of the blade (Simard *et al.*, 2004).

As for face angle, at TC, the ELITE group tended to display a slightly positive angle, while the REC group positioned their blade closer to a neutral (i.e. blade and shaft in line along the projected global frontal plane) position. Both groups maintained this negative blade orientation through HC, reaching a minimum value at ~15% of shot. From this minimum, the blade shifted towards a positive orientation, reaching positive face angle at ~25% of shot, immediately prior to PC. Face angle continued to increase in the positive direction through PC until it reached its maximum value, near 40% of shot. The overall range of face angle was significantly greater in the REC group. This may be an indication of the REC group utilising a greater overall excursion in the frontal plane than the ELITE group. However, since horizontal distance between the feet and the puck was not standardised between subjects, the variability between subjects was too great to accurately discern this.

After reaching its maximum face angle the blade approached a neutral position and eventually became increasingly positive through S-OFF as the stick began to enter follow-through. Initially, it was hypothesised that the amount of opening/closing of the blade would be a function of the individual blade stiffness properties; however, no significant differences were found between stick models in this investigation.

The most substantial differences in blade orientation between skill groups occurred in loft angle. As earlier linear kinematic data and previous research suggests, the toe end of the blade tends to make contact with the ground first (Polano, 2003); so it was not surprising that at TC both groups displayed a positive loft angle. However, the ELITE group tended to demonstrate a significantly greater loft angle than the REC group. As the blade moved to HC, loft angle became progressively more negative; thus indicating that the heel portion of the blade was making ground contact. The combined shift from positive to negative face and loft angles at TC and HC, respectively seems to indicate that upon stick–ground contact the blade pivoted about the toe and translated forward (i.e. toward the target in the sagittal plane) as the heel shifted vertically downward to make ground contact. HC ultimately resulted in the toe portion of the blade shifting vertically upwards as the blade 'rocked' about the heel (Fig. 4).

This phenomenon was further quantified through the vertical change in displacement of the heel and toe portions of the blade. During the initial Δt_1 phase, the total change in vertical displacement of the heel portion of the blade was significantly greater in the ELITE group. This apparent continued downward momentum in ELITE shooters may represent the beginning of a more efficient (i.e. longer) loading phase identified by other authors (Roy *et al.*, 1974; Villaseñor-Herrera, 2004), which is marked by increased translational components of acceleration of the stick (Woo, 2004).

Following the rocker phase, blade orientation varied dramatically between skill groups. The ELITE group maintained an increasingly negative loft through HC to its minimum value at ~20% of shot (i.e. midway between HC and PC), at which point the orientation shifted to become increasingly positive through PC and towards its maximum (~80% of shot). From its maximum loft (i.e. 10°) the ELITE groups' values became increasingly less positive through S-OFF. However, the REC group maintained an increasingly negative loft orientation through HC and PC to a minimum value at ~50% of shot, where the orientation shifted to a positive maximum value at S-OFF.

Overall, the substantially greater range of loft angle demonstrated by ELITE subjects (particularly during Δt_1), seems to indicate their ability to better utilise the rocker phase. However, the question of whether or not this effect can produce a superior shot remains a subject for further investigation.

Blade linear kinematics

The results of this study confirm observations by Polano (2003) that initial blade-to-ice contact typically occurs between the toe portion of the blade and the ice, as opposed to the entire bottom edge of the blade. In this study, all trials demonstrated initial contact made by the toe, which was then followed by the heel portion of the blade. As such, the first phase of the slap shot was defined as toe-to-heel contact or the period of time from TC to HC.

Initiation of the downswing (from the top of the backswing) causes a linear increase in stick displacement away from the origin in the sagittal plane (towards the target), resulting in an increase in linear velocity of the stick (Hoerner, 1989; Polano, 2003; Woo, 2004).

As the stick approaches TC, v_b began to decrease as the process of loading of the stick (shaft deflection) was initiated. Mean values of v_b of 20.7 m s^{-1} and 20.4 m s^{-1} for the ELITE and REC groups, respectively (Table 4), are similar to the 20 m s^{-1} reported by Roy and colleagues (1974), but substantially less than those reported by Polano (2003), where values ranged from 27.5 to 30.9 m s^{-1}, with a mean of 29.7 m s^{-1}. However, Polano's (2003) calculations were based on data from the three highest velocity slap shots performed by only three subjects.

The decrease in v_b continued through HC, where the velocity tended to stabilise and remain constant; thus following Polano's (2003) observation that the toe's initial contact with the ground results in a dramatic decrease in velocity. The values obtained in the present study are substantially larger than the mean of 13.7 m s^{-1} reported by Polano (2003). However, these data represent the minimum toe velocity as opposed to the actual HC event.

The v_b remained constant until immediately prior to the PC event whereupon the velocity decreased to its minimum value (i.e. 0.47 and 0.52 m s^{-1} for ELITE and REC groups, respectively) at ~45% of the shot duration (Table 3). The resulting total decrease in v_b from TC through PC likely corresponded to the initial shaft deflection which, in skilled shooters, typically began at the instant of blade–ground contact; whereas, in unskilled shooters deflection began much later, as much as halfway through blade–ground contact (Villaseñor-Herrera, 2004).

At PC, v_b were 17.7 and 18.3 m s^{-1} for the ELITE and REC groups, respectively. These values were substantially less than the 29.1 and 26.5 m s^{-1} obtained by Woo (2004) for ELITE and REC shooters, respectively. However, Woo's (2004) data represents an overall resultant blade velocity as data were not examined in terms of its respective components. From its minimum value, v_b increased steadily; the REC group's velocity tended to peak at ~80% of the shot, whereas ELITE shooters were able to peak closer to S-OFF (i.e. ~95%) at substantially larger velocities.

Conclusions

The current study has provided a comprehensive examination of the blade's three-dimensional response during the slap shot. Contrary to popular and industry opinion, the different construction parameters of blades currently on the market did not alter the blade's global position and/or orientation (either positively or negatively) during the slap shot. The results were consistent with previous examination of shaft construction, demonstrating no significant difference in performance variables (Doré & Roy, 1978; Marino, 1998; Pearsall *et al.*, 1999; Roy & Doré, 1975; Roy & Doré, 1979; Roy *et al.*, 1974; Wu *et al.*, 2003). However, these analyses identified a unique rocker phase within the execution of the slap shot, demonstrated by both elite and recreational groups. Within the rocker phase, elite shooters tended to alter timing parameters (i.e. phase length), magnitude of linear variables (i.e. displacement, velocity and acceleration) and the overall blade orientation that may correspond to higher puck velocity. As such, these findings provoke a series of additional research questions relevant to design engineers, as well as coaches and athletes.

Future studies should attempt to address the role and purpose of this phase to determine if it is merely a function of the geometric constraints (e.g. lie angle or blade curvature) of the stick or if it has performance-enhancing characteristics. For instance, when combined with translational acceleration and blade torsion (Therrian & Bourassa, 1982; Woo, 2004), might the rocker phase be used to generate increased torque about the stick and ultimately increase the energy transferred to puck, increasing velocity (Villaseñor-Herrera, 2004)? If so, might changes in lie angle improve this energy transfer? Once a better understanding of the rocker phase's role, or lack thereof, in a successful slap shot is achieved, manufacturers and designers will be better equipped to develop products that maximise or minimise the phase as necessary.

The methodologies employed in the present study demonstrated several strengths in terms of instrumentation and consistency of results for the measurements presented. Measurement error was calculated to be ~0.2 cm; however, some experimental limitations did exist and should be noted. For instance, the polyethylene sheets that served as the shooting surface do not exactly mimic on-ice conditions or frictional coefficients; the puck used was at room temperature and as such may have responded slightly differently than the frozen pucks used in game situations; the subjects performed only stationary slap shots, as opposed to the skating slap shots used in games; whole shaft kinematics were not examined; and subjects did not wear full hockey gear, only gloves.

As such, several methodological improvements could be made for future studies, including utilising a larger sample size and standardising the horizontal distance from the feet to the puck in order to reduce subject variability and improve statistical power. Also, improving the grounding of the accelerometer circuit to reduce signal drift would provide a definitive definition of total puck–blade contact time and a description of the blade's role in accelerating the puck. The ability to employ a system with a similar resolution and a larger field of view would allow a more thorough examination of the stick's motion pre- and post-ground contact. Also, employing such a system at a higher sampling frequency may increase resolution enough to record accurately the torsional response of the lower shaft and blade.

Similarly, the use of a higher sensitivity, triaxial accelerometer within the puck would provide detailed puck acceleration profiles that could be used to determine the precise moment the puck leaves the blade, energy transfer and impulse between the puck and blade. The recent inclusion of wireless technology in accelerometer design may also allow researchers to eliminate cumbersome cables in this type of investigation, thus providing a more natural puck response and allowing researchers to address questions of puck movement and accuracy within various hockey shots.

Additionally, the fundamental question of the role of blade construction in the execution of the slap shot could be more effectively analysed using a greater variety of sticks. The present study limited itself to those commercially available, which must conform to strict NHL guidelines in terms of dimensions and material properties. Yet comparing samples with extreme differences in stiffness properties, geometric dimension, lie angles, etc. could provide more useful insight into the blade's function in a slap shot.

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References

Alexander, J.F., Haddow, J.B. & Schultz, G.A. (1963) Comparison of the ice hockey slap and wrist shots for speed and accuracy. *Research Quarterly*, **34**, 259–266.

Caljouw, S.R., Van Der Kamp, J. & Savelsbergh, G.J.P. (2005) Bi-phasic hitting with constraints on impact velocity and temporal precision. *Human Movement Science*, **24**, 206–217.

Doré, R. & Roy, B. (1978) Influence de la rigidité des bâtons sur la cinématique et la cinétique des tirs au hockey sur glace (Influence of stick stiffness on kinematics and kinetics of ice hockey shots). Montréal, QC, Ecole Polytechnique de Montréal.

Falconer, T. (1994) How hockey works: Anatomy of a slap shot. *Equinox*, **13**(73), 54–68.

Hayes, D. (1965) A mechanical analyses of the hockey slap shot. *Journal of the Canadian Association for Health, Physical Education,& Recreation*, **31**, 17, 31–32, 39.

Hoerner, E.F. (1989) The dynamic role played by the ice hockey stick, in C.R. Castaldi & E.F. Hoerner (eds) *Safety in Ice Hockey*, ASTM STP 1050. American Society for Testing & Materials, Philadelphia, PA, USA.

Marino, G.W. (1998) Biomechanical investigations of performance characteristics of various types of ice hockey sticks, in H.J. Riele & M.M. Vieten (eds) *International Society of Biomechanics of Sports*, Konstanz, Germany.

Marino, G.W. & VanNeck, C. (1998) Static and dynamic characteristics of aluminium versus wooden hockey sticks, in H.J. Riele & M.M. Vieten (eds) *International Symposium on Biomechanics in Sports*, Konstanz, Germany.

Mason, B.R., Thinnes, R.L. & Limon, S.L. (1992) A kinetic and kinematic analysis of the golf swing. *Journal of Biomechanics*, **25**, 711.

Merkel, R. & Blough, T. (1999) Dynamic characterization and comparison of golf clubs. *Journal of Sound & Vibration*, **33**, 28–31.

Montgomery, D.L., Nobes, K., Pearsall, D.J. & Turcotte, R.A. (2004) Task analysis (hitting, shooting, passing, and skating) of professional ice hockey players, in D.J. Pearsall & A.B. Ashare (eds) *Safety in Ice Hockey*, ASTM STP 1446. 4th ed. American Society for Testing & Materials. West Conshohocken, PA, USA.

Neal, R.J. (1983) *Three Dimensional Analysis of the Golf Swing*. University of Queensland, Brisbane, Australia.

Nigg, B.M. & Herzog, W. (1999) *Biomechanics of the Musculo-skeletal System*. John Wiley & Sons Inc., New York, NY, USA.

Pearsall, D.J., Montgomery, D.L., Rothsching, N. & Turcotte, R.A. (1999) The influence of stick stiffness on the performance of ice hockey slap shots. *Sports Engineering*, **2**, 3–11.

Pearsall, D.J., Turcotte, R.A. & Murphy, S.D. (2000) Biomechanics of ice hockey, in W.E. Garrett & D.T. Kirkendall (eds) *Exercise and Sport Science*. Lippencott, Williams & Wilkins, Philadelphia, PA, USA.

Polano, R.N. (2003) *3-D Kinematical Analysis of the Ice Hockey Slap Shot*. M.Sc. Thesis, University of Western Ontario, Canada.

Roberts, J.R., Jones, R., Mansfield, N.J. & Rothberg, S.J. (2005) Evaluation of vibrotactile sensations in the 'feel' of a golf shot. *Journal of Sound & Vibration*, **285**, 303.

Roy, B. & Delisle, G. (1984) Caractéristiques géométriques et dynamiques des bâtons de hockey en regard de leur performance (Geometric and dynamic characteristics of hockey sticks and their effect on performance). *Canadian Journal of Applied Sport Sciences*, **9**, 214–219.

Roy, B. & Doré, R. (1975) Incidence des caractéristiques des bâtons de hockey sur l'efficacité gestuelle des lancers (Influence of hockey stick characteristics on the efficiency of shots). *Ingenieur*, **306**, 13–18.

Roy, B. & Doré, R. (1976) Kinematics of the slap shot in ice hockey as executed by players of different age classifications, in P. Komi (ed.) *Fifth International Congress on Biomechanics*, University Park Press, Baltimore, USA.

Roy, B. & Doré, R. (1979) Dynamic characteristics of hockey sticks and efficacy of shooting in ice hockey. *Canadian Journal of Applied Sport Sciences*, **4**, 1–7.

Roy, B., Doré, R., Parmentier, P.H., Deroy, M. & Chapleau, C. (1974) Facteurs bioméchaniques caractéristiques de différents types de lancers au hockey sur glace (Biomechanical characteristics of different types of ice hockey shots). *Mouvement*, **9**, 169–175.

Simard, E., Roy, E., Martin, G., Cantin, H. & Therrien, R. (2004) Static and dynamic characteristics of composite one-piece hockey sticks, in M. Lamontagne, D.G.E. Robertson & H. Sveistrup (eds) *XXIInd International Symposium on Biomechanics in Sports*, Faculty of Health Sciences University of Ottawa, Canada.

Therrian, R. & Bourassa, P. (1982) Mechanics application to sports equipment: Protective helmets, hockey sticks, and jogging shoes, in D.N. Ghista (ed.) *Human Body Dynamics: Impact, Occupational and Athletic Aspects*. Clarendon Press, Oxford, UK.

Villaseñor-Herrera, A. (2004) *Recoil Effect of the Ice Hockey Stick during a Slap Shot*. M.Sc. Thesis, McGill University, Montréal, Canada.

Whittaker, A.R. (1999) A study of the dynamics of the golf club. *Sports Engineering*, **1**, 115–124.

Williams, K.R. & Sih, B.L. (2002) Changes in golf clubface orientation following impact with the ball. *Sports Engineering*, **5**, 65–80.

Woo, T.K. (2004) *Three Dimensional Kinematic Analyses of the Stationary Ice Hockey Slap Shot: Elite versus Recreational*. M.Sc. Thesis, McGill University, Montréal, Canada.

Worobets, J.T., Fairbairn, J.C. & Stefanyshyn, D.J. (2006) The influence of shaft stiffness on potentional energy and puck speed during wrist and slap shots in ice hockey. *Sports Engineering*, **9**, 191–200.

Wu, T.-C., Pearsall, D.J., Hodges, A., Turcotte, R., Lefebvre, R., Montgomery, D.L. & Bateni, H. (2003) The performance of the ice hockey slap shot and wrist shots: The effects of stick construction and player skill. *Sports Engineering*, **6**, 31–40.