The Effect of Shaft Stiffness on the Performance of the Ice Hockey Slap Shot.

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Abstract

The purpose was to examine the effect of shaft stiffness on puck velocity and response characteristics of the stick during performance of a slap shot. Six elite male ice hockey players performed 6 slap shots with 4 sticks of different shaft stiffness designated as medium (13 N/m), stiff (16N/m), extra (17 N/m) and pro stiff (19 N/m). These four levels represent the range in stiffness of sticks available to hockey players. The mechanics of the slap shot were evaluated by recording ground reaction forces and kinematics from high speed filming and a radar gun. Data were analyzed with a 3-way repeated measures ANOVA for 7 dependant variables – puck velocity, peak Z force, peak Y force, time to achieve peak Z force, time to achieve peak Y force, peak deflection and time to peak deflection of the shaft. Results indicated: (1) the stick with shaft stiffness of 13 N/m produced the highest puck velocity, the greatest amount of shaft deflection, the longest time to peak deflection and the lowest peak Z forces; (2) time to obtain peak forces in the Y and Z directions were similar across level of shaft stiffness; (3) puck velocity was influenced by the interaction of subject and stiffness; (4) variability in performance measures across subjects was greater than the variability across stiffness.

Résumé

Plusieurs facteurs influencent la vélocité du lanceur au hockey sur glace. Le but de cette étude était d'évaluer l'effet de la rigidité du bâton sur la vitesse de la rondelle ainsi que les caractéristiques du bâton lors d'un lancer frappé (slap shot). Six joueurs de hockey élites masculins ont exécuté six lancers avec quatre bâton différents; moyen (13 N/m), rigide (16 N/m), extra (17 N/m) et pro rigide (19 N/m). Ces niveaux de rigidité représentent ce qui est disponible pour les joueurs de hockey. Les forces (F) dans chacune des directions x, y et z ont été enregistrées à 1000 Hz au moment exacte où la rondelle était frappée de sur la plate-forme. La combinaison de timbres réflecteurs positionnés sur la bâton et d'une caméra à haute vitesse a permis d'enregistrer les lancers à une vitesse de 480 images par seconde. Un fusil radar était utilisé pour documenter la vitesse maximale de la rondelle a chaque lancer. Les données ont été analysées à l'aide d'une analyse de variance a mesures répétées (trois facteurs indépendants). Un total de sept variables dépendants ont été analysées - vélocité de la rondelle, force z maximale, force y maximale, délai d'obtention de force maximale z, délai d'obtention de force maximale y, déformation maximale du bâton et le temps requis pour atteindre cette déformation. Les résultants peuvent être résumés comme suit; (1) Le bâton moyen a permis d'obtenir la plus grande vitesse de rondelle, la plus grande deformation de bâton et la plus petite force maximale z, (2) Le délai d'obtention de forces maximales z et y était semblable indépendamment des niveaux de rigidité, (3) Une interaction entre les sujets et le niveau de rigidité influençait la vitesse de la rondelle, (4) La variabilité de la vélocité des lancers entre les sujets était plus grande que celle dû à la rigidité du bâton utilisé.

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Introduction

While the origins of ice hockey date back to 1853, the game has been witness to consistent evolution. Some of the changes to the game are attributed to modification in the equipment used by players of the sport. Both creativity in equipment design and technical advances allowing for better equipment construction have led to countless modifications and overall improvement in equipment quality. Technical advances over the past century in the fields of equipment construction and material selection, for example, have resulted in equipment that is lighter, more durable and more expensive. This increase in equipment utility has translated into improved safety and a heightened performance of the skills necessary in playing ice hockey.

The hockey stick is fundamental to the game of ice hockey. It is used to propel and manoeuvre the puck. The ability to shoot the puck with optimal velocity and precision is a decisive factor in the overall performance of a player (Lariviere and Lavallee, 1972). Even this seemingly simple piece of equipment has undergone several major changes over the past 100 years.

The original hockey sticks were made entirely from a single piece of wood. This practice changed in the 1950's when both shaft and straight blade were constructed separately and later joined to form a stick. In the late 1960's, the stick was modified with curvature applied to the blade. This simple modification led to increased manoeuverability of the puck during forehand stickhandling as well as significantly increased shooting velocity (Nazar, 1971). Inherent in this new design, the difference between right and left-handed hockey sticks was more pronounced. The trend of the 1970's was to envelope the wood core of the blade with fibreglass and plastics, thereby reducing the amount of wood used in each stick. In the 1980's, manufacturers added plastic inserts to the bottom of the blade to increase durability. More recently, the hockey sticks of the 1990's utilize aluminum or composite materials such as carbon fiber. In these sticks only the blade may contain wood.

The Official Rule Book of the Canadian Amateur Hockey Association (CAHA, 1993) contains Rule 21(a) "All sticks may be made of wood, fiberglass or aluminum and/or any other material approved by the CAHA Board of Directors. This rule does allow for many material combinations and is not very restrictive. The dimensions of the hockey stick are defined in Rule 21(b) as follows. The stick shall not exceed 1.4m (55 inches) from the heel to the end of the shaft, and 31.75cm (12.5 inches) from the heel of the shaft to the end of the blade. The blade of the stick shall not be less than 5.08cm (2 inches) nor greater than 7.62 cm (3 inches) in width. The curvature of the blade of the stick shall not exceed 1.27 cm (0.5 inch)".

Definitions

1. <u>Composite shaft:</u> the hockey stick shafts used in this study were constructed of fiberglass and carbon (graphite) fiber bound together by an epoxy resin matrix.
2. <u>Pre-loading:</u> refers to the action of the ice hockey stick in the downward phase of the slap shot when the stick makes contact with the ice surface prior to striking the puck.
3. <u>Shaft stiffness:</u> refers to the flexibility of the shaft and is measured by the linear deformation in the minor axis. (Classification of composite shafts by Bauer.)
5. <u>Slap shot:</u> refers to a technique ice hockey players use to impact the puck resulting in a shot that is significantly faster than the snap or forehand. The slap shot is the shot during which the greatest loads are put on the stick.

Significance of the Study

In the sport of ice hockey it was common for both coaches and players to initiate changes in their equipment for various purposes such as enhancement of performance, prevention of injuries, protection of an already sustained injury and aesthetics. These advantages consisted of improving the overall effectiveness and reliability of the equipment being used or decreasing the potential of player injury. Some of the advances in equipment design influenced the regulations set by the American Standards of Tests and Measures (ASTM), Canadian Standards Association (CSA), Committee European de Normilation (CEN) and International Standards Organization (ISO). Many times these modifications have raised the technical level in which ice hockey is played.

The significant modifications that have occurred to ice hockey equipment are not unique to this sport alone. The process of upgrading and adopting new equipment by players can result in an immediate effect on the performance of the sport as well as its universal adoption by participants. This was the case in pole vaulting. Once the metal pole was replaced by one made of fibreglass, the world record was soon raised by over two feet. The performance of a pole vault was changed forever by technology. Since that technological change, every top pole vaulter in the world uses fibreglass or non-metal poles (Ryan, 1971).

Another example of equipment modification influencing performance is in the sport of golf. The use of graphite in place of steel in the construction of golf club shafts is now very common. The advantages of graphite shafts in golf are not as clear as the benefit in pole vaulting; however, golfers, especially seniors, benefit by being able to hit golf balls as far with graphite shafted clubs as they were in their youth with steel shafted clubs. The use of graphite shafts has not become as prolific in golf as in the use of fibreglass (or non-metal) poles in pole vaulting. Still, the variance available in graphite shafts to be matched to a golfer's swing characteristics has allowed it to remain a popular choice with many golfers.

In ice hockey the use of composite shafts in sticks rather than wood has become more wide spread. Similar to the graphite shafts in golf, the composite shafts in ice hockey are not the only types of shaft available to players. The recent popularity of the composite material shaft is due to the ability of manufacturers to modify the sticks mechanical characteristics to meet with individual player specifications. This is especially true with regard to an individual player's preference in shaft stiffness and mass.

Today large amounts of money are being devoted to continually upgrading the ice hockey stick, thus enabling players to perform skills involving the stick with ease and efficiency. Player demand for better equipment and competition among equipment manufacturers using modern technology and materials have led to an increased pace in equipment development. Many of these improvements have not been studied in depth. More specifically the wider range in shaft stiffness has not been accompanied by research on its effect on slap shot velocity.

Purpose of the Study

The purpose of this study was to determine the effect of shaft stiffness on the velocity of the puck and response characteristics of the stick during the performance of a slap shot. The seven dependant variables were - puck velocity, peak Z force, peak Y force, time to achieve peak Z force, time to achieve peak Y force, peak deflection and time to peak deflection of the shaft.

Limitations

1. Limitations of this study include the possibility that the shooters may have fatigued during the testing procedure since they performed approximately 40 (maximal effort) slap shots in one testing session. To limit the effects of fatigue, a minimum of 30 seconds between shots and 3 minutes between the four sticks was implemented.
2. The subjects for this study were specifically chosen to be elite players. Therefore the results may not be generalized to the entire population of hockey players because only one ability level was tested.
3. All sticks used were of the same length.

Methodology

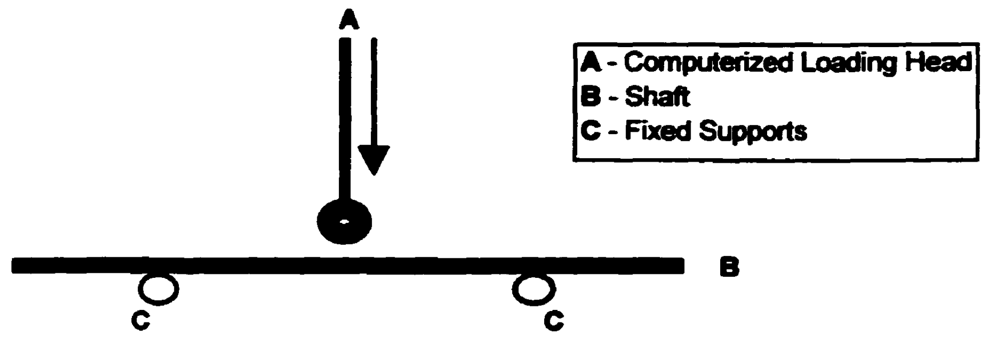
Hockey Sticks

The composite shafts and left-handed blades were provided by Bauer Inc. The Bauer 300 (P66) blade was used for all sticks. The blade had a mass of 205 grams. Each stick was coded so that the testers and subjects were unaware of the shaft characteristics during testing. The shafts were similar in material construction (carbon-fibre composite), length (160 cm), mass (320 grams) and deflection in the major axis. The only difference among the sticks existed in deflection along the minor axis which is commonly known as shaft stiffness. Four types of shaft stiffness were tested: medium (13 N/m), stiff (16 N/m), extra (17 N/m) and pro stiff (19 N/m). These four levels are representative of the range in stiffness readily available to elite hockey players. Three sticks in each stiffness category were provided by Bauer Inc.

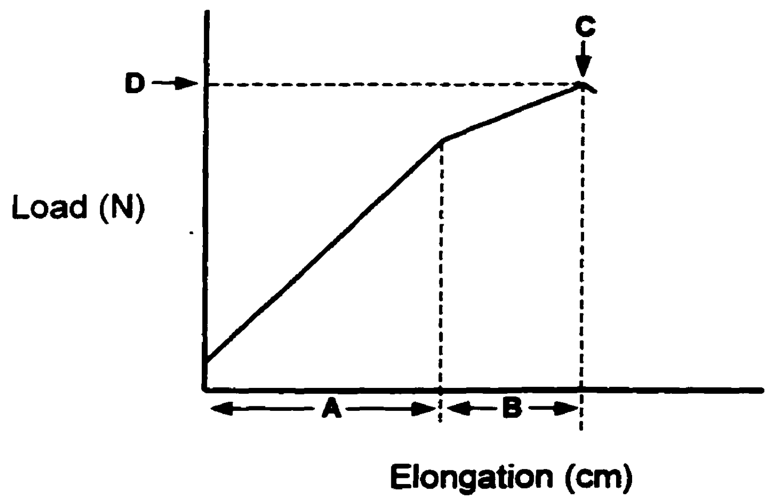
Bauer determines the static bending stiffness of the shaft using a linear deformation test. This test is performed on the major and minor axis of the shaft. Stiffness categories are defined by results from the test through the minor axis. Bauer uses the following procedures for the deformation tests.

1) The stick is supported by two pins a specific distance apart.
2) A computerized loading head applies force at a controlled velocity mid-way between the two pins.
3) The force required to bend the shaft until to its breaking point is calculated by the computer.

Note: The linear deformation test was slightly modified for the sticks used in this study. The test was terminated before the shafts were permanently damaged.



The graph of the linear deformation test is used to identify four characteristics of the shaft – elastic component, plastic component, failure point and total load to break the shaft. The shaft bends when a sufficient load is applied to it. The *elastic* portion of the graph represents the range in force whereby the shaft can still regain its original form when the load is removed. This is illustrated as **A** in the deformation graph. (This test was terminated once a consistent slope in section **A** occurred, thereby not damaging the shafts.) The *plastic* portion of the graph is illustrated as **B**. In this range, the slope is decreased and the shaft remains permanently deformed when the load is removed. The *failure point* represents the force required to break the shaft. This is illustrated as **C** in the deformation graph. The fourth characteristic (**D**) represents the *total load to break the shaft* and is expressed as peak values for stress (N) and elongation (cm).



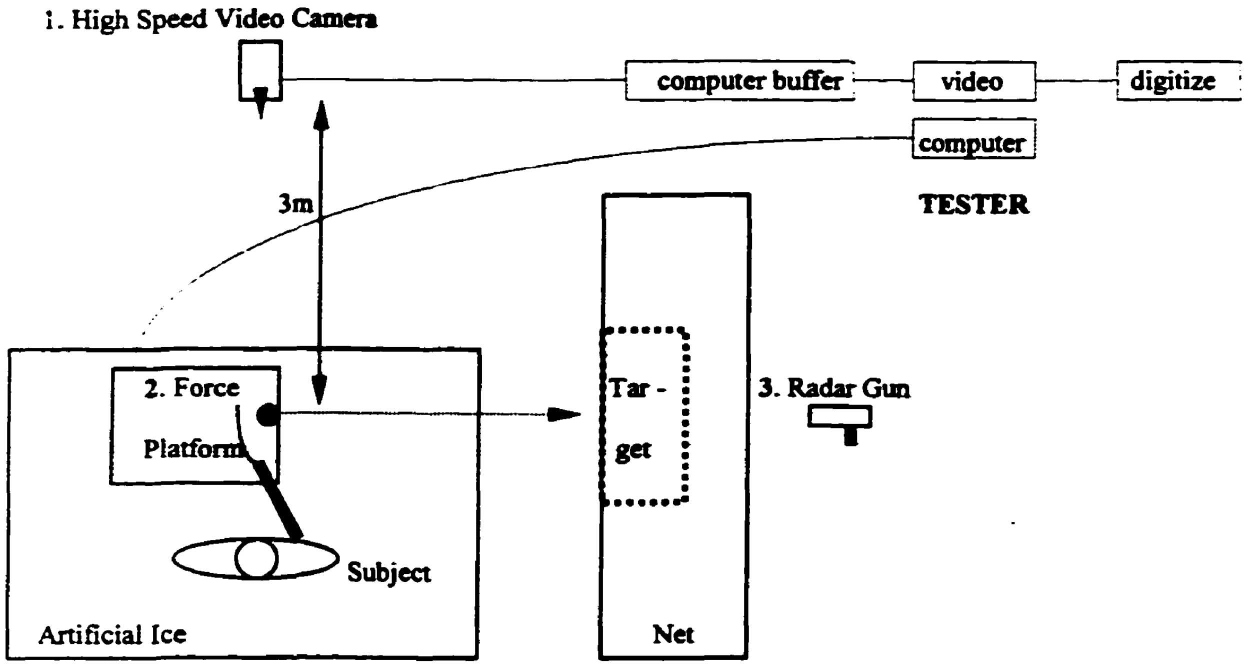
Subjects

Six male, elite ice hockey players volunteered for the study. All subjects were left-handed shots. Table 1 shows the physical and experience characteristics of these subjects. The hockey players were between 20 and 29 years of age and averaged 4.8 years of elite experience which was defined as participation in university, Junior A and professional leagues.

Table 1. Description of Subjects

Subject	Age (yrs)	Height (cm)	Mass (kg)	Experience (yrs)
1	24	185	88.0	3
2	22	180	83.5	6
3	23	185	86.5	5
4	20	175	79.5	3
5	29	180	86.0	6
6	22	177	77.0	6
Mean	23.3	180.3	83.4	4.8
S.D.	3.1	4.1	4.3	1.5

Data were collected in the Biomechanics Laboratory of the Seagram's Sports Science Centre at McGill University. The set-up for data collection follows:



The subjects wore skates and stood on a 3m square piece of 0.4 cm thick polyethylene (artificial ice) to execute the slap shots. Subjects performed a minimum of three practice trials with each stick. Each subject took six slap shots with the four stick types in random order. A minimum of thirty seconds occurred between each trial of one stick type and a three minute rest period between sticks of different stiffness. A shot was considered an official trial if: (1) the puck went into the target area (60cm x 60cm), (2) the stick made contact with the force platform, and (3) the subject was satisfied that the trial was a maximal effort.

Data Acquisition

Slap Shot

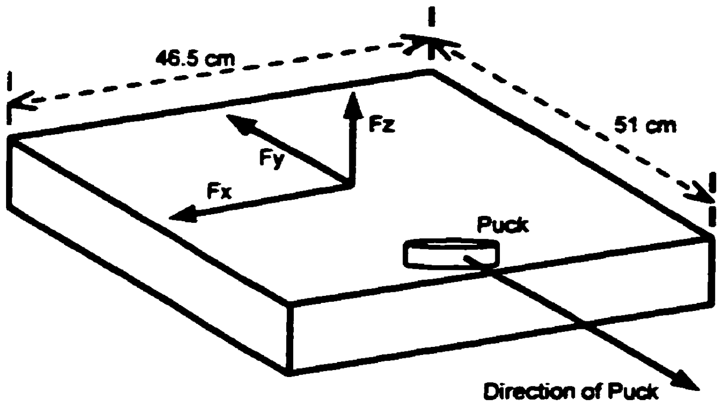
The slap shot was chosen as the shot to be tested in this study for the following reasons: 1) it results in a shot of high velocity, 2) shaft stiffness is an important characteristic in the performance of a slap shot and 3) individual variation may be less than with other types of shot (i.e. snap or forehand).

Force Platform

A model OR6-5 Biomechanics Platform from Advanced Mechanical Technology Inc recorded the force when the stick contacted the force plate. Naud and Holt (1975) reported that the stick contacts the ice about 10 to 15 cm behind the puck. Pilot data for this study showed that contact was made up to 40 cm behind the puck. This information guided puck position to the front edge of the force platform to ensure that the stick struck the platform during the pre-loading phase. The dimensions of the force platform were 51.0 x 46.5 cm. Oil (WD-40) was applied to the force platform to reduce friction between the platform and the puck.

In the performance of the slap shot friction in the Y direction was examined by comparing four conditions: (1) metal platform, (2) metal platform + WD-40, (3) metal platform covered with artificial ice, (4) metal platform covered with artificial ice + WD-40. One of the test sticks was weighted to 150 N. A cord was attached to the shaft-blade junction. A force-time graph was constructed by dragging the stick across the force platform. When comparing the four conditions, the metal platform + WD-40 was the condition with the least friction. This condition is illustrated in Appendix A.

During data collection, force was recorded at 1000 Hz for 2 seconds. Data acquisition was controlled by Labview (version 3.1.1) and stored in Microsoft Excel files on a 486 computer. Force in Newtons was recorded in the X, Y and Z directions as illustrated in the following diagram. Since forces in the X direction (lateral) were minimal, these data are not reported.

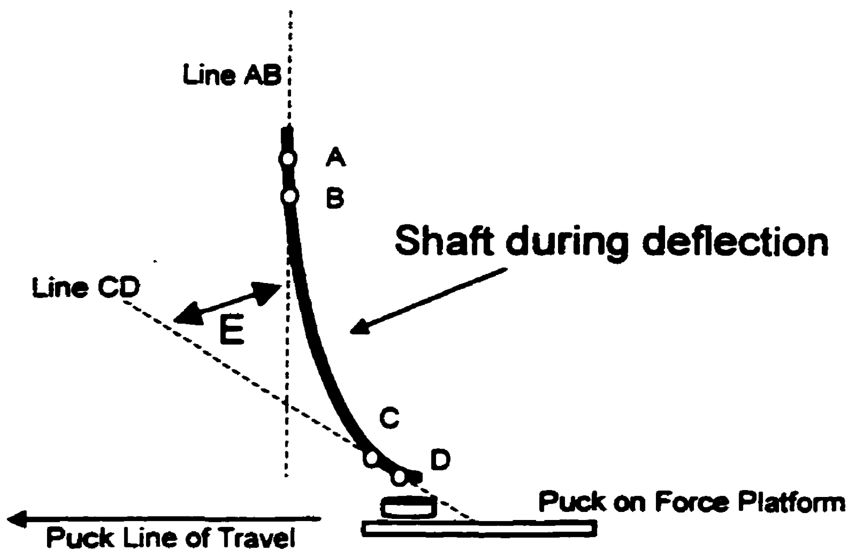


High Speed Camera

Thirteen reflective markers were placed on the shaft at 10 cm intervals for the purpose of digitization. One marker was placed on the second knuckle of the left thumb (lower hand on stick). In addition one marker was placed on the wall to establish a fixed point as the origin for digitization.

An Ariel Performance Analysis System (APAS) high speed camera recorded the performance of the slap shot at 480 frames per second with storage of the images on a VHS video cassette. The camera was positioned 3.3 m laterally to the direction of the puck and 1.83 m vertically above the puck.

The APAS software package required manual digitization of two frames per trial with automatic digitization of the remaining frames. Peak deflection and time to peak deflection were the two dependant variables obtained from this analysis. Peak deflection was calculated as the angle E between lines AB and CD as depicted in the stick figure.



Radar Gun

A Sports Radar Gun (Model SR 3300) was used to record the peak velocity of the puck (mph) for each trial. The radar gun uses the principle of doppler radar. The gun sends out a signal that bounces off the puck and sends the signal back to the radar gun. Accuracy is best when the object being tracked (in this case the puck) is moving toward the radar gun. The slap shots were performed at a target in the net. Therefore the radar gun was located behind the net. Only shots into the target area were recorded as official trials. The reliability of the radar gun was verified using a tennis ball launcher and comparing the distance the ball traveled with the velocity recorded by the radar gun.

Experimental Design and Statistical Analysis

The experimental design included three independent variables – Subjects (n = 6), Trials (n = 6) and Stiffness (n = 4). The four levels of shaft stiffness were 13, 16, 17, and 19 N/m. Six subjects performed six slap shots with four sticks of different shaft stiffness. The statistical analysis was a repeated measures ANOVA for each of the seven dependant variables - puck velocity, peak Z force, peak Y force, time to achieve peak Z force, time to achieve peak Y force, peak deflection and time to peak deflection of the shaft. The ANOVA is described as $Su_6 \times T_6 \times St_4$. Statistical significance was declared if $P < 0.05$ and post-hoc analysis performed using the Bonferroni procedure. The experimental design is:

Subjects	Shaft Stiffness			
	13	16	17	19
1	1,2,3...6	1,2,3...6		
2				
3				
4				
5				
6				

Results

Subjects

Physical characteristics and skill in shooting contributed to significant differences for subjects in the following dependant variables - puck velocity, peak forces, time to achieve peak forces, peak deflection and time to peak deflection of the shaft. ANOVA results for subjects, warranted further analysis for all seven variables. These post-hoc analyses are located in Appendix B. Differences among subjects are not discussed in this report since the focus was to examine shaft stiffness.

Puck Velocity

The data for puck velocity are shown in Tables 2 and 3. The ANOVA and post-hoc analyses are summarized in tables 4 and 5. The significant interaction effects are found in Appendix C.

There was a significant difference for shaft stiffness, subject and the interaction of subject X stiffness. Puck velocity was highest for the stick with stiffness of 13 N/m (108.2 km/hr) and lowest for the stick with stiffness of 17 N/m (105.9 km/hr). This was the only statistically significant difference among the four shaft types. The interaction of subjects X stiffness is illustrated in Figure 1 with the significant differences outlined in Appendix C. Stiffness and subjects accounted for 56% of the variation in puck velocity.

Table 2. Puck Velocity Summarized by Stiffness and Subject

Variable	Velocity (km/hr) Mean	S.D.
Stiffness (n=36)		
13	108,2	4,6
16	107,0	4,4
17	105,9	5,4
19	106,3	6,0
Subject (n=24)		
1	107,1	5,7
2	102,3	4,5
3	107,3	3,6
4	107,1	4,0
5	112,4	3,4
6	104,9	3,7

Table 3. Puck Velocity for Stiffness within Subjects (n=6 trials)

Subject	Stiffness	Velocity (km/hr) Mean	S.D.
1	13	105.1	6.2
	16	105.6	6.0
	17	107.7	5.0
	19	109.9	5.5
2	13	104.3	3.1
	16	104.5	4.7
	17	98.9	5.5
	19	101.3	2.6
3	13	110.7	3.1
	16	105.9	2.9
	17	109.1	1.2
	19	103.7	2.4
4	13	107.2	3.9
	16	110.7	2.4
	17	106.1	4.1
	19	104.5	3.3
5	13	112.8	2.2
	16	110.9	2.6
	17	110.4	4.0
	19	115.5	2.4
6	13	109.3	1.9
	16	104.3	2.1
	17	102.9	1.3
	19	102.9	4.3

Table 4. ANOVA for Puck Velocity

Source	SS	df	MS	F	P
Subject (Su)	1346.489	5	269.298	19.312	0.001 *
Stiffness (St)	113.636	3	37.879	2.716	0.048 *
Su X St	657.564	15	43.838	3.144	0.001 *
Error	1673.387	120	13.945		
				N:	144
				Multiple R:	0.747
				Squared Multiple R:	0.559

* $P < 0.05$

Table 5. Bonferroni Post-hoc Analysis of Puck Velocity for Stiffnes

Stiffness	13	16	17	19
13	1.000			
16	0.960	1.000		
17	0.047 *	0.998	1.000	
19	0.191	0.998	0.998	1.000

* $P < 0.05$

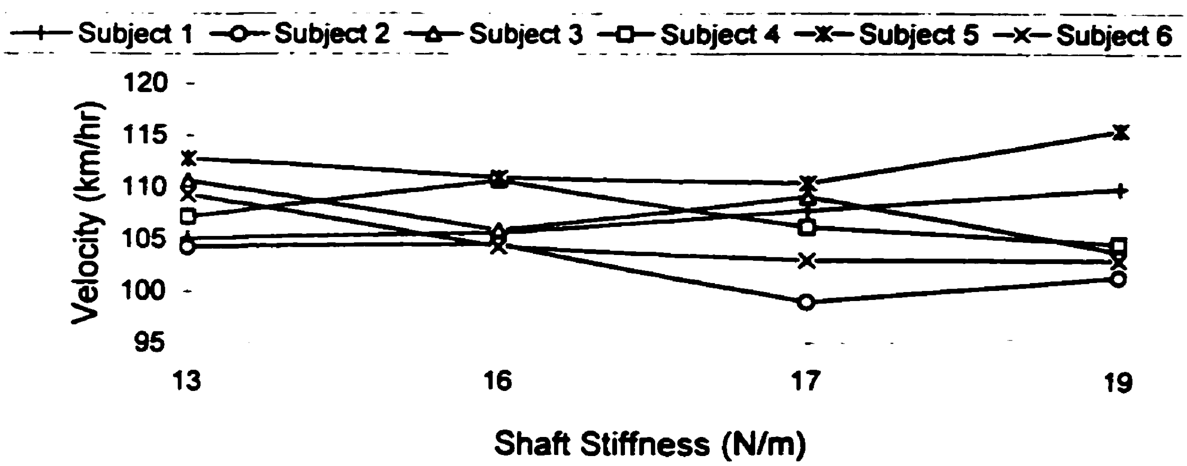


Figure 1. Puck Velocity and Shaft Stiffness

Force Platform Data

The force platform data included four dependant variables – time to peak Z, peak Z force, time to peak Y and peak Y force. These data are summarized in Tables 6 and 7. The ANOVA and post-hoc analyses are summarized in tables 8 - 12. The significant interaction effects are found in Appendix D and E.

Peak Z force showed a significant difference for shaft stiffness, subject and the interaction of subject X stiffness (Table 9). Peak Z force was highest for the stick with stiffness of 17 N/m (134.7 N) and lowest for the stick with stiffness of 13 N/m (121.9 N). This was the only statistically significant difference among the four shaft types. The interaction of subjects X stiffness is illustrated in Figure 2 with the significant differences outlined in Appendix D.

There were no differences in peak Y force among the four shaft types (Table 12). However, there was a significant interaction of subjects X stiffness which is illustrated in Figure 2. The significant differences are outlined in Appendix E. As expected there were significant differences among the six subjects for peak force in the Z and Y directions (Tables 9 and 12).

There were no differences in time to achieve peak forces in the Z and Y directions among the four shaft types (Tables 8 and 11). When averaged across subjects, peak forces in the Z and Y directions occurred between 24 and 26 ms following stick contact with the force platform (Table 6).

There were significant differences in time to achieve peak forces in the Z and Y directions among the six subjects (Tables 8 and 11). When averaged across stiffness, peak forces in the Z and Y directions occurred between 22 and 30 ms following stick contact with the force platform (Table 6).

Table 6. Z and Y Force Platform Data Summarized by Stiffness and Subject

Variable	Z Force				Y Force			
	Time to Peak (ms)		Peak (N)		Time to Peak (ms)		Peak (N)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Stiffness								
13	24	5	121,9	30,5	25	5	16,0	8,5
16	25	5	126,1	30,2	26	5	14,3	4,9
17	24	4	134,7	38,1	26	4	17,6	5,9
19	25	5	131,7	37,4	25	5	16,1	5,1
Subjects								
1	22	5	86,9	43,1	22	5	17,3	6,2
2	22	5	148,8	29,2	24	5	25,7	6,6
3	26	5	96,0	32,2	26	5	14,0	5,5
4	30	5	161,1	36,2	28	3	15,0	6,6
5	24	4	142,2	33,8	27	4	14,0	7,2
6	23	5	136,4	31,0	24	4	9,8	5,6

Table 7. Z and Y Force Platform Data for Stiffness within Subjects (n=6 trials)

Subject	Stiffness	Z Force				Y Force			
		Time to Peak (ms)		Peak (N)		Time to Peak (ms)		Peak (N)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	13	21	2	75,7	14,7	21	2	19,3	3,7
	16	25	6	94,1	20,8	23	4	15,8	2,9
	17	21	4	89,4	20,4	22	4	18,0	3,8
	19	19	1	88,5	12,2	22	4	16,2	2,7
2	13	22	1	134,6	16,3	24	1	31,2	4,8
	16	22	2	140,6	20,5	24	2	21,5	6,2
	17	24	2	166,4	26,8	26	3	25,6	2,0
	19	21	1	153,8	21,2	22	2	24,6	2,9
3	13	27	7	103,7	16,2	28	6	9,1	2,1
	16	28	7	93,3	21,7	27	7	12,0	2,2
	17	24	6	94,3	13,0	25	5	18,7	3,0
	19	27	8	92,8	20,5	26	6	16,4	3,0
4	13	31	5	160,0	21,6	28	6	13,5	4,2
	16	28	6	133,4	27,4	28	5	11,6	2,9
	17	30	4	170,0	25,4	30	5	20,8	2,1
	19	31	1	181,0	30,2	26	6	14,1	2,1
5	13	23	1	133,0	7,7	26	3	14,0	2,0
	16	25	3	143,9	15,6	28	5	13,3	1,6
	17	25	2	153,8	18,6	29	1	13,9	2,8
	19	24	1	138,2	3,8	27	2	14,7	1,7
6	13	22	2	124,2	14,8	21	2	8,6	4,4
	16	23	1	151,5	10,1	24	3	11,7	4,3
	17	22	1	134,1	16,8	25	4	8,6	1,4
	19	26	4	135,6	17,8	25	4	10,4	3,9

Table 8. ANOVA for Time to Peak Z

Source	SS	df	MS	F	P
Subject (Su)	955.378	5	191.076	9.411	0.001 *
Stiffness (St)	3.888	3	1.296	0.064	0.979
Su X St	335.636	15	22.376	1.102	0.362
Error	2395.867	118	20.304		
				N:	142
				Multiple R:	0.589
				Squared Multiple R:	0.347

Table 9. ANOVA for Peak Z

Source	SS	df	MS	F	P
Subject (Su)	103030.148	5	20606.03	57.112	0.001 *
Stiffness (St)	3979.561	3	1326.52	3.677	0.014 *
Su X St	12335.701	15	822.38	2.279	0.007 *
Error	42574.452	118	360.80		
				N:	142
				Multiple R:	0.859
				Squared Multiple R:	0.738

Table 10. Bonferroni Post-hoc Analysis for Peak Z (Stiffness)

Stiffness	13	16	17	19
13	1.000			
16	0.998	1.000		
17	0.014 *	0.302	1.000	
19	0.152	0.998	0.998	1.000

* - $P < 0.05$

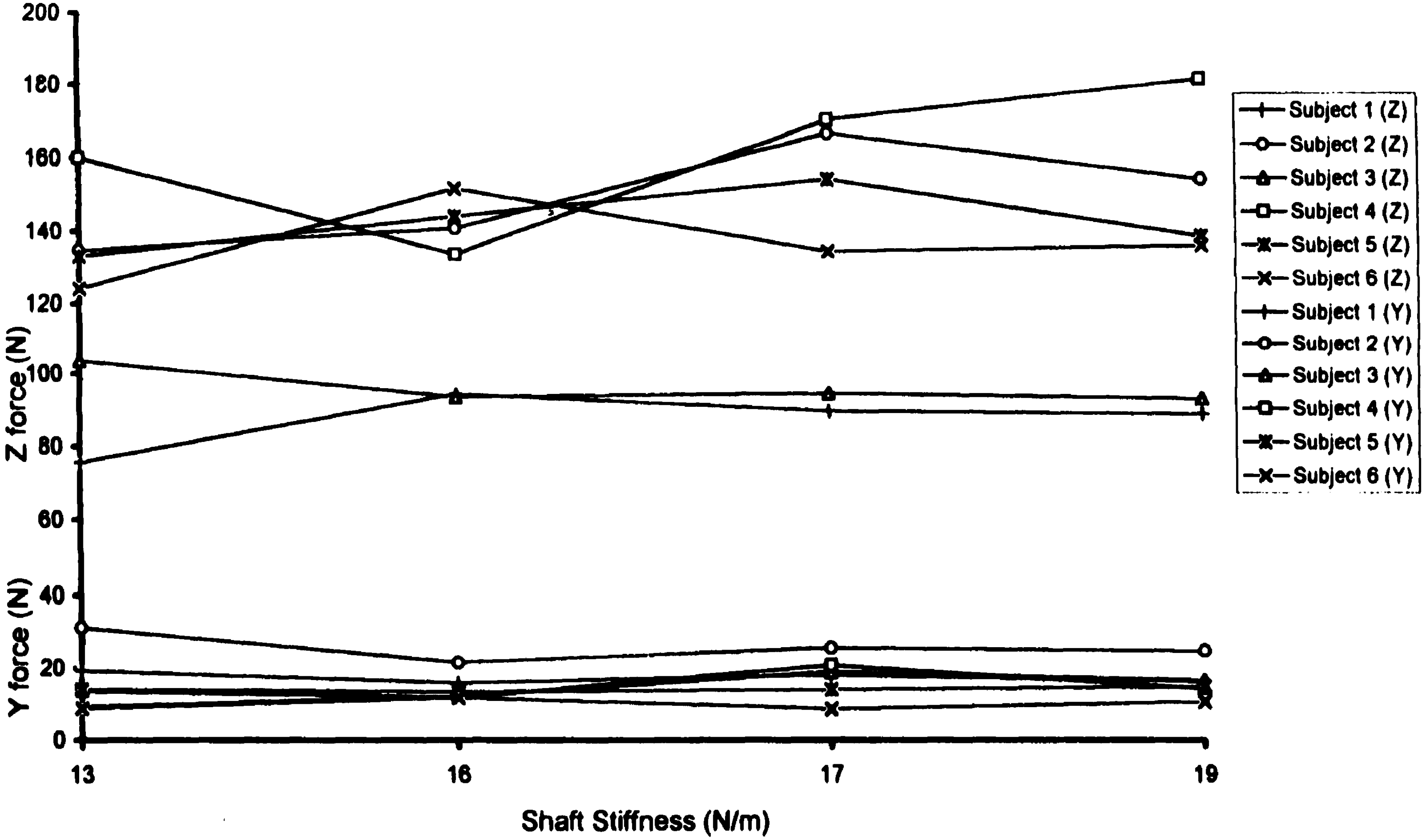


 Figure 2. Z- and Y-Force and Shaft Stiffness

Table 11. ANOVA for Time to Peak Y (ms)

Source	SS	df	MS	F	P
Subject (Su)	994.275	5	198.855	10.937	0.001 *
Stiffness (St)	16.640	3	5.547	0.305	0.822
Su X St	352.142	15	23.476	1.291	0.218
Error	2145.467	118	18.182		
				N:	142
				Multiple R:	0.621
				Squared Multiple R:	0.386

Table 12. ANOVA for Peak Y

Source	SS	df	MS	F	P
Subject (Su)	3216.242	5	643.248	61.160	0.001 *
Stiffness (St)	66.075	3	22.025	2.094	0.105
Su X St	987.328	15	65.822	6.258	0.001 *
Error	1241.067	118	10.518		
				N:	142
				Multiple R:	0.880
				Squared Multiple R:	0.775

* $P < 0.05$

High Speed Camera Data

The high speed camera data included two dependant variables – peak deflection measured in degrees and time to peak deflection measured in ms. The effect of stiffness on peak deflection for each subject is illustrated in Figure 3 and in Appendix F1-6. The data are summarized in Tables 13 and 14. The ANOVA and post-hoc analyses are summarized in tables 15 – 18.

Peak shaft deflection and time to peak deflection were both different for stiffness and subject. The stick with stiffness of 13 N/m deflected more than the other stiffness types (Figure 4). In addition the stick with stiffness of 13 N/m had a greater time to peak deflection than sticks with stiffness of 17 and 19 N/m. The interaction of Subjects X Stiffness for time to peak deflection is illustrated in Figure 5 with the significant differences outlined in Appendix G. Stiffness and subjects accounted for 67% of the variation in peak shaft deflection and only 44% of the variation in time to peak deflection.

There were significant differences in peak shaft deflection and time to peak deflection among the six subjects (Tables 15 and 17). When averaged across stiffness, peak shaft deflection ranged from 18 to 22 degrees. Time to peak deflection ranged from 23 to 27 ms following stick contact with the force platform (Table 13).

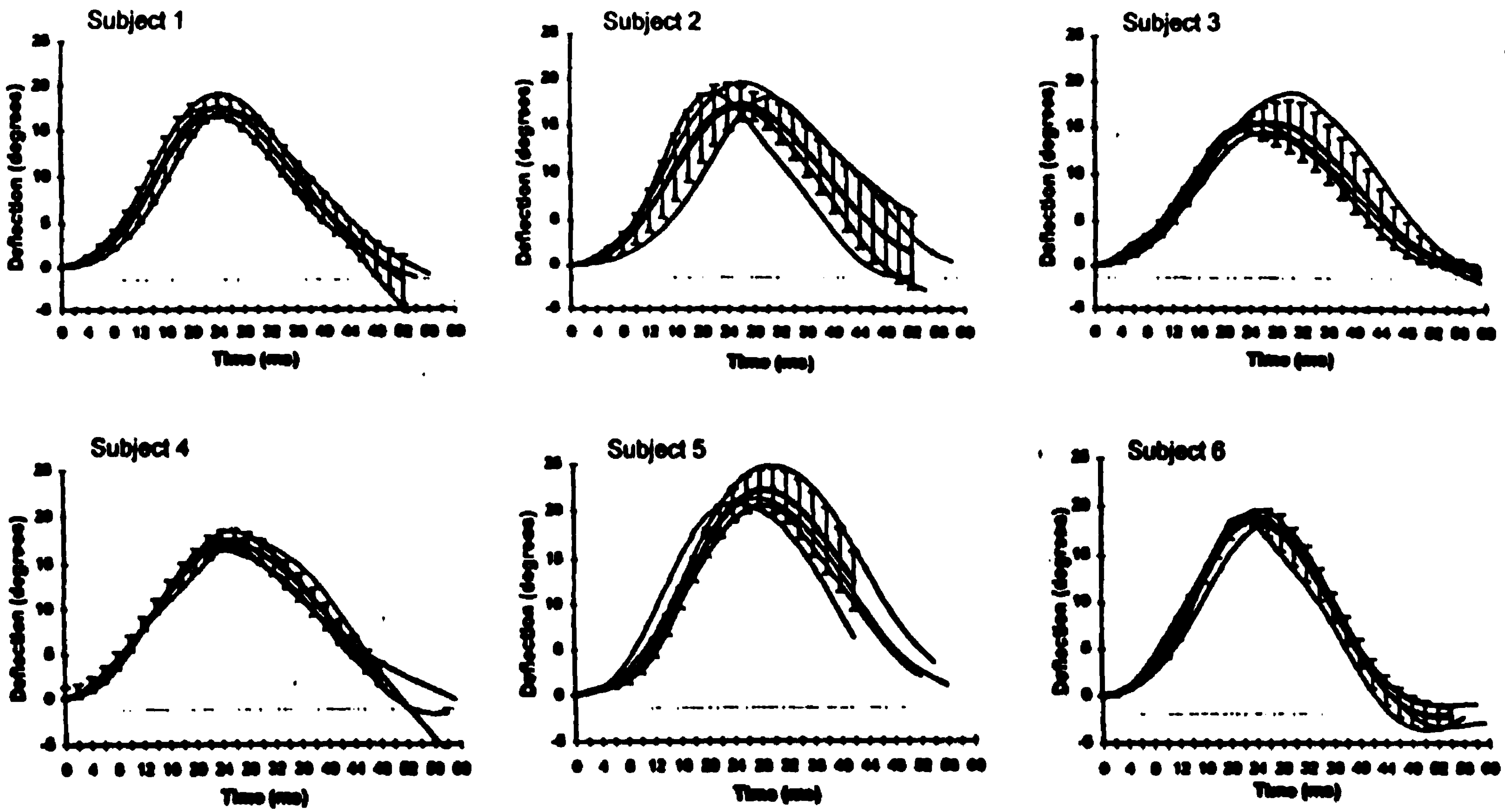


Figure 3. Peak Deflection Patterns Across 4 Types of Shaft Stiffness for Subjects 1 - 6

Table 13. Shaft Deflection Summarized by Stiffness and Subject

Variable	Peak Deflection (°)		Time to Peak (ms)	
	Mean	S.D.	Mean	S.D.
Stiffness				
13	20.4	2.6	28	4
16	18.7	2.3	26	4
17	18.4	2.2	25	5
19	17.9	2.3	24	3
Subject				
1	18.1	1.7	25	4
2	19.2	1.9	27	7
3	16.5	2.1	26	4
4	18.0	1.7	25	3
5	22.0	2.2	27	4
6	19.1	1.6	23	2

Table 14. Shaft Deflecton for Stiffness within Subjects (n=6 trials)

Subject	Stiffness	Peak Deflection (°)		Time to Peak Deflection (ms)	
		Mean	S.D.	Mean	S.D.
1	13	19.5	1.4	27	4
	16	17.5	1.2	26	3
	17	17.6	1.7	23	3
	19	17.7	2.1	24	4
2	13	20.2	2.2	28	7
	16	19.5	2.0	30	5
	17	18.5	2.2	30	9
	19	18.8	0.7	21	2
3	13	18.9	1.9	31	2
	16	15.9	1.3	25	4
	17	16.1	1.7	24	3
	19	15.0	1.0	26	4
4	13	19.3	1.3	29	3
	16	17.8	1.2	23	3
	17	18.5	2.2	27	2
	19	16.7	1.4	24	3
5	13	25.0	1.3	30	2
	16	21.4	1.1	30	2
	17	20.5	1.7	25	4
	19	20.8	0.7	23	2
6	13	19.3	1.1	24	3
	16	19.8	1.6	23	1
	17	19.1	1.3	21	2
	19	18.2	2.1	25	2

Table 15. ANOVA for Peak Shaft Deflection

Source	SS	df	MS	F	P
Subject (Su)	397.0	5	79.4	32.1	0.001 *
Stiffness (St)	119.7	3	39.9	16.1	0.001 *
Su X St	57.9	15	3.9	1.6	0.095
Error	291.6	118	2.5		
				N:	142
				Multiple R:	0.816
				Squared Multiple R:	0.665

Table 16. Post-hoc Analysis of Peak Shaft Deflection for Stiffness

Stiffness	13	16	17	19
13	1.000			
16	0.001 *	1.000		
17	0.001 *	0.998	1.000	
19	0.001 *	0.234	0.887	1.000

Table 17. ANOVA for Time to Peak Deflection

Source	SS	df	MS	F	P
Subject (Su)	273.2	5	54.6	4.2	0.001 *
Stiffness (St)	346.2	3	115.4	9.0	0.001 *
Su X St	565.7	15	37.7	2.9	0.001 *
Error	1518.7	118	12.9		
				N:	142
				Multiple R:	0.662
				Squared Multiple R:	0.439

Table 18. Post-hoc Analysis of Time to Peak Deflection for Stiffness

Stiffness	13	16	17	19
13	1.000			
16	0.118	1.000		
17	0.002 *	0.998	1.000	
19	0.001 *	0.058	0.998	1.000

* - P < 0.05

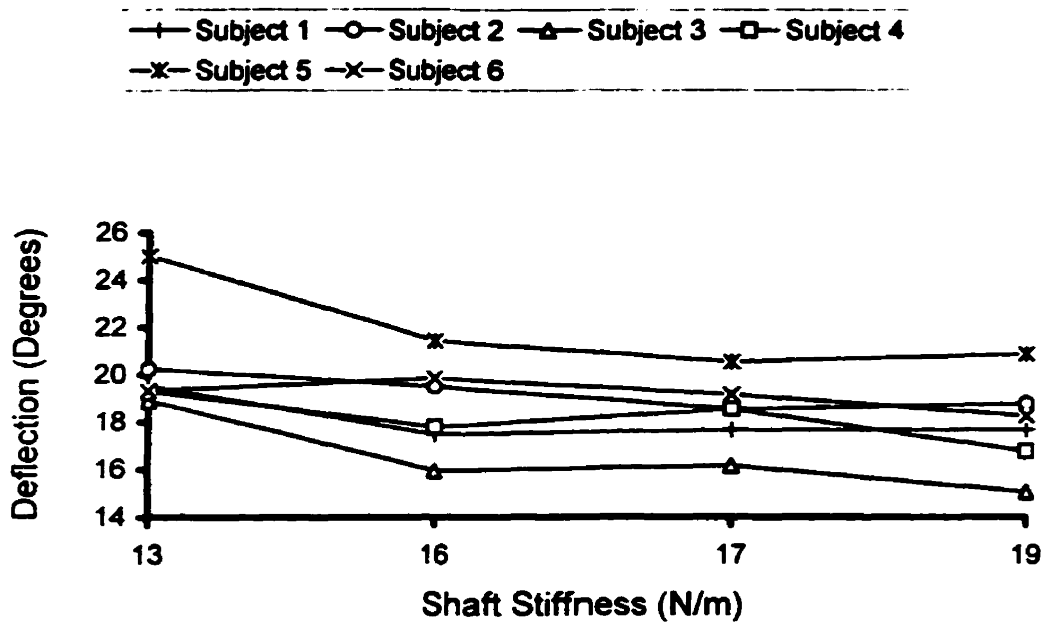


Figure 4. **Peak Shaft Deflection and Stiffness**

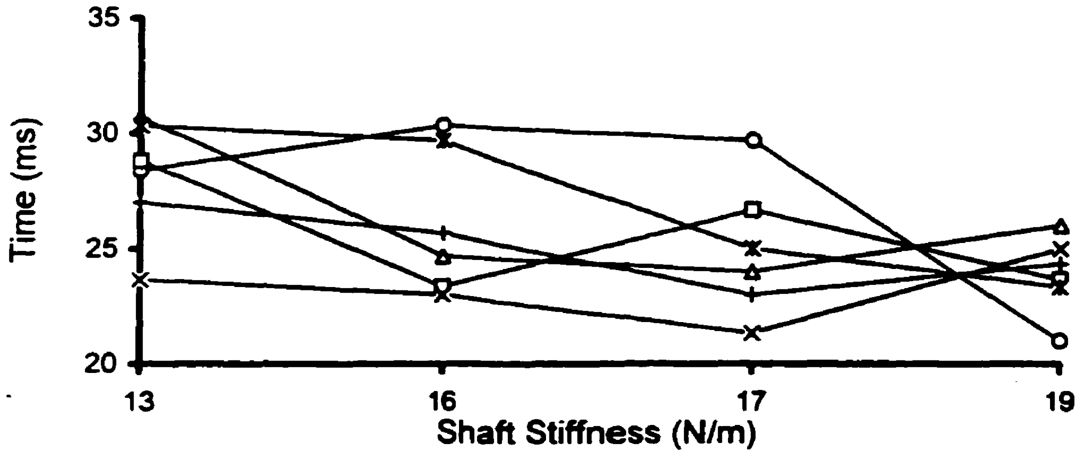


Figure 5. **Time to Peak Deflection and Shaft Stiffness**

Reliability for the Seven Dependant Variables

Subjects 3 and 6 repeated the experimental protocol on a second day. On Day 1 and Day 2, the subjects performed 24 slap shots (4 sticks X 6 trials per stick). Reliability was examined for the following seven dependant variables - puck velocity, peak forces, time to achieve peak forces, peak deflection and time to peak deflection of the shaft. The reliability data are summarized in Table 19.

Table 19. Reliability for the Seven Dependant Variables (n=48)

Variable Subject #	Day 1 Mean	 S.D.	Day 2 Mean	 S.D.	t - test
Puck Velocity (km/hr)					
3	107.3	3.6	103.2	4.1	0.452
6	104.9	3.7	107.7	2.8	
Time to Peak Z (ms)					
3	26	6.5	26	4.6	0.030
6	22	1.5	29	5.4	
Peak Z (N)					
3	96.0	17.6	127.3	20.0	0.944
6	136.4	17.3	106.0	24.6	
Time to Peak Y (ms)					
3	26	5.8	26	4.6	0.202
6	24	3.6	27	6.0	
Peak Y (N)					
3	14.0	4.5	13.3	3.5	0.796
6	9.8	3.7	10.2	3.2	
Peak Deflection (o)					
3	16.5	2.1	17.8	2.6	0.189
6	19.1	1.6	17.2	1.5	
Time to Peak Deflection (ms)					
3	26	4.0	23	2.8	0.629
6	23	2.3	28	3.5	

Discussion

In the 1990's the mention of sports brings to mind million dollar contacts, large franchises, major international competitions, and high tech functional and expensive equipment. The sports industry is no longer limited to a small percentage of the population that can afford to spend their time and money frivolously. The sporting world is a huge multi-billion dollar industry in North America alone. As the amount of money involved in sport has increased so has the amount devoted to the development of sports equipment. The benefit of improved performance through better design and material construction of equipment can be observed in pole vaulting and golf.

The sport of pole vaulting was bettered by the introduction of a fibre glass pole which quickly replaced all bamboo poles that were previously used. The fibre glass material was more suitable for the pole used in pole vaulting due to the bending characteristics it possesses. In golf the introduction of graphite shafted clubs allows players to benefit from the wider variety of stiffness characteristics available. Today a golfer can be "fitted" for exactly the appropriate type of shaft based upon the speed of the golfer's swing. A goal of all sport equipment producing companies is to maximize the athlete's performance through understanding and then matching the correct equipment needs with the athletes characteristics.

Recent improvements in the construction of the ice hockey stick involves using a carbon fibre composite to vary the stiffness of the shaft. The purpose of this study was to determine the effect this wider range of shaft stiffness would have on the performance of the slap shot. The premise is that a stick could be build using non-wood materials to allow for better performance of the slap shot resulting in a faster shot.

The seven variables recorded in this study were – puck velocity, peak Z force, peak Y force, time to achieve peak Z force, time to achieve peak Y force, peak deflection and time to peak deflection.

Puck Velocity: Sim and Chao (1978) reported velocities of up to 200 kph for the pros they tested. Based on data from other studies and this study, the values by Sim and Chao appear excessively high. The velocities observed during this study with elite players ranged from 105.9 to 108.2 kph. These velocities were similar to the findings of Marino & VanNeck (1991). The medium (13 N/m) stick produced the fastest mean shot at 108.2 kph and was significantly different from the extra (17 N/m) stick which had a mean of 105.9 kph.

Force Platform Data: Sim and Chao (1978) reported that the ground reaction forces were 1.5 – 2.5 times the players mass. During this study the Z (or downward) forces ranged from 121.9 (medium 13 N/m) – 134.7 (extra 17 N/m) Newtons. The "medium" and "extra" shafts produced significant differences in force and were different from Sim and Chao's report. The ground reaction forces encountered here were only one quarter to one fifth the mass of the subjects. The force recorded in the Z direction was the only force platform variable to yield significant findings.

Kinematic Analysis: The 13 N/m shaft was significantly different from the 16, 17, and 19 N/m shafts for the peak deflection variable (20.4 for 13 N/m shaft versus 18.7, 18.4 and 17.9 degrees respectively). Within the time to peak deflection variable, the 13 N/m shaft was significantly different from the 17 and 19 N/m shafts (28 for 13 N/m shaft versus 26, 25 and 24 ms respectively).

There were significant differences across subjects for all seven variables however the trend was not evident. There was a main effect for stiffness. The "medium" shaft

(13 N/m) differed from the other three shafts as it produced the shot with the greatest velocity, lowest Z force, greatest shaft deflection and longest time to peak shaft deflection.

The camera used to film was able to record at 480 frames per second. In comparison, Naud and Holt (1975a) filmed at 60 Hz while Naud and Holt (1975b) filmed at 200 Hz. This study found that the time between pre-loading of the shaft and release of the puck from the blade was about 50-60 ms. Even while using a camera that captures 480 frames per second some of the reflectors to be digitized were blurred. A camera with a faster shutter rate or with a higher frame per second recording rate would be ideal to use in the future.

The interaction of subjects and shaft stiffness was significant. The differences across subjects were greater for the seven dependant variables than the differences across types of shaft. The subjects were highly skilled and may have been able to adjust their shooting technique during the practise period thereby minimizing the differences across types of shaft. The interaction effect is significant in that it demonstrates the need for a wide variety of equipment to cater to the individual differences among players in ice hockey.

Conclusions

Within the limitations of this study the following conclusions are warranted.

(1) The variability in shooting velocity across subjects was greater than the variability across shaft stiffness.

(2) Subjects differed in 1) peak Z force, 2) time to achieve peak Z force, 3) peak Y force, 4) time to achieve peak Y force, 5) peak deflection and 6) time to peak deflection.

(3) Puck velocity was highest for the stick with stiffness 13 N/m and lowest for the stick with stiffness 17 N/m.

(4) Puck velocity was influenced by the interaction of Subjects and Stiffness.

(5) Time to obtain peak forces in the Y and Z directions were similar across levels of shaft stiffness.

(6) Peak Z force was highest for the stick with stiffness 17 N/m and lowest for the stick with stiffness 13 N/m.

(7) There were no differences in peak Y force among the four shaft types.

(8) The interaction of Subject and Stiffness was a significant determinant of peak Y and Z forces.

(9) Peak shaft deflection and time to peak deflection differed across shaft stiffness. The shaft of 13 N/m produced the greatest shaft deflection and the longest time to peak deflection.

Recommendations

This study was a preliminary examination of how shaft stiffness affects shot velocity. It is suggested that a future study examine four potential questions:

(1) Does deflection of the shaft above the lower hand versus deflection of the shaft below the lower hand differ? It appears that the flexion is greater below the hand.

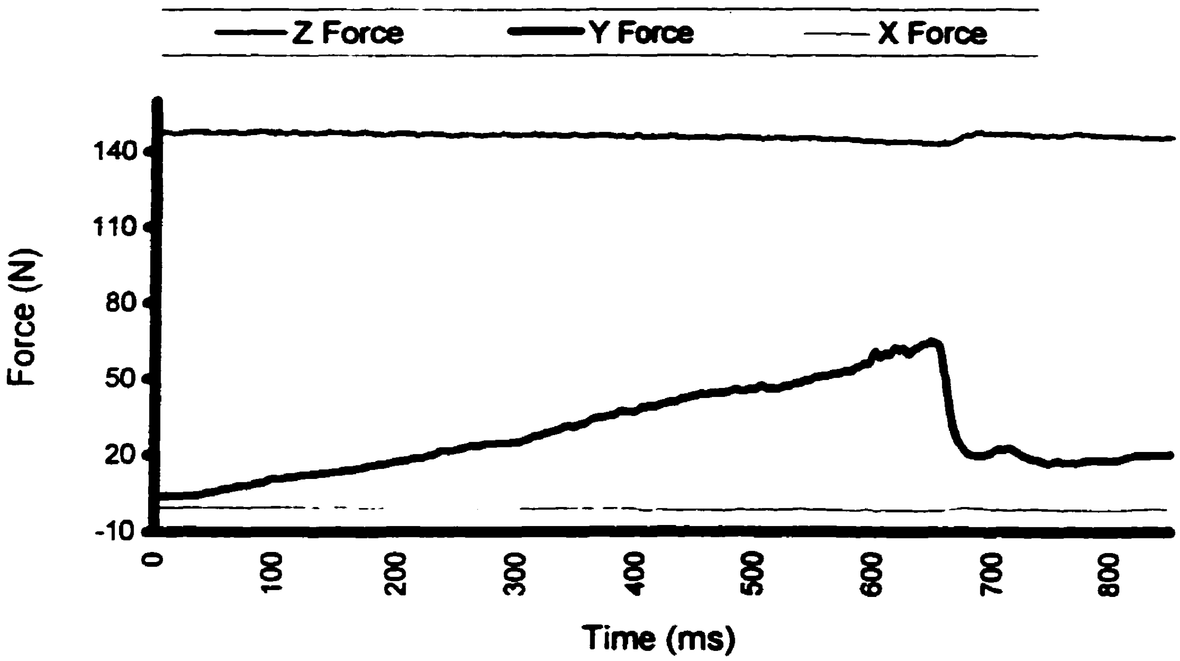
(2) Does lower hand position influence the deflection characteristics of the shaft and shot velocity?

(3) Does the type of shot (slap versus forehand) affect the magnitude of shaft deflection, time to peak deflection and surface reaction forces (Y and Z directions).

(4) What characteristics of the shooter (weight, height, strength, experience) influence the selection of a stick in terms of shaft stiffness?

Appendix A. Friction on the Force Platform

Condition 2 – Metal platform + WD-40



Appendix B1. **Post-hoc Analysis of Puck Velocity for Subjects**

Subject	1	2	3	4	5	6
1	1.000					
2	0.001 *	1.000				
3	0.998	0.001 *	1.000			
4	0.998	0.001 *	0.998	1.000		
5	0.001 *	0.001 *	0.001 *	0.001 *	1.000	
6	0.652	0.261	0.358	0.564	0.001 *	1.000

Appendix B2. **Post-hoc Analysis of Peak Z Force for Subjects**

Subject	1	2	3	4	5	6
1	1.000					
2	0.001 *	1.000				
3	0.998	0.001 *	1.000			
4	0.001 *	0.483	0.001 *	1.000		
5	0.001 *	0.998	0.001 *	0.017 *	1.000	
6	0.001 *	0.370	0.001 *	0.001 *	0.998	1.000

Appendix B3. **Post-hoc Analysis of Time to Peak Z for Subjects**

Subject	1	2	3	4	5	6
1	1.000					
2	0.998	1.000				
3	0.106	0.371	1.000			
4	0.001 *	0.001 *	0.019 *	1.000		
5	0.638	0.998	0.998	0.002 *	1.000	
6	0.998	0.998	0.998	0.001 *	0.998	1.000

* $P < 0.05$

Appendix B4. **Post-hoc Analysis of Time to Peak Y for Subjects**

Subject	1	2	3	4	5	6
1	1.000					
2	0.998	1.000				
3	0.043 *	0.977	1.000			
4	0.001 *	0.001 *	0.065	1.000		
5	0.001 *	0.004 *	0.811	0.998	1.000	
6	0.998	0.998	0.998	0.001 *	0.005 *	1.000

Appendix B5. **Post-hoc Analysis of Peak Y Force for Subjects**

Subject	1	2	3	4	5	6
1	1.000					
2	0.001 *	1.000				
3	0.998	0.001 *	1.000			
4	0.998	0.001 *	0.998	1.000		
5	0.227	0.001 *	0.998	0.998	1.000	
6	0.001 *	0.001 *	0.001 *	0.001 *	0.001 *	1.000

* $P < 0.05$

Appendix B6. Post-hoc Analysis of Peak Deflection for Subjects

Subject	1	2	3	4	5	6
1	1.000					
2	0.168	1.000				
3	0.012	0.001 *	1.000			
4	0.998	0.201	0.012	1.000		
5	0.001 *	0.001 *	0.001 *	0.001 *	1.000	
6	0.292	0.998	0.001 *	0.346	0.001 *	1.000

Appendix B7. Post-hoc of Time to Peak Deflection for Subjects

Subject	1	2	3	4	5	6
1	1.000					
2	0.403	1.000				
3	0.998	0.998	1.000			
4	0.998	0.998	0.998	1.000		
5	0.698	0.998	0.998	0.998	1.000	
6	0.998	0.002 *	0.053	0.388	0.005 *	1.000

* $P < 0.05$

Appendix C. **Bonferroni Post-hoc Analysis of Puck Velocity for (Subjects X Stiffness)**

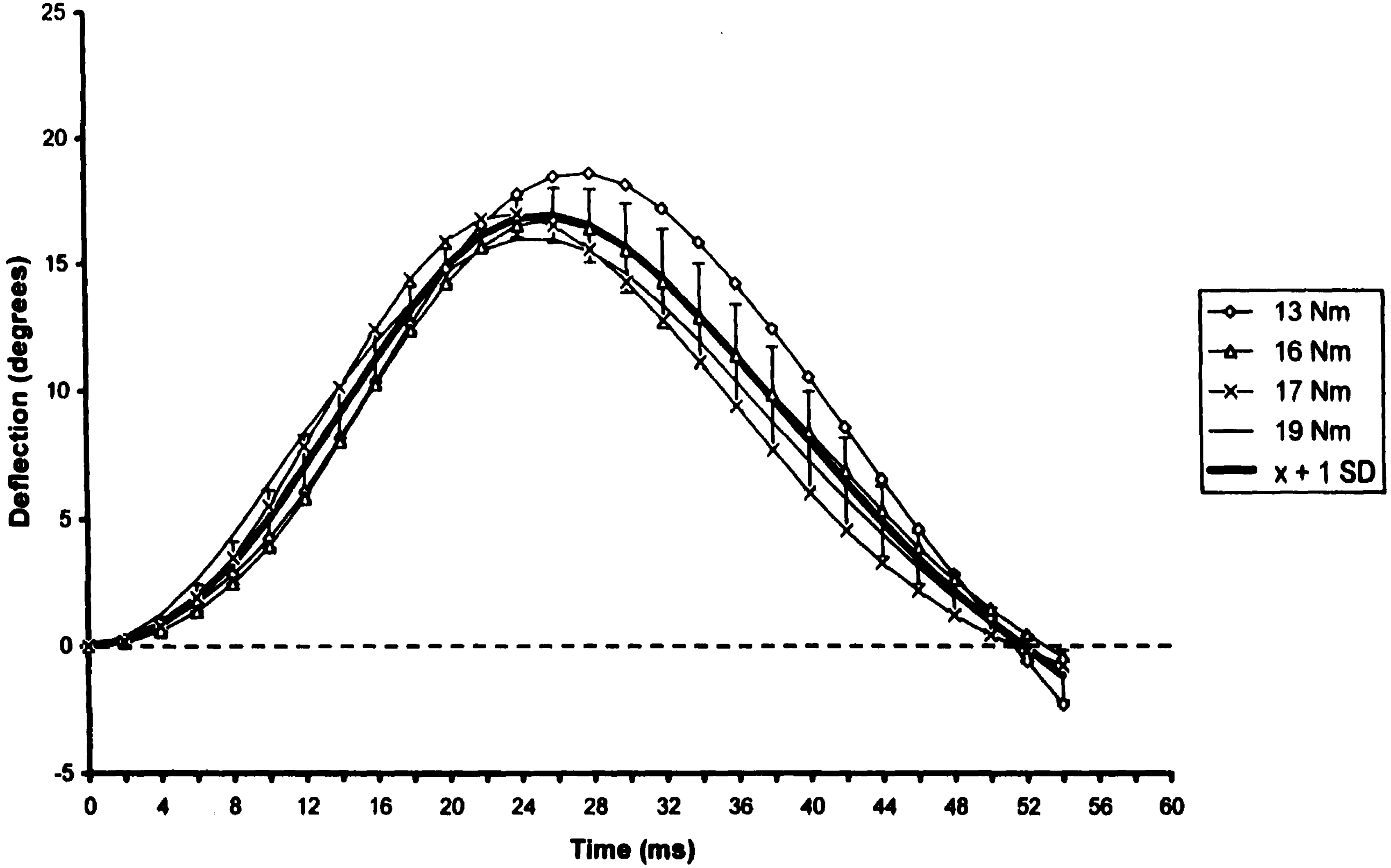
Su X St	vs	Su X St	P
1 & 13		5 & 19	0.001
1 & 16		5 & 19	0.003
1 & 17		2 & 17	0.022
1 & 19		2 & 17	0.001
1 & 19		2 & 19	0.035
2 & 13		5 & 13	0.035
2 & 17		3 & 13	0.001
2 & 19		3 & 13	0.009
2 & 19		4 & 16	0.009
2 & 19		5 & 13	0.001
2 & 19		5 & 16	0.005
2 & 19		5 & 17	0.014
2 & 19		5 & 19	0.001
3 & 16		5 & 19	0.005
3 & 19		5 & 13	0.014
3 & 19		5 & 19	0.001
4 & 17		5 & 19	0.009
4 & 19		5 & 19	0.001
5 & 13		6 & 16	0.035
5 & 13		6 & 17	0.003
5 & 13		6 & 19	0.003
5 & 19		6 & 16	0.001
5 & 19		6 & 17	0.001
5 & 19		6 & 19	0.001

Appendix D. Bonferroni Post-hoc Analysis of Peak Z Force for (Subjects X Stiffness)

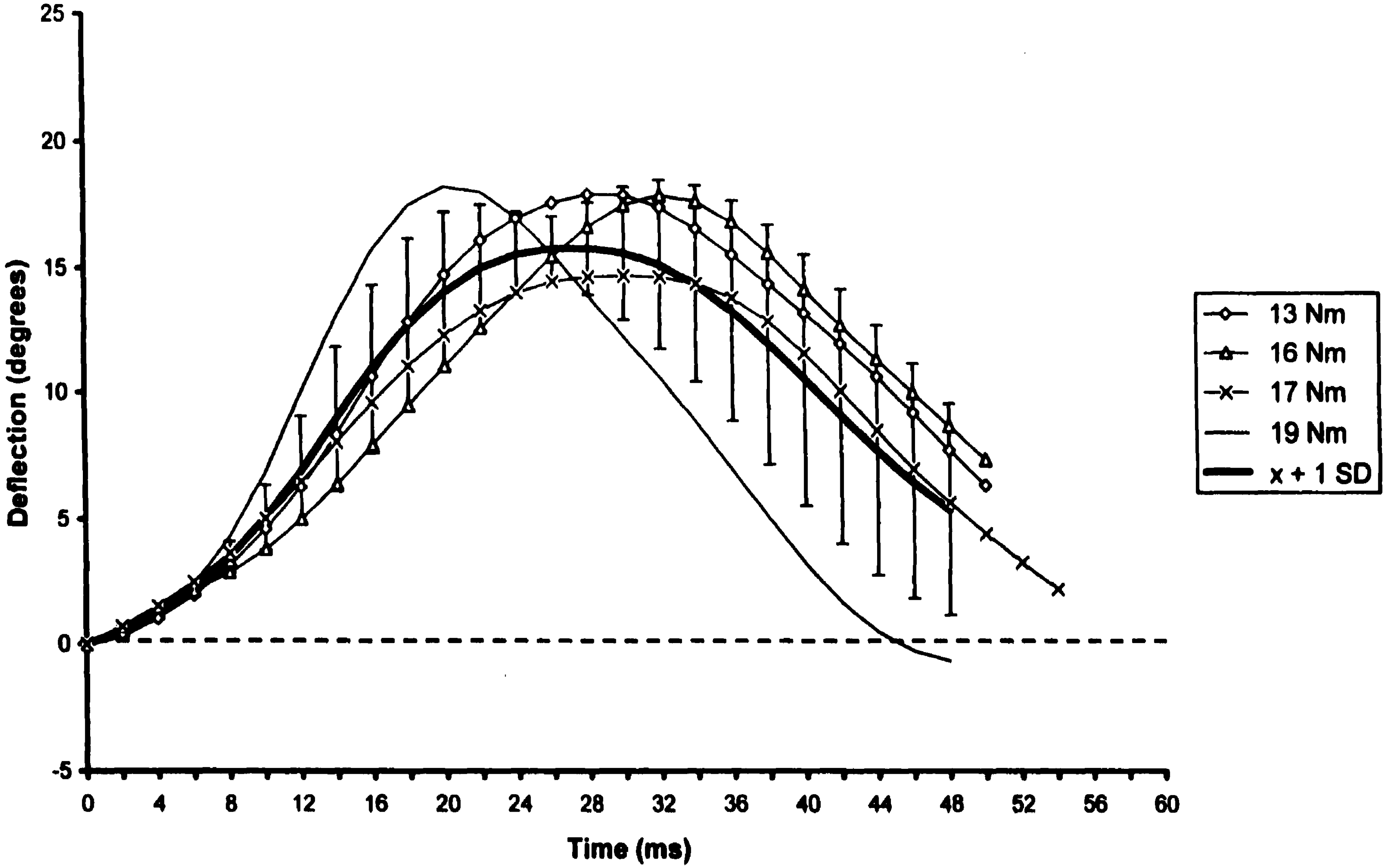
Su X St	vs Su X St	P	Su X St	vs Su X St	P
1 & 13	2 & 13	0.001	1 & 19	5 & 19	0.019
1 & 13	2 & 16	0.001	1 & 19	6 & 16	0.001
1 & 13	2 & 17	0.001	1 & 19	6 & 17	0.034
1 & 13	2 & 19	0.001	1 & 19	6 & 19	0.021
1 & 13	4 & 13	0.001	2 & 13	4 & 19	0.012
1 & 13	4 & 16	0.001	2 & 16	3 & 16	0.015
1 & 13	4 & 17	0.001	2 & 16	3 & 17	0.015
1 & 13	4 & 19	0.001	2 & 16	3 & 19	0.009
1 & 13	5 & 13	0.001	2 & 17	3 & 13	0.001
1 & 13	5 & 16	0.001	2 & 17	3 & 16	0.001
1 & 13	5 & 17	0.001	2 & 17	3 & 17	0.001
1 & 13	5 & 19	0.001	2 & 17	3 & 19	0.001
1 & 13	6 & 13	0.005	2 & 19	3 & 13	0.003
1 & 13	6 & 16	0.001	2 & 19	3 & 16	0.001
1 & 13	6 & 17	0.001	2 & 19	3 & 17	0.001
1 & 13	6 & 19	0.001	2 & 19	3 & 19	0.001
1 & 16	2 & 16	0.013	3 & 13	4 & 13	0.001
1 & 16	2 & 17	0.001	3 & 13	4 & 17	0.001
1 & 16	2 & 19	0.001	3 & 13	4 & 19	0.001
1 & 16	4 & 13	0.001	3 & 13	5 & 17	0.003
1 & 16	4 & 17	0.001	3 & 13	6 & 16	0.008
1 & 16	4 & 19	0.001	3 & 16	4 & 13	0.001
1 & 16	5 & 16	0.004	3 & 16	4 & 17	0.001
1 & 16	5 & 17	0.001	3 & 16	4 & 19	0.001
1 & 16	6 & 16	0.001	3 & 16	5 & 16	0.004
1 & 17	2 & 16	0.009	3 & 16	5 & 17	0.001
1 & 17	2 & 17	0.001	3 & 16	6 & 16	0.001
1 & 17	2 & 19	0.001	3 & 17	4 & 13	0.001
1 & 17	4 & 13	0.001	3 & 17	4 & 17	0.001
1 & 17	4 & 17	0.001	3 & 17	4 & 19	0.001
1 & 17	4 & 19	0.001	3 & 17	5 & 16	0.004
1 & 17	5 & 16	0.003	3 & 17	5 & 17	0.001
1 & 17	5 & 17	0.001	3 & 17	6 & 16	0.001
1 & 17	5 & 19	0.044	3 & 19	4 & 13	0.001
1 & 17	6 & 16	0.001	3 & 19	4 & 17	0.001
1 & 17	6 & 19	0.048	3 & 19	4 & 19	0.001
1 & 19	2 & 13	0.030	3 & 19	5 & 16	0.003
1 & 19	2 & 16	0.040	3 & 19	5 & 17	0.001
1 & 19	2 & 17	0.001	3 & 19	5 & 19	0.047
1 & 19	2 & 19	0.001	3 & 19	6 & 16	0.001
1 & 19	4 & 13	0.001	4 & 16	4 & 19	0.011
1 & 19	4 & 16	0.033	4 & 17	6 & 13	0.016
1 & 19	4 & 17	0.001	4 & 19	5 & 13	0.007
1 & 19	4 & 19	0.001	4 & 19	6 & 13	0.001
1 & 19	5 & 16	0.001	4 & 19	6 & 17	0.011
1 & 19	5 & 17	0.001	4 & 19	6 & 19	0.018

Appendix E. Bonferroni Post-hoc Analysis of Peak Y Force for (Subjects X Stiffness)

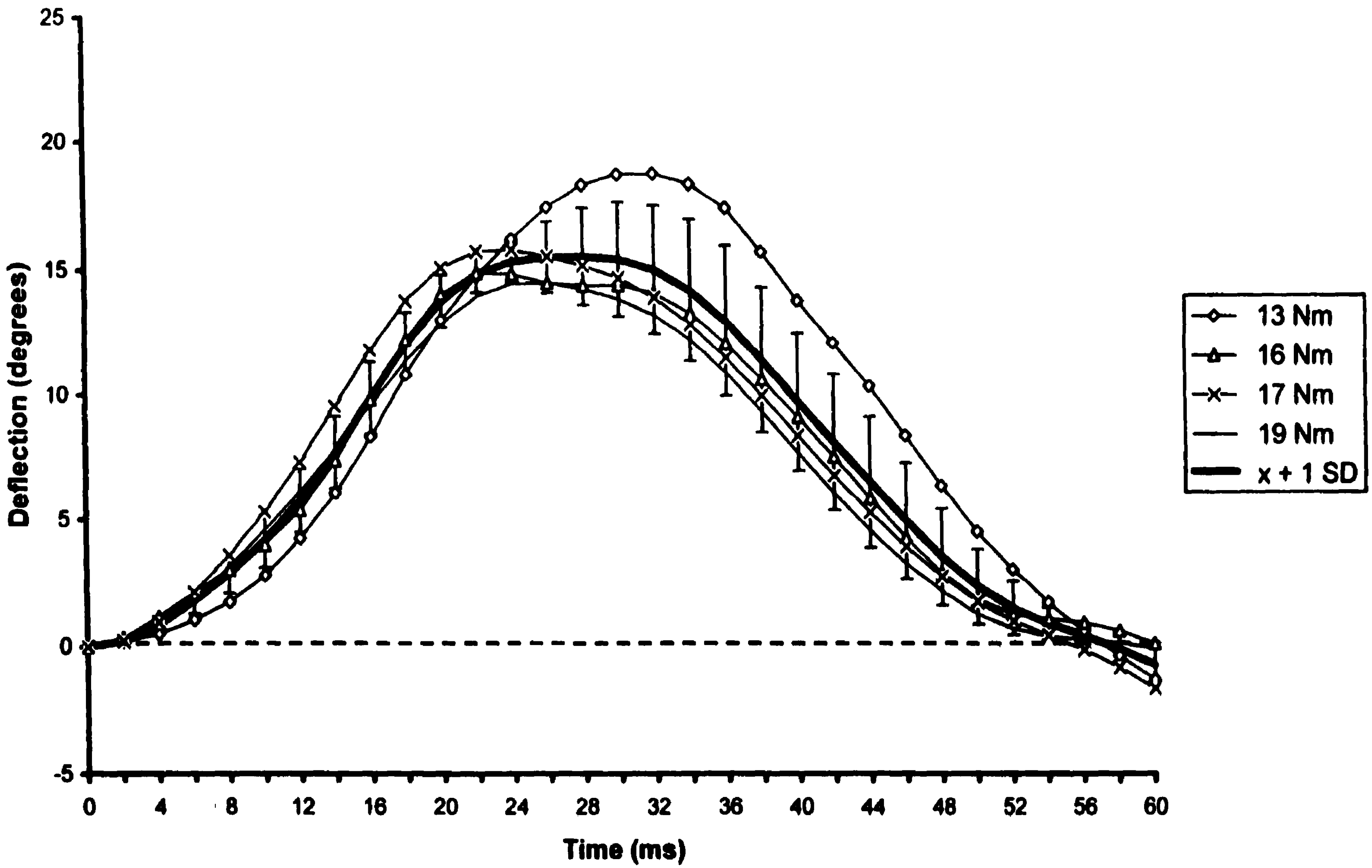
Su X St	vs Su X St	P	Su X St	vs Su X St	P
1 & 13	2 & 13	0.001	2 & 17	3 & 13	0.001
1 & 13	3 & 13	0.001	2 & 17	3 & 19	0.001
1 & 13	6 & 13	0.001	2 & 17	4 & 13	0.001
1 & 13	6 & 16	0.035	2 & 17	4 & 16	0.001
1 & 13	6 & 17	0.001	2 & 17	4 & 19	0.001
1 & 13	6 & 19	0.002	2 & 17	5 & 13	0.001
1 & 16	2 & 13	0.001	2 & 17	5 & 16	0.001
1 & 16	2 & 17	0.001	2 & 17	5 & 17	0.001
1 & 16	2 & 19	0.001	2 & 17	5 & 19	0.001
1 & 17	2 & 13	0.001	2 & 17	6 & 13	0.001
1 & 17	2 & 17	0.001	2 & 17	6 & 16	0.001
1 & 17	2 & 19	0.001	2 & 17	6 & 17	0.001
1 & 19	2 & 13	0.001	2 & 17	6 & 19	0.001
1 & 19	2 & 17	0.002	2 & 19	3 & 13	0.001
1 & 19	2 & 19	0.009	2 & 19	3 & 19	0.001
2 & 13	2 & 16	0.001	2 & 19	4 & 13	0.001
2 & 13	3 & 13	0.001	2 & 19	4 & 16	0.001
2 & 13	3 & 16	0.001	2 & 19	4 & 19	0.001
2 & 13	3 & 17	0.001	2 & 19	5 & 13	0.001
2 & 13	3 & 19	0.001	2 & 19	5 & 16	0.001
2 & 13	4 & 13	0.001	2 & 19	5 & 17	0.001
2 & 13	4 & 16	0.001	2 & 19	5 & 19	0.001
2 & 13	4 & 17	0.001	2 & 19	6 & 13	0.001
2 & 13	4 & 19	0.001	2 & 19	6 & 16	0.001
2 & 13	5 & 13	0.001	2 & 19	6 & 17	0.001
2 & 13	5 & 16	0 001	2 & 19	6 & 19	0.001
2 & 13	5 & 17	0.001	3 & 13	3 & 16	0.001
2 & 13	5 & 19	0.001	3 & 13	3 & 17	0.001
2 & 13	6 & 13	0.001	3 & 13	4 & 17	0.001
2 & 13	6 & 16	0.001	3 & 16	6 & 13	0.001
2 & 13	6 & 17	0.001	3 & 16	6 & 17	0.001
2 & 13	6 & 19	0.001	3 & 16	6 & 19	0.005
2 & 16	3 & 13	0.001	3 & 17	6 & 13	0.001
2 & 16	3 & 19	0.001	3 & 17	6 & 17	0.001
2 & 16	4 & 13	0.026	3 & 17	6 & 19	0.005
2 & 16	4 & 16	0.002	3 & 19	4 & 17	0.016
2 & 16	5 & 16	0.017	4 & 16	4 & 17	0.023
2 & 16	6 & 13	0.001	4 & 17	6 & 13	0.001
2 & 16	6 & 16	0.001	4 & 17	6 & 16	0.011
2 & 16	6 & 17	0.001	4 & 17	6 & 17	0.001
2 & 16	6 & 19	0.001	4 & 17	6 & 19	0.001



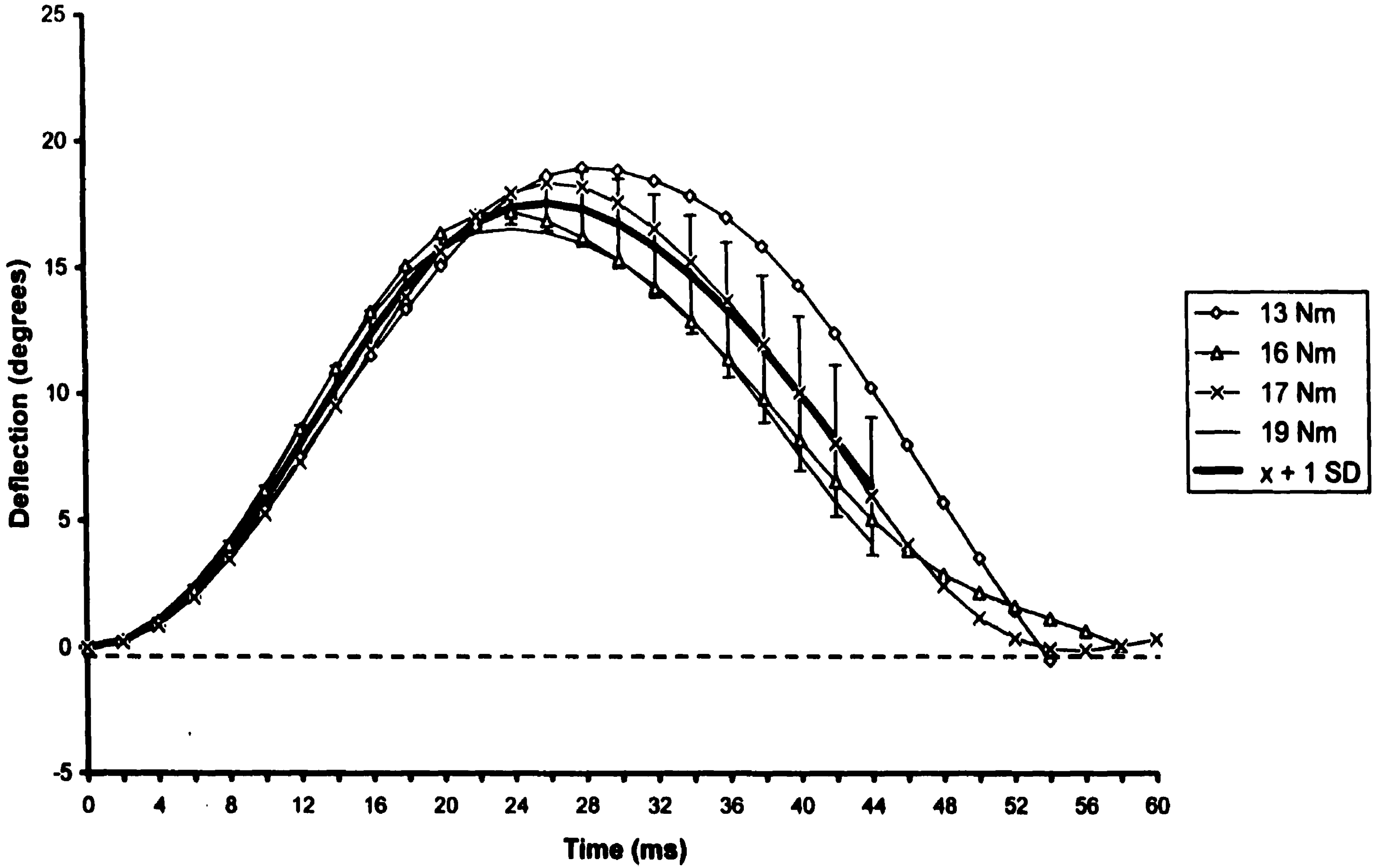
 Appendix F1. Shaft Deflection vs Time for Subject 1



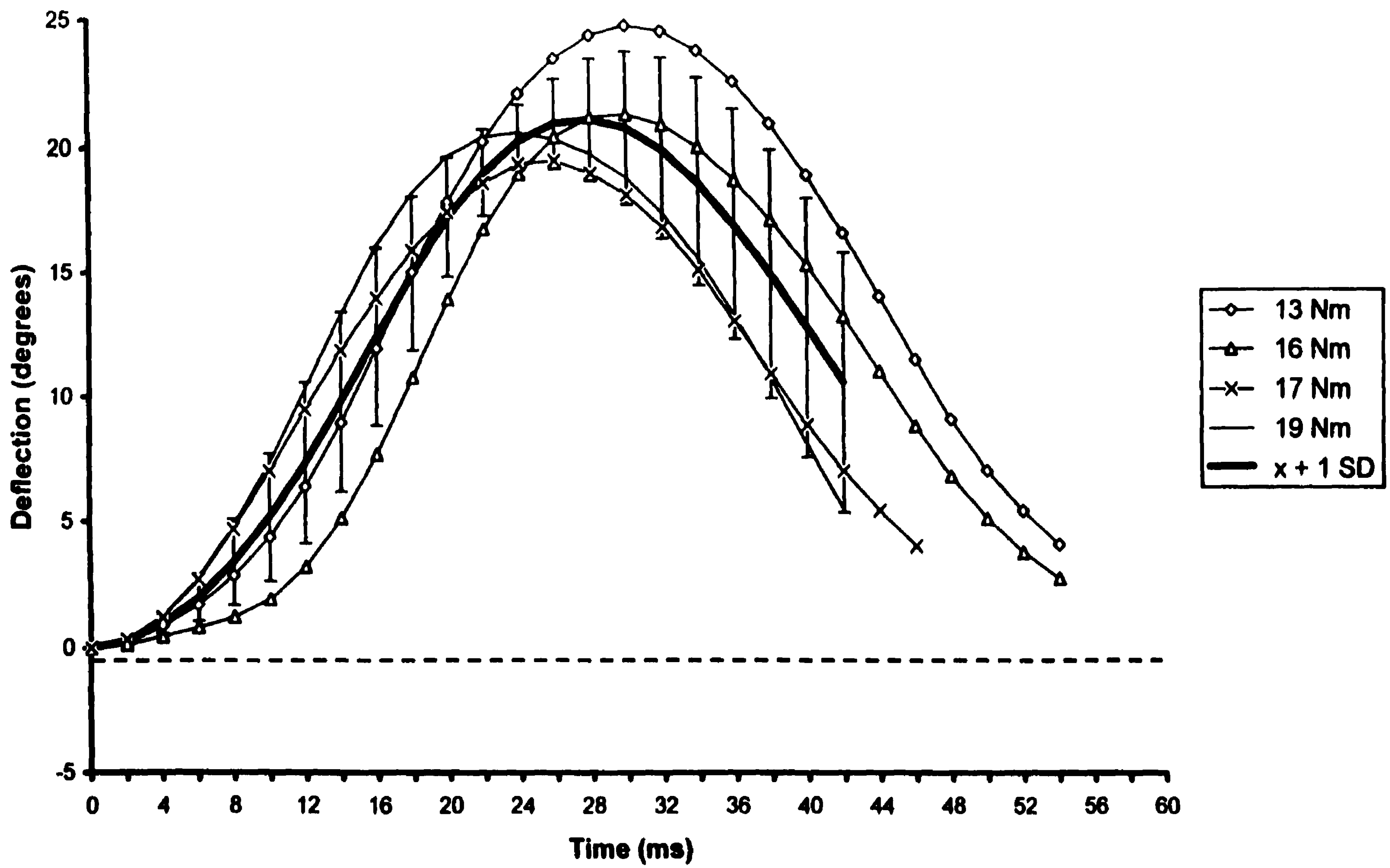
Appendix F2. Shaft Deflection vs Time for Subject 2



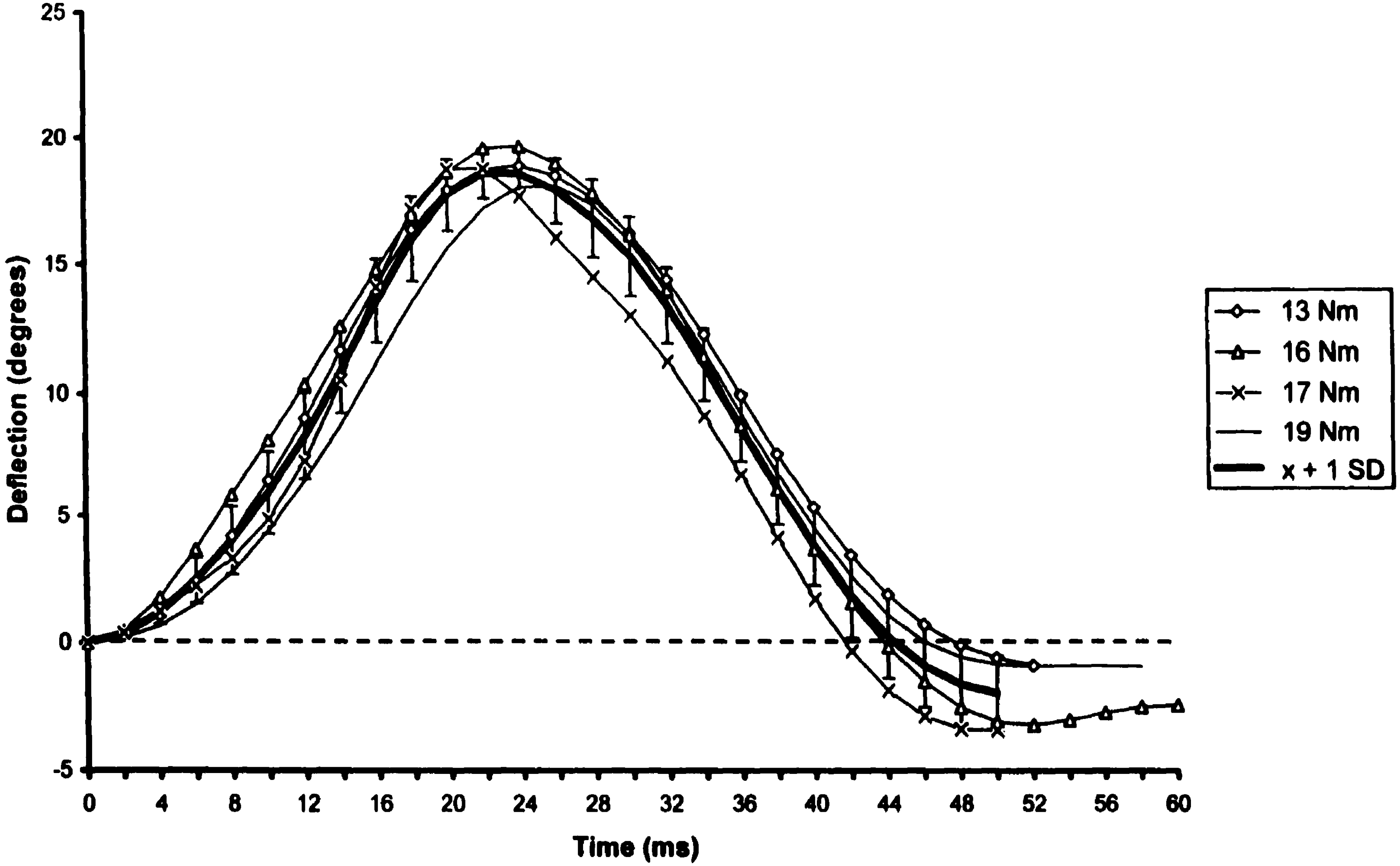
 Appendix F3. Shaft Deflection vs Time for Subject 3



Appendix F4. Shaft Deflection vs Time for Subject 4



 Appendix F5. Shaft Deflection vs Time for Subject 5



 Appendix F6. Shaft Deflection vs Time for Subject 6

Appendix G. Bonferroni Post-hoc Analysis of Time to Peak Deflection for (Subjects X Stiffness)

Su X St	vs	Su X St	P
2 & 16		2 & 19	0.004
2 & 16		6 & 17	0.008
2 & 17		2 & 19	0.015
2 & 17		6 & 17	0.028
2 & 19		3 & 13	0.002
2 & 19		5 & 13	0.004
2 & 19		5 & 16	0.015
3 & 13		6 & 17	0.004
5 & 13		6 & 17	0.008
5 & 16		6 & 17	0.028

Review of Literature

Phases in the Performance of the Slap Shot

The phases of the slap shot are:

1) *backswing* - movement of the stick in a backwards direction away from the puck until about shoulder level

2) *downswing* - stick is accellerated downward from the top of the backswing toward the puck

3) *pre-load* - blade makes contact with the ice, bending (pre-loading) the shaft prior to touching the puck. This begins to store elastic energy in the shaft.

4) *load* - blade makes contact with the puck and the shaft bends (loads) further, thus increasing the amount of stored elastic energy in the shaft.

5) *release* - shaft unbends as it first ends contact with the ice and second releases the puck from the blade. This unbending transfers the stored elastic energy from the shaft to the puck.

6) *followthrough* - stick continues to be raised and decellerates until coming to rest at hip to shoulder height.

Factors Influencing Slap Shot Velocity

There are many factors which influence the speed of a slap shot in ice hockey. Some of these factors are: (1) coordinated movements (mechanics) of the shooter, (2) size of shooter (height and mass), (3) velocity of the distal end of the shaft prior to puck contact, (4) pre-loading of the stick, (5) stiffness characteristics of the stick, (6) contact time with the puck and (7) pre-loading time.

Several mechanical variables are thought to influence the efficiency of the slap shot. The maximum force a player produces on the stick alone does not determine the puck velocity (Dore & Roy, 1973). Differences in players' shooting mechanics may explain why an increase in force on the stick does not necessarily mean an increase in puck velocity. For example, players may use a very stiff shaft and therefore need to apply a large amount of downward force to pre-load and load the shaft. On the other hand, players may use a less stiff shaft and need to apply less downward force in order to load and pre-load the shaft. The loss of potential elastic energy due to using a less stiff shaft may be offset by an increase in blade speed due to the lower amount of downward force required.

The performance of a slap shot, regardless of specific technique, requires the following contribution from different body parts: 25% trunk, 40 to 45% shoulder, and 30 to 35% elbow and wrist movement (Wells, 1976). Most players incorporate these principles into their performance of a slap shot yet there is still high inter-shooter variability in mechanics.

The shooter's physical make-up in terms of height and mass influence the velocity of the slap shot. Roy and Dore (1979) reported that young players (9-10 years old) had shots that were faster and more accurate when shooting with a flexible stick as compared to a more rigid one. A young and weak player when compared to a professional does not have the strength to load a stiff stick in order to receive the benefits such a stick could provide. According to Roy and Dore (1979) a player with a greater amount of muscle mass is able to use a more rigid shaft and when trained, can slap a puck faster as compared to a weaker player. The shooter's height is also a factor that influences the velocity of the slap shot. A taller player has longer limbs and usually uses a longer stick.

This translates into longer levers being used as compared to a shorter player. Levers of greater length give taller players an increase in potential to generate a higher shaft/blade velocity that in turn increases the velocity of the slap shot.

The velocity of the stick blade just prior to contact with the puck influences the velocity of the slap shot. A positive correlation exists between shaft/blade velocity before impact and puck velocity (Norman, 1975).

Pre-loading the stick is vital when taking a slap shot. All players strike the ice prior to contact with the puck, i.e. to pre-load the stick. The blade of the stick encounters a friction force when it is in contact with the ice. Friction is a force acting parallel to the interface of two surfaces that are in contact during the motion of one surface over the other (Hamill & Knutzen, 1995).

The blade in the slap shot presses downward on the ice and the ice exerts a vertical upward force against the blade as it moves along the ice. The large horizontal force of the blade is sufficient in overcoming the minimal friction of the ice/blade interface. The friction force does vary when playing on different surfaces. For example smooth versus rough ice, or ice versus asphalt will affect the force required to pre-load the shaft appropriately. Pre-loading the stick during the slap shot causes the shaft to bend. This bending action stores elastic energy in the shaft and is released as the puck leaves the stick.

The variability in pre-loading can be attributed to two factors. The first factor is the initial distance ground contact is made behind the puck. The second factor is the amount of downward, vertical force the shooter applies to the ice. To a certain degree, an increase in pre-loading force increases the shaft elastic energy through deflection. This increases the velocity of the puck upon the conversion of the elastic energy into kinetic energy simultaneous with the unbending of the shaft and release of the puck from the blade of the stick. Naud and Holt (1975a) concluded "With equal bend, the stiffer the shaft, the greater the energy storage and as a result, the more velocity in the shot."

The construction and characteristics of the materials of the shaft differ among sticks. Shafts react differently to pre-loading. Traditionally, shaft stiffness was limited to the inherent stiffness of the types of wood being used in the construction of the stick. The use of new composite materials and recent technological advances in stick construction have increased the variability in the stiffness of composite hockey shafts. Given the growing availability of sticks with varying stiffness there needs to be a study of the effect of shaft flexibility on shooting speed.

The ability to shoot the puck with optimal velocity and precision is a decisive factor in the overall performance of a player (Lariviere and Lavallee, 1972). Although shooting is an important skill involved in the game of ice hockey, little research has been devoted to it. Alexander et al. (1963) was the first study to investigate shooting. The study investigated the velocities of standing and skating wrist and slap shots and the accuracy of the same shots. The average velocity of the standing slap shot was reported to be greater than that of the standing wrist shot, and the average velocity of the skating slap was superior to the skating wrist shot. The greatest average velocity was attained with the skating slap shot and the lowest with the standing wrist shot. This held true for the four levels of playing ability tested. No one shot type was found to be statistically more accurate, regardless of ability level. The average standing slap shot velocity ranged from 74.5 ± 4.8 mph (120 ± 7.7 kph) for pro players from the Western Hockey League (N=11) to 69.0 ± 4.3 mph (110 ± 6.9 kph) for Canadian university players (N=6).

Alexander, Drake, Reichenbach and Haddow (1964) in their study on the speed of shots, proved conclusively that the velocity attained by the slap shot was significantly greater than the velocity of the conventional wrist shot. These two studies were ground breaking back in the early sixties when the slap shot first began to be widely used. Hockey traditionalists were slow to accept the fact that the game of ice hockey was being revolutionized by this high velocity shot (Hayes, 1964). Nazar compared the straight blade with the curved blade on shooting velocity and accuracy in university varsity ice hockey players at the University of Minnesota in 1971. Twenty-six subjects were divided into two groups. All subjects performed wrist and slap shots in both stationary and skating positions. It was found that the skating slap shot had the highest velocity and the least accuracy and the stationary wrist shot was the slowest and most accurate. The curved blade hockey stick imparted a significantly greater velocity and was significantly more accurate than the straight blade for both groups.

Dore and Roy in 1973 measured the variation in time of the forces applied on a hockey stick by players while shooting at a target. Dore and Roy used instrumented hockey sticks for force measurements. The sticks had strain gauges appropriately located along the shaft and blade of the stick. The analysis of the results revealed that some difference exists in the shape of the force-time diagrams between different type of shots performed by the same player. The average puck velocity was 26.9 ± 1.5 m/sec (96.9 ± 5.4 kph) for the stationary slap shot and 29.0 ± 1.4 m/sec (104.4 ± 5.0 kph) for the skating slap shot.

Roy and Dore in 1973 investigated the kinematics of the slap shot as executed by players of three different age classifications. The following anthropometric measures for each individual were recorded: height, weight, and trunk and upper segment lengths.

These measures were then cross referenced with the velocity of their slap shot to establish correlations. No trends could be established by observing the resulting correlations other than "it seems that younger players must rely more on their morphological and muscular strength attributes than the older players to achieve relatively the same skill". Usually younger players use the same type of stick as the older players. This puts them at a disadvantage especially as far as the weight and stiffness of the stick are concerned. It was concluded that sticks which were less stiff should be used by less physically mature individuals. In this study Roy and Dore reported slap shot velocities ranging from 19.2 ± 2.9 m/sec (69.2 ± 10.5 kph) for 11 – 12 year-old to 26.7 ± 1.7 m/sec (96.2 ± 6.1 kph) for 17+ year old boys.

Naud and Holt in 1975 analyzed two former professional ice hockey players taking stationary wrist, slap and snap shots. This was the first study to analyze the contact and release points of the puck on the blade of the stick during the performance of three different types of shot. A 16 mm camera recorded the trials from in front of the shooter at 200 frames per second. The wrist shot had the blade making initial contact with the puck at the heel and the release point was at the toe of the blade. During the performance of the slap shot the film recorded the blade making initial contact with the center of the blade and then being released off of the toe of the blade. The snap shot had the puck first touch the blade near the toe and then release further toward the tip of the blade. In defining the performance of the slap shot Naud and Holt describe the initial contact with the ice beginning 4 to 6 inches (10 to 15 cm) behind the puck.

The second article written by Naud and Holt in 1975 was titled "A cinematographic analysis of stick dynamics in the wrist, slap, and snap shots in ice hockey". This was the first article that investigates the need for greater understanding of stick dynamics which will lead to a greater understanding of shooting and as a result will improve the teaching and coaching of shooting skills. A 16 mm camera set at 60 frames per second was used to film two former professional ice hockey players performing three different types of forehand shots. It was reported that the two players averaged 1 ⅛, 1 ¼ and 2 ½ inches of shaft bend along the minor axis for the wrist, snap and slap shots respectively. The average velocities for the two shooters was 55 mph (88 kph), 61 mph (97.6 kph) and 83 mph (132.8 kph) for the wrist, snap and slap shots respectively. In conclusion the authors note "it appears that the greater the bend in the shaft of the stick the greater the velocity of the shot, provided the shaft straightens during the time the puck is rolling down the face of the blade. Furthermore, with equal bend, the stiffer the shaft, the greater the energy storage and as a result the more velocity in the shot".

Sim and Chao performed an in-depth biomechanical analysis of the game of ice hockey in 1978. Cinematographic motion analysis was used to measure the velocities of players and pucks. Players velocities ranged from 32 to 48 kph (20 to 30 mph). The puck traveled at velocities up to 150 kph (90 mph) for high school students and up to 200 kph (120 mph) for college and professional players. This is the only study which mentions the use of a force platform. It was reported that the vertical reaction of the player ranged from 1.5 to 2.5 times the player's body weight.

In 1991, Marino and VanNeck from the University of Windsor researched static and dynamic characteristics of aluminum versus wooden hockey sticks. They reported that the mean slap shot velocity for wooden sticks was 104.84 ± 10.36 kph (65.5 ± 6.5 mph) and 107.17 ± 11.56 kph (70.0 ± 7.2 mph) for aluminum sticks. Among their conclusions were: 1) aluminum hockey sticks are somewhat lighter than wooden sticks with some brands being significantly lighter, 2) there is no difference in the stiffness of aluminum versus wooden sticks, 3) there is no significant difference in slap shot velocity when using aluminum versus wooden hockey sticks, 4) aluminum hockey sticks provide a slightly lighter and stronger alternative to wooden sticks.

Harel, Hujeir and Marson (1994) aided in the development of computer generated models of hockey stick shafts using I-DEAS finite element software. Their report observed that progress was being made, but the computer model was not yet accurate for certain analyses.

Garone, Sanzari and Yigit (1995) analyzed the behavior and motions of a hockey stick when performing a slap shot. Their results were not conclusive. Some shots supported a "cantilever" theory to explain the forces acting on the shaft. In a cantilever case the shear force is constant throughout the shaft and the bending moment increases linearly from one end of the shaft. Other shots totally opposed this theory. They concluded that rather than the puck creating one force that acts on the shaft, a stress wave was emanating from where the puck and the stick collided and this wave propagated to the lower hand of the shooter.

The following chart summarizes the findings of all studies involving the slap shot.

Author	Year	N	Velocity (kph)	Comments
Alexander et al.	63	11 pro	119.2 +/- 7.7	Skating Slap Shot fastest & Stationary Wrist slowest
Alexander et al.	64			Velocity of Slap Shot significantly greater than velocity of the Wrist Shot
Nazar	71	26	Skating Slap Stationary Wrist	Fastest & least accurrate Slowest & most accurrate Curved blade significantly different from straight blade in velocity & accurracy
Dore & Roy	73		96.8 +/- 5.4 104.4 +/- 5.0	Stationary Skating
Roy & Dore	73	10 10 19	69.1 +/- 10.4 94.4 +/- 5.76 96.12 +/- 6.1	11 - 12 years old 15 - 16 years old 17 + years old
Naud & Holt	75	2 pro		Pre-load 4 - 6 inches (15 - 20 cm) behind puck
Naud & Holt	75	2 pro	88 Wrist 98 Snap 133 Slap	1 1/8" (2.9 cm) shaft bend 1 1/4" (3.2 cm) shaft bend 2 1/2" (3.8 cm) shaft bend
Sim & Chao	78		150 200	high school college & pro Force plate: 1.5 - 2.5 times players weight
Marino & VanNeck	91		105 +/- 10 107 +/- 11	Wood Aluminum No signif. dif. - Wood vs Aluminum
Harl et al.	94			Computer to model stresses of hockey stick
Garone et al.	95			Behavior of stick
Rothsching et al.	97	6 university	108.2 +/- 4.6 107.0 +/- 4.4 105.9 +/- 5.4 106.3 +/- 6.0	13 N/m - medium 16 N/m - stiff 17 N/m - extra 19 N/m - pro stiff 17.9 - 20.4 deg; 11cm (4 1/4") shaft bend 121.9 - 134.7 Newtons on force platform

References

Alexander, J. F., Drake, C. J., Reichenbach, P. J. and Haddow, J. B. 1964. Effect of strength development on speed of shooting of varsity ice hockey players. Research Quarterly. 35: 101-106.

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

Canadian Amateur Hockey Association. (CAHA) 1993. Official Rule Book of the Canadian Amateur Hockey Association.

Dore, R. and Roy, R. 1973. Dynamometric analysis of different hockey shots. Biomechanics VI-B. Proceedings of the Fourth International Congress of Biomechanics. 277-285.

Emmert, W. 1984. The slapshot – strength and conditioning program for hockey at Boston College. National Strength and Conditioning Association Journal. 6(2): 4-6, 68, 71, 73.

Garone, M., Sanzari, L. and Yigit, C. 1995. Dynamic analysis of a hockey stick. Unpublished paper. Department of Engineering, McGill University. (L. B. Lessard and J. Nemes.)

Hamill, J. and Knutzen, K. M. 1995. Biomechanical Basis of Human Movement. Publisher: Williams and Wilkins, media, PA 19063-2043 USA. Pages 403-405.

Harel, D., Hujeir, R. A. and Marson, J. 1994. Analysis and testing of graphite hockey sticks. Unpublished paper. Department of Engineering, McGill University. (L. B. Lessard and J. Nemes.)

Hayes, D. 1965. A mechanical analysis of the hockey slap shot. Journal of the Canadian Association for Health, Physical Educatiion and Recreation. 31: 17.

Hoerner, E. F. 1989. The dynamic role played by the ice hockey stick. Safety in ice hockey, ASTM STP 1050, C. R. Castaldi and E. F. Hoerner Eds., American Society for Testing and Materials, Philadelphia, 154-163.

Lariviere, G. and H. Lavallee. 1972. Evaluation du niveau technique de joueurs de hockey de categorie moustique. (Technical evaluation of young hockey players.) Mouvement 7: 101-111.

Marino, W. G. and VanNeck, C. 1991. Static and dynamic characteristics of aluminum versus wooden hockey sticks. Department of Kinesiology, University of Windsor.

Naud, R. L. and Holt L. E. 1975a. A cinematographical analysis of the contact and release point in the wrist, slap and slap shots in ice hockey. Unpublished paper. 7 pages.

Naud, R. L. and Holt L. E. 1975b. A cinematographic analysis of stick dynamics in the wrist, slap and snap shots in ice hockey. Unpublished paper. 3 pages.

Nazar, P. R. 1971. A comparison between the curved blade and straight blade hockey sticks on shooting velocity and accuracy in university varsity ice hockey players. M.A. in Physical Education, University of Minnesota. (J. F. Alexander) 143 pgs.

Norman, R. 1975. Presentation of previous studies on the slap shot. University of Waterloo.

Roy, B. and Delisle, G. 1984. Caracteristiques geometriques et dynamiques des batons de hockey en regard de leur performance. (Geometric and dynamic characteristics of hockey sticks with regard to their performance.) Canadian Journal of Applied Sport Science. 9:4 214-219.

Roy, B. and Dore, R. 1973. Kinematics of the slap shot in ice hockey as executed by players of different age classifications. Biomechanics IV-B. Proceedings of the Fourth International Congress of Biomechanics. 286-290.

Roy, B. and Dore, R. 1974. Facteurs biomecaniques caracteristiques des differents types de lacers au hockey sur glace. (Biomechanical factors of the different types of shots in ice hockey.) Mouvement 9: 169-175.

Roy, B. and Dore, R. 1974. Incidence des caracteristiques des batons de hockeys sur l'efficacite gestuelle des lancers. (Influence of hockey stick characteristics on the efficiency of shots.) Procedures of the 1st Annual Meeting, Canadian Society for Biomechanics. 1: 1-24.

Roy, B. and Dore, R. 1979. Caracteristiques dynamiques des batons et efficacite des tirs au hockey sur glace. (Dynamic characteristics of the stick and efficiency of shooting in ice hockey.) Canadian Journal of Applied Sport Science. 4: 1-7.

Ryan, F. 1971. Pole Vault. New York. The Viking Press.

Sims, F. H. and Chao, E. Y. 1978. Injury potential in modern ice hockey. American Journal of Sports Medicine. Volume 6: 378-384.

Sims, F. et al. 1987, January. Ice hockey injuries. American Journal of Sports Medicine. Volume 15: 1. 30-40.

Wells, K. F. and Luttgens, K. 1976. Kinesiology, scientific basis of human motion. Philadelphia: W. B. Saunders Company.