Kinematic Analysis of a Stickhandling Task in Ice Hockey and the Effect of Stick Inertial Properties

By

Robert C. Lawrie

A thesis

Submitted to McGill University

In partial fullfilment of the requirements for the degree of:

Master of Science

Department of Kinesiology and Physical Education

McGill University

Montreal, Quebec, Canada

July 2014

Acknowledgments

I'd like to take a moment to thank a few people who have had a part in this thesis. It was tougher than I ever imagined and I couldn't have done it without any of them. I'd first like to thank the three individuals who put their names behind mine from the start. Frank Cain, thank you for going out of your way to help a rinkrat scratch an item off of his personal to-do list; I owe you one big time. Dr. Owen Roberts, thank you for inspiring my curiousity and being a role model for myself and I'm sure many others. Thank you Dr. Jim Dickey for encouraging students to be inquisitive in your class and for mentioning to me that you were disappointed in me when I failed one of your midterms. Your classes are among my favourites of all time.

Next I'd like to thank all of the participants who donated their time to my data collection. Even if they don't read this, it does not diminish how important they were to the project. I'd also like to acknowledge Bauer Hockey Inc. for their generous donation of funding and materials to this project. In particular, I'd like to thank Ken Kovo and Carolyn Steele for their collaboration and ideas which went into this project.

Thank you Dr. Pearsall for affording me the opportunity to study at McGill in the ice hockey research lab; it has been the opportunity of a lifetime. Thank you for your wisdom, insight and support in completing this project. Thank you Yannick Michaud-Paquette; for being a patient teacher, helping me process my data and to develop some of the figures in this manuscript. Thank you to the undergrads (Chris, Matt, Kevin Dan and Hannah), for being eager to do all the (admittedly tedious and boring) work I asked of you.

Thanks to my friends (in no particular order) who helped me maintain an acceptable level of sanity. Thanks to Dave for being a mentor and a great friend and for the hand-me-down BBQ. Thanks to Meghan and Ryan Ouckama for your wisdom and support, and smuggling Steamwhistle into the province for me. Thanks to Marc, Leo and Phil for a few good "nioghts". Thanks to Michèle for the Big Mac delivery service, smuggling even more Steamwhistle into the province for me and all the hugs a guy could've ever needed.

The biggest thank you goes to mom and dad for all of your unconditional love and support in seeing this through. I would never have been able to do this without you. I'm spoiled to have two people who care so much for me. I hope I've made you proud.

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Abstract

Stickhandling tasks in ice hockey are varied, making quantitative analysis difficult. Thus little data concerning the kinematic movement patterns are available. This study examined one controlled task commonly used in training development (puck cycling through a "figure-8" route about two static obstacles) to address how skill level and the inertial properties of the stick might influence a repetitive stickhandling task. Twenty-seven male subjects were recruited in order to evaluate the difference between skill level and stick inertial condition. A 3D optoelectric motion capture system was used to record the movements of the puck and stick. Though two techniques were expected (a "plough-push" and "volley-and-catch" technique), four identified patterns of puck displacement (rectilinear, curvilinear and two hybrid patterns) suggested otherwise. Varsity players complete the task in 18% less time than recreational players without increased error. The largest discrepancy in completion time was in the right phase where varsity players completed the phase 25% faster. Varsity players also exhibited different forwards and backwards translation. The range of translation was similar between groups, but the puck patterns were shifted 5cm further forward for varsity players. In side-to-side movements recreational players had greater right side obstacle clearance (approximately 30%) than varsity players, which might have led to longer phase time and slower progress into the backhand phase. In addition, varsity players realized higher peak velocities and accelerations of the stick and puck. Variation in stick mass and inertial properties had a negligible effect on the gross movement patterns of the stick.

Abrégé

Tâches Stickhandling dans le hockey sur glace sont variées, et analyse quantitative difficile. Donc peu de données concernant la cinématique schémas de mouvement sont disponibles. Cette étude a examiné une étude contrôlée tâche couramment utilisé dans le cadre de la formation développement (puck cyclisme grâce à une "figure-8" route environ deux obstacles statiques) à l'adresse comment niveau de compétence et les propriétés d'inertie du bâton peut influencer un répétitif stickhandling tâche. Vingt-sept sujets masculins ont été recrutés afin d'évaluer la différence entre niveau de compétence et d'inertie stick condition. UN 3D opto-électronique motion capture system a été utilisé pour enregistrer les mouvements du puck et le bâton. Si deux techniques étaient attendus (un "la charrue-push" et "volley-et-catch " technique), quatre schémas identifiés de puck (déplacement rectiligne et curvilinéaire et deux modèles hybrides) a suggéré le contraire. Varsity joueurs terminer la tâche en 18% moins de temps que les loisirs les joueurs sans erreur accrus. Le plus grand écart de temps d'achèvement était dans la bonne phase où varsity joueurs terminé la phase 25% plus rapide. Varsity joueurs présentaient aussi différents en avant et en arrière de traduction. La gamme de services de traduction était semblable entre les groupes, mais le palet patterns ont été décalés 5cm plus loin vers l'avant pour varsity joueurs. Dans les mouvements latéraux de loisirs joueurs avaient une plus grande côté droit de franchissement d'obstacles (environ 30%) que varsity les joueurs, qui ont peut-être conduit à plus longue durée de la phase et de ralentir les progrès dans le lutrin phase. En outre, les joueurs varsity réalisé pic supérieur vitesses et accélérations du stick et puck. Variation de masse stick et propriétés d'inertie a eu un effet négligeable sur le brut schémas de mouvement du stick.

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Introduction

The game of ice hockey, in North America, is played on an enclosed ice surface measuring 200 feet in length and 85 feet in width (National Hockey League, 2010). Two teams ice six players who compete to deposit the game piece (a hockey puck) in the other team's goal. "Forwards" and "defensemen" use a stick (Figure 1; contructed of wood or fibreglass or any other material approved by the governing body) to advance the puck towards the opposing goal (Hockey Canada, 2010a; National Hockey League, 2010; USA Hockey, 2011). Gripped at the butt end and approximately midway along its length, the stick is used to control the puck during offensive (shooting), defensive (passing) and "transition" play (stickhandling, deking, etc.). The "transition" game is the most captivating of the three and superb stickhandlers can greatly increase their team's chances of winning. In 2005, the three-man shootout was introduced into the NHL rulebook. Following five minutes of overtime play, if a winning team had not been decided a best-of-three penalty shot competition would decide the winning team(SI.com, 2005). In these situations, stickhandling and puck control skills are put on display and highly advantageous to the offensive player.

It can be difficult to identify specifically what influences a player's ability to control the puck before a shot is initiated, however, the stick, being the link between player and puck, is a logical area of focus. It is subject to a number of rules and guidelines designed to prevent cheating and unfair advantages, however these rules generally only stipulate the materials and general dimensions of the stick (National Hockey League, 2010; USA Hockey, 2011). These regulations place only minimal restrictions on the depth and length of the blade and the lie, curve and face characteristics of the blade are up to the player's preference. In addition, there is no limit imposed on the gross weight and weight distribution of a stick. A select group of stick manufacturers tried taking advantage of this leniency and offer sticks with this in mind. For example, Easton offered Focus Weight Technology (FWT) in high end stick models (Easton Hockey, 2011a, 2011b). By placing weight at the "impact area" of the hockey stick, the company claimed the new sticks were "engineered to keep the puck on your blade to control the game" (Easton Hockey, 2011b). In addition to improved control, the technology claimed to facilitate catching "the toughest passes", "deliver more power and velocity" to shots and optimize balance and "swing weight" with the use of custom-weighted end caps (Easton Hockey, 2011b). The exact advantage gained from alterations of any of the unregulated stick parameters on transition skills has not been previously evaluated quantitatively. The lack of experimentation and knowledge of the outcomes associated with such stick alterations make it difficult to review the effectiveness of the manipulations to the unregulated parameters.

Rationale for Study

The amount of research dedicated to "transition game" (i.e. stickhandling) skills is minimal compared to shooting skills such as the slap shot or wrist shot. Quantitative descriptions of sticks and stick tasks have focused on shooting with little attention paid to passing or puck handling (Pearsall, 2000). On-ice stickhandling performance can be influenced by numerous properties of the stick including blade pattern, shaft angle, shaft texture, taping, cross-sectional geometry and weight. The investigation of shooting tasks with respect to the properties of the stick has yielded only marginal evidence that any given stick can offer improved performance over another. While mechanical property test have demonstrated an advantage, shooting research has yielded little evidence that high end composite sticks improve the shot performance of any given player compared to wooden sticks (Lomond, Turcotte, & Pearsall, 2007; Michaud-Paquette, Pearsall, & Turcotte, 2009; Pearsall, Montgomery, Rothsching, & Turcotte, 1999; Woo, Loh, Turcotte, & Pearsall, 2004). Most studies specifically related to ice hockey indicate, that while the stick has an influence on skill execution, human factors have an equal if not larger influence as well.

One particular study has investigated how certain properties of the hockey stick can affect its usage. Hove and his colleagues assessed how the haptically-perceived inertial properties of a stick influenced choice for different game-like tasks (Hove, Riley, & Shockley, 2006). In the first experiment of the study, naïve subjects (no hockey knowledge) who only had the opportunity to hold the stick in their hands rated the usability of hockey sticks for a power task (i.e. slap shot) and a precision task (i.e. puck interception or "pass catching"). Haptically perceived inertial properties were manipulated by affixing weight to three locations on the shaft of the stick; either at the distal end, in the middle or at the proximal (butt) end. The results of the experiment found naïve subjects could perceive the differences in each stick when given the opportunity to hold them. Distal weighted sticks were deemed to be best for power and proximal weighted sticks best for precision. After having the opportunity to use the sticks, the numerical ratings changed but the rating trends from the first part of the experiment stayed consistent. Expert subjects rated the usability of the same sticks differently than naïve subjects. They deemed the proximally-weighted stick to be more appropriate for both the power and interception manoeuvres. When asked to clarify their ratings, they cited a preference for a stick that felt the lightest because it would be most appropriate for stickhandling; a task the researchers had not considered in their experimental design. The second most important factor cited by expert players in choosing sticks for power or precision tasks was shaft "flex". Presumably this was due to their hockey knowledge. Easton only offered Focus Weight Technology in high end sticks which does not align with Hove's finding that expert players prefer an overall lighter-feeling stick. This conundrum has sparked an interest to investigate the effects of adding weight to the blade of the stick.

To my knowledge, there is no available data concerning the 3D kinematic variables during stickhandling tasks in ice hockey. As alluded to, the investigation of transition skills is novel with the majority of research having been focussed on the more spectacular and consequential task of shooting. The specifics of puck control need to be clarified to complete our collective knowledge of the game of hockey.

Objectives and Hypotheses

There are three major objectives of this research project. The primary objective of this experiment is to evaluate the effect of player skill on stick motion with respect to time during a repetitive “figure-8” stickhandling task. In addition to evaluating peak excursion, velocity and acceleration of the stick and puck, the absolute and normalized timing of these peaks will also be assessed. Furthermore, this will provide a basic quantitative description of the stickhandling task. The secondary objective of the experiment will be to investigate the effect that changing the inertial properties of the stick has on the same repetitive stickhandling task; to accomplish this, mass will be added to the stick in order to change the location of the centre of mass (CoM). Finally, this experiment will investigate if there is a relationship between skill level and inertial properties of the stick. This study is the first of its kind and the research will explore the basic observable stick motion during a repetitive stickhandling task and provide a base of knowledge for future studies to grow upon. Because this research is novel, hypotheses have been formulated with limited insight gleaned from previous scientific research.

As with any skill-based research, I presume that the more skilled athletes will be more proficient in task execution than less skilled athletes. I surmise that skilled athletes will complete the experimental task committing fewer corrective maneuvers, errors and outright failures.

The control outcome of a skilled athlete is greater than that of a novice. Because stickhandling proficiency is going to be rated on scales of speed and accuracy, I expect skilled athletes to show less linear displacement (stick and puck in x-, y- and z- directions) and complete the task in less absolute time compared to unskilled athletes. We anticipate two major techniques to emerge as a result of these differences; a “plough-push” (PP) and a “volley-and-catch” (VAC) technique. The PP technique would be primarily exhibited by the recreational players with the puck almost perfectly matching the displacement, velocity and acceleration of the stick. The VAC technique would be primarily exhibited by varsity players with the puck being less coordinated with the velocity and acceleration of the stick. With respect to linear velocity and acceleration (stick and puck in the x-, y- and z-directions), it is expected that high calibre players will exhibit larger peaks in the variables.

Furthermore, I expect to find differences in the normalized timing of all monitored events to corroborate our expectations in a difference in style between varsity and recreational players. In an absolute time frame I expect to find a disparity when the monitored events occur; the timing of all the important events will occur absolutely sooner when a varsity player completes the task.

I expect that the changes in the inertial properties of the stick will exert a meaningful effect on the completion of the task. I hypothesize that ability to control the puck will diminish as the accessory mass moves away from the butt end of the stick causing larger displacements, velocity and acceleration peaks as the subject attempts to maintain their level of performance. I believe that the temporal relationships will grow longer in duration as the accessory mass moves away from the butt end of the stick.

Limitations and Delimitations of the Study

The following is a list of limitations that are associated with the current in-lab testing protocol

1. In the current experiment, the experimental protocol took place on an artificial (polyethylene; by Viking®) ice surface which mimics real ice. A silicon spray can be applied to lubricate the surface and minimize the coefficient of friction
2. All materials (sticks and pucks) were stored and used at room temperature (20^{o}-23^{o}C)
3. To make it possible to accurately place the retro reflective markers skates were the only hockey equipment worn by subjects during testing
4. The figure-8 pattern might not be truly indicative of an in-game manoeuvre

In order to limit variance to reasonable levels the current study was subject to the following delimitations:

1. Sticks differed only in the location of externally applied weights
2. Subjects fell within a specific range of heights so that sticks were of appropriate length
3. Subject's feet remained stationary while performing the task
4. The same set of instructions was read to each subject
5. The distance between the obstacles was normalized with respect to each subject's height
6. Subjects wore their own skates

Operational Definitions

The following list is a summary of acronyms that are used commonly throughout this paper:

1. CoM – Centre of mass
2. NHL – National Hockey League

3. fhx – forehand cross (phase)
4. bhx – backhand cross (phase)

The following list is a summary of specific terminology and language used in this paper:

Stick (shaft) Specific Descriptors

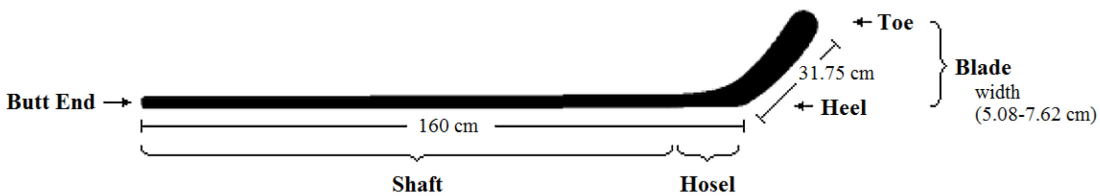

Figure 1. The parts of a hockey stick. Labelled are the important parts and their maximum acceptable dimensions allowed by the NHL

1. Butt end: The top end of the (shaft of the) hockey stick.
2. Shaft: The long, straight, uniformly rectangular section of a hockey stick gripped by the player. Hockey Canada and NHL regulations stipulate that the stick be no longer than 160 cm (63 inches) from the heel of the blade to the butt end (note: this length measurements includes the hosel) (National Hockey League 2010; Hockey Canada 2010a).
3. Hosel: The tapered portion of the hockey stick which connects the shaft with the blade.
4. Blade: Opposite the butt end, the player uses it to control the puck during game play. A left-handed blade curves right when the stick is gripped at the butt end and held out in front of the player and vice versa. The blade may be no more than 31.75 cm from heel to toe (12 inches). The broad face of the blade may be no more than 7.62 cm (3 inches) wide and no less than 5.08 cm (2 inches) wide. (Hockey Canada, 2010a; National Hockey League, 2010; USA Hockey, 2011).
5. Flex: Referring to the stiffness of the shaft. Technically, it is the amount of force that is required to deflect the shaft by one inch in a laboratory 3-point bend test

Stick (blade) Specific Descriptors

6. Lie (blade angle): The angle between the long axes of the shaft and the blade. Lie angles are rated numerically between 4 and 8. A lie 4 represents an angle of 136.5^{o} and each whole number increase indicates a decrease of 1.5^{o} (lie 5 equates to an angle of 135^{o}, and so on) (Magee, 2009).
7. Curve: Denotes where the curvature in the blade is concentrated. A heel curve curves gradually from heel to toe. A mid curve means the blade is straight until midway along its length. A toe curve means the blade is mostly straight, beginning to curve approximately 2/3 of the way from the heel to the toe.
8. Face (face angle): The angle between the face of the blade and the shaft of the stick. A neutral face indicates no difference in angle. An open face indicates the blade is positioned at a reclined angle relative to the shaft (like a wedge style golf club).

Specific Stick Motion Descriptors

9. Figure-8: A movement having the shape of the number or digit eight
10. Correction: An event during a trial (as a result of the test participant's own actions) which required a noticeable deviation in the path of the puck and stick to maintain continuous motion
11. Error: An event during a trial (as a result of the test participant's own actions) which halted the continuous motion of the puck (i.e. the puck came to an unintentional rest)
12. Failure: An occurrence of a subject being unable to complete a full trial as a result of his own actions

Review of Literature

Stickhandling is an essential hockey skill for the strategic need to maintain puck possession (Pearsall, 2000) and is primarily heuristically learned. The mechanics of this skill are difficult to generalize due to the substantial movement variability and dynamic, multi-player game contexts. To better understand this skill's mechanics, quantification of the typical spatial and temporal movement patterns of the stick and puck is warranted.

In the following text, a review of pertinent research including topics of skill competency and performance, the relationship of tool properties and skill performance, and the nature of bimanual skills and co-ordination will be presented.

The Effect of Skill Level on Task Performance

Skill execution is crucial to performance outcome in many vocational and athletics activities. Often considered are the spatial (e.g. club maximal excursion in golf) and temporal (e.g. body segment co-ordination and/or sequential segment timing) movement patterns in relation to a meaureable outcome. In many sports, velocity and/or accuracy of projection of the token game piece (e.g. ball, puck, dart) is the main descriptor of performance; that is, the faster or more accurate these variables are, the more "skilled" the athlete is said to be. Furthermore, differences in spatial and temporal parameters of selected skills may well define the difference between recreational and elite athletes. In several sports such as golf, baseball and ice hockey, one can observe distinct kinematic differences in the body and/or game implement that are associated with more skilled performers and improved performance.

For instance, using 3D motion capture equipment, Myers and colleagues investigated the difference in swing mechanics of 100 different golfers (Myers et al., 2008). Tee shot velocity was positively associated with skill level; golfers with lower handicaps exhibit higher ball velocity (BV; BV < 58.1 m/s and a handicap of 15.1 ± 5.2 strokes compared to BV > 71.8 m/s and a handicap of 1.8 ± 3.2 strokes). Several body measures of pelvis and upper torso rotation angles revealed skill-based differences; for example, the better golfers "coiled" their body more (i.e. rotated their torso and hips further from neutral; $61.8^{o} \pm 7.8^{o}$) than lower skilled players ($45.6^{o} \pm 8.0^{o}$). Similarly, measures of club swing ranges also differentiated between lower and higher skill levels ($44.2^{o} \pm 7.7^{o}$ versus $59.1^{o} \pm 8.2^{o}$) (Myers et al., 2008). These kinematic measures may provide proxy measurement cues for training shot techniques. For example, the authors infered that the extent of separation of the torso and pelvis segments influences ball velocity; an "en bloc" swing strategy (observed in lower calibre golfers) may limit the final tee shot exit velocity.

Another example where motion analysis was used to quantify skill differences was carried out by Lopez De Subijana and her colleagues who studied field hockey players during drag-flick penalty corner shots (López De Subijana, Juárez, Mallo, & Navarro, 2010). For this specific skill, expert players used a smaller range of motion than the novice group. For example, foot-to-ball and drag distances were significantly shorter in the expert than the novice player (1.18 ± 0.07 versus 1.38 ± 0.16 m / body height). Conversely, experts showed greater knee start angles than novice players (165 ± 1.7^{o} versus 156 ± 7.6^{o}). Skill based timing differences were also noted. In addition to a difference in the sequence of events, when expressed as ratio of the total time of skill execution, the difference in timng of those events were no less than less 2.6% (López De Subijana et al., 2010). Again, these quantitative measures may infer meaningful technique differences that can be used to guide player development.

Temporal measures may be more relevant than spatial in distinguishing skill level differences. For example, in Shaffer and colleagues' study of swing patterns of baseball batters using surface electromyography (sEMG) they noted that the swing of an elite batter relied on "a co-ordinated transfer of muscle activity from the lower extremities to the trunk and finally to the upper extremity" (Shaffer, Jobe, Pink, & Perry, 1993). This led to shorter completion times (and thus greater segment velocities), culminating in faster bat speed and ball projection velocity.

In the game of ice hockey, several studies have detailed kinematic analyses of shooting tasks. For instance, Wu and colleagues examined the kinematic differences between skill levels in terms of stick movement and deformation during slap and wrist shots (Wu et al., 2003). Using end puck velocity as a descriptor of performance, two key spatial parameters showed substantial (skill level) differences: peak shaft angular and linear deflection. Both of these measures were shown to be strongly correlated to puck velocity (e.g. $r = 0.80$ when using angular or linear shaft deflection to explain puck velocity).

In a separate experiment using 3D electromagnetic sensors (Polhemus Motion Tracking) Woo and colleagues evaluated skill level, body kinematic differences during slap shots (Woo et al., 2004). Skilled players demonstrated a proximal to distal sequence in upper limb joint peak angular velocities. Both skill groups showed similar angular stick downswing velocities; however, skilled players also displayed greater linear stroke movement. Similar findings were reported by Lomond and colleagues using multiple high speed cameras to analyze the 3D kinematics of slap shot technique of skilled and unskilled shooters (Lomond et al., 2007). They reported no skill differences during initial downswing and stick-ground contact; however, at the end of ground contact, skilled players had 15 cm greater forward displacement and velocity (27.5 ± 4.3m/s versus unskilled 15.1 ± 6.2 m/s).

In terms of shot accuracy, Magee examined the kinematic characteristics of the stick and shooter's body across skill levels during stationary wrist shots. Significant differences in joint and segment angles were observed at the trailing ankle, trailing knee, trailing hip, trunk, lead shoulder, lead elbow and lead forearm pronation-supination across skill level (Magee, 2009). Regression analysis of these kinematic variables accounted for 61.3% to 97.7% of the variation in shooting accuracy. For example, an elite subject shooting at the bottom-contralateral corner of the net exhibits 30° less pronation and 12° increased lead wrist flexion/extension range of motion. Again, though a direct causal relationship cannot be directly attributed to kinematic differences, these latter measures may provide meaningful cues for improving the training of shot techniques.

The Effect of Tool Properties on Task Performance

From the above, kinematic measures of the player's body and sport-specific equipment (e.g club, bat, stick) were shown to relate to skill technique and performance. Performance is dependent on interplay between the player's technique and the tool's mechanical properties. With regards to the latter, much attention has been focused on incorporating new materials, construction and manufacturing methods in sport equipment. To what extent the sport tool's physical properties have on performance outcomes is often not self-evident. What determines the optimal physical properties depends much on the interaction with the user. The physical dimensions and weight of the equipment (e.g. mass, center of mass, stiffness, elasticity, harmonic vibrations frequencies, "sweet spots") are crucial when the equipment extends the reach of the upper limb to execute the task.

In a series of experiments, Bongers, Smitsman and Michaels demonstrated that tactile perceptions of a rod's (tool's) physical properties can determine how it is used for a reaching task (Bongers, Smitsman, & Michaels, 2003). In the first subset of experiments the length, homogeneous mass and mass distribution of a tool were assessed for the effect each had on the organization of the bodily “action system”. Presumably, adding a tool to any action system would lead to a change in the functional effectivities since the specific properties of the tool would require postural adjustments within the body-tool system (Bongers, Michaels, & Smitsman, 2004; Bongers et al., 2003). The specific task was to displace an object resting on a table using one of several tools. When mass was manipulated, tools were visually identical to one another. It was assumed that changes would manifest themselves in the selected distance to the table and the body posture at the time of contact between tool and object (Bongers et al., 2003). In summary, participants were highly sensitive to the length of the tool and moderately effected by the mass.

These authors also examined whether changing the position of a rod’s center of mass would perturb the weildability of the rod (Bongers et al., 2003). In theory, shifting a rod’s center of mass may alter the magnitude of the hand torques required for the task and lead to postural or movement adaptations to effectively maneuver the rod. A more distal rod center of mass resulted in subjects stopping further from the target and increased the variance of postural adaptations. Furthermore, the authors assert that “elbow adjustments were similar for both heavier rods and rods with mass in the tip, whereas the chosen distance was adapted differently for those two rod types” (Bongers et al., 2003).

In a subsequent experiment, the researchers manipulated the accuracy demand of the task. Specifically, the participants were required to use a tool to move an object of variable size. The authors suggested that the haptic perceptions of the tool would influence the subject’s motor control patterns (Bongers et al., 2004). Object size and rod center of mass location had a statistically significant level of interaction. When the object was reduced in size or when the rod had less rotational inertia subjects substantially modified their posture. This study demonstrated that the haptically-perceived properties of the tool influence its use. Indeed, this latter finding has been confirmed in the context of ice hockey sticks. Hove and colleagues demonstrated that differences in a tool's haptic properties could be detected (even by unskilled users) and that those properties guided the perceived utility of the tool (Hove et al., 2006).

Haptic and visual perceptions of a tool's physical properties often interact. Vision provides inferred "prior" expectations about a tool's physical properties, and tactile proprioceptive afferents help to modulate those a priori motor control and movement patterns. To examine the effects that tactile receptors have on movement, dextrous movements have been studied.

Several experiments by Johansson and colleagues have investigated the direct effect that haptic perceptions have on motor control. In one experiment, subjects grasped objects with a pinch grip and performed a lift-hold-replace protocol while the coefficient of friction of the object was manipulated (Johansson & Westling, 1984). Paired strain gauges were used to measure the pinching (grip) force and vertical lifting force (load force) applied to the object during each action phase and an ultrasonic device gathered real-time position data from the object (Johansson & Westling, 1984, 1987). They observed that the grip force and the rate of change of grip force was principally effected by the frictional properties of the material in contact with the skin during the preloading and loading phases (Johansson & Westling, 1984). Motor commands to lift the object were released once tactile signals verified appropriate contact had been made between the fingers and the object (Johansson & Westling, 1984, 1987). Furthermore, grip force was not only adapted to the frictional demands of the surface but remained consistent even when the mass of the load increased. That is, the size and variability of a lifting “safety margin” were consistent across the different surface structures and different loads (Johansson & Westling, 1984).

Bimanual Skills and Neural Co-ordination

Co-ordinating two hands is essential in ice hockey because the basic skills of the game require the use of both limbs simultaneously. Each hand has a different but complementary role. Bimanual tasks are context dependent and exhibit a high degree of modularity (Swinnen & Wenderoth, 2004). The movements of the hands are constrained in two ways. Firstly, by “hard constraints”; the intrinsic properties and limits of the musculoskeletal system (i.e. the effectivities) that directly affect the task (Summers, 2002). And secondly, by “soft constraints”, or in other words the co-ordination tendencies of each limb (i.e. the neural activation patterns) (Summers, 2002). Of particular importance with respect to neural activation is neural crosstalk. Neural crosstalk is the “leakage” that contaminates motor patterns of one limb when multiple segments are activated at the same time (Swinnen & Wenderoth, 2004). Soft constraints are present at different loci (e.g. cortical, spinal) within the CNS (Swinnen & Wenderoth, 2004). Tasks are completed most successfully when neural interference can be effectively suppressed and the task occurs within and optimal range of the effectivities (i.e. when soft and hard constraints are well aligned for movement).

The better that hard and soft constraints align, the more stable and accurate the observable movement will be (Swinnen & Wenderoth, 2004). To illustrate what is meant by this, consider an in-phase and anti-phase movement. That is one where homologous muscle groups in each arm are activated (in-phase activation) and one where non-homologous muscle groups are activated (anti-phase activation) (Summers, 2002). The specific case to consider is one where in-phase activation produces symmetrical movement of the hands in opposite directions (i.e. concurrent supination of both hands) and anti-phase activation produces symmetrical movement of the hands in the same direction (i.e. concurrent pronation and supination) (Temprado, Chardenon, & Laurent, 2001). At slow speeds, both patterns can be reproduced accurately with high levels of stability, but as the speed (frequency) of movement increases, the anti-phase pattern transitions to an in-phase pattern (Swinnen & Wenderoth, 2004; Temprado et al., 2001). The observed "phase wander" (Carson, Chua, Byblow, Poon, & Smethurst, 1999) is thought to emerge when constraints on movement align better during the in-phase motion than the anti-phase motion (Swinnen & Wenderoth, 2004). While the task (or hard constraint) is relatively simple and stable for each scenario, neural activation (or soft constraints) of the same muscle groups to produce opposing motion is more stable than activating antagonistic ones. Morrison and his colleagues suggested that the magnetic attraction between limbs was achieved through common efferent output to both limbs which reduces the overall incidence of neural crosstalk (Morrison, Hong, & Newell, 2009).

On the continuum of movement stability, in-phase movements do not represent the top end of the spectrum. Phase wander is also observed when the frequency of movement is increased (Carson et al., 1999). It has been documented that when bimanual rhythmic movements (voluntary) approach the ceiling frequency (for movement) in-phase patterns deteriorate to an asymmetric pattern of movement where the dominant limb becomes primarily active (Morrison et al., 2009). Morrison used a timed clapping task to demonstrate this phenomenon. By concurrently collecting EMG and kinematic data while subjects clapped at a consistently increasing frequency (1 Hz which eventually increased to 15 Hz over a 10 second interval), in-phase bimanual tasks broke down (Morrison et al., 2009). They found that muscular co-activation was greater at the end of each trial as well as in the non-preferred limb. The authors assert that at the ceiling clapping frequency (6.92 Hz ± 0.56Hz) the motion of the non-preferred limb was effectively halted while the preferred limb sustained the maximal movement frequency (Morrison et al., 2009). It has been shown that with extensive practice individuals become more adept at maintaining complex patterns of movement at higher speeds. For example, expert musicians exhibit less entrainment and magnetic attraction between limbs when performing complex bimanual tapping patterns (Summers, 2002).

It is imperative that hard and soft constraints align well if a movement is to be automatic, repeatable and long lived. Constraints on the movement of the hands with respect to each other as well as independently must be different between elite and recreational level players if they exhibit different patterns of execution. Since the grip dimensions on the stick are universal and there are no alternate grip patterns, all players regardless of skill level are subject to the same hard constraints on the task. Presumably, due to extensive training, skilled hockey players can complete the task more deftly than unskilled players because of improved command over soft constraints that impinge on the task.

Methods

Within this section the methods will be presented. The subjects, sticks, mass and center of mass configurations to be tested, as well as the motion capture procedures, task definition, testing protocol, data analysis and dependent variable extraction will be described.

Sticks

Stock (150cm butt-heel length), senior-sized, one-piece, carbon fibre Bauer® (St. Jerome, Quebec, Canada) One100 hockey sticks (weight: 445g) were tested. A medium length blade with blade pattern P88 (rounded toe profile, slight-open face with mid curve inflection point) and lie 6 was used. Sticks were matte finish to minimize unwanted reflections that would interfere with accurate data collection. Four different stick conditions were used in this study: one unaltered control stick (cont), one stick weighted at the centre of balance (CoM), one stick weighted distally to the centre of balance (i.e. towards the blade of the stick; named 'dist') and one stick weighted proximally to the centre of balance (named 'prox'). A large butterfly-style paperclip was used to attach a 50g accessory mass to the shaft in order to create each of the weighted (inertial) conditions (figure 2).

Table 1: Stick inertial properties

Stick	Location of centre of balance (cm from butt)	Percent change in centre of balance from 'cont'	moment of inertia (kg*m^2)	percent change in MOI from 'cont'	percent change in MOI from 'CoM'
Cont	106		0.0050000		-10.10%
Prox	99	-7.00%	0.0048515	-2.97%	-12.77%
CoM	106	0.00%	0.0055618	11.24%	
Dist	111	5.00%	0.0060989	21.98%	9.66%

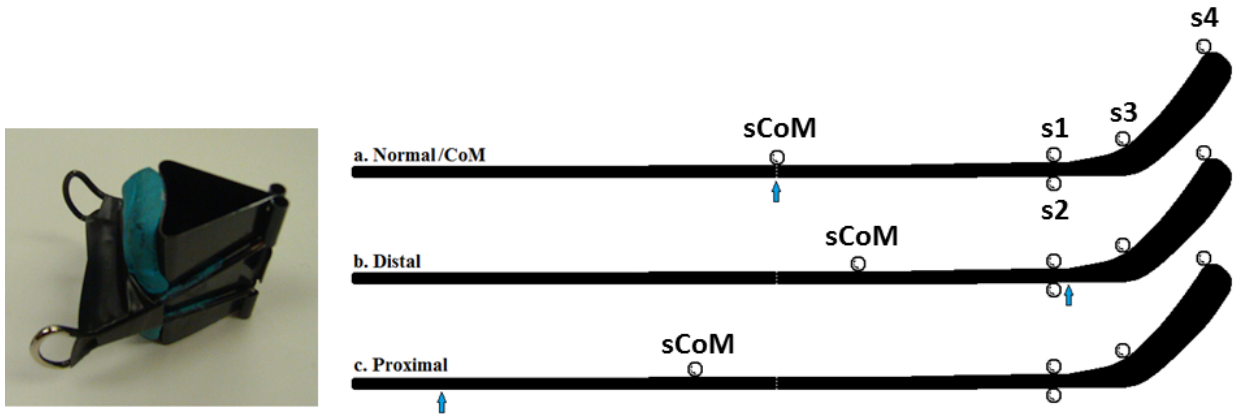

Figure 2. At left: Accessory mass. At right: The marker arrangement of each stick condition; the blue arrows indicate the location where the accessory mass was affixed the CoM, prox, and dist conditions.

All sticks had a tape grip with the same pattern, ending 15cm from the butt-end of the shaft. The blade of the stick was taped from toe to heel leaving one half inch of the blade tip exposed.

Subjects

Two groups of male subjects were recruited: high-calibre (varsity, n = 13) and low-calibre (recreational, n = 14) players (table 2). Thorough pilot testing identified the required sample size. Varsity players included subjects at the collegiate level (Canadian Interuniversity Sport; NCAA Division I leagues) or better (North American major junior, North American minor professional or North American major professional leagues) and were not more than 2 years removed from active competition. Subjects included in the recreational division were players with functional hockey knowledge and may have played organized minor hockey.

Table 2: Average subject descriptive data

	Varstiy	Recreational
Age (years)	23.0 ± 2.2	26.9 ± 6.2
Height (m)	1.82 ± 0.04	1.83 ± 0.04
Weight (kg)	84.2 ± 7.1	86.4 ± 13.9
Playing experience (years)	17.9 ± 2.7	14.5 ± 6.8

Test Apparatus

A three dimensional motion capture system was used to quantify the stick and puck movement created by each subject. The test protocol was carried out in a laboratory setting on a Viking® artificial ice surface (Wilsonville, OR, USA) measuring 9.12 m by 5.70 m. The active capture area measured 2.60 m by 2.60 m (figure 3). Eight (8) Vicon® MX3+ (Vicon®, Oxford, UK) cameras were positioned about the capture area. Recording frame rate was maintained at 240Hz (as determined through thorough pilot testing). The Vicon® Nexus (v1.8.2) software interface mediated the operation of the cameras.

The spatial movement patterns of 16 retro-reflective marker spheres (14 mm diameter) were dynamically recorded in each trial (figure 4). These markers included: one (1) puck marker, two (2) obstacle markers, five (5) stick markers, a single marker on the back of each hand and three (3) markers to define each foot (as in the Vicon® Plug-in-Gait model) (figure 4).

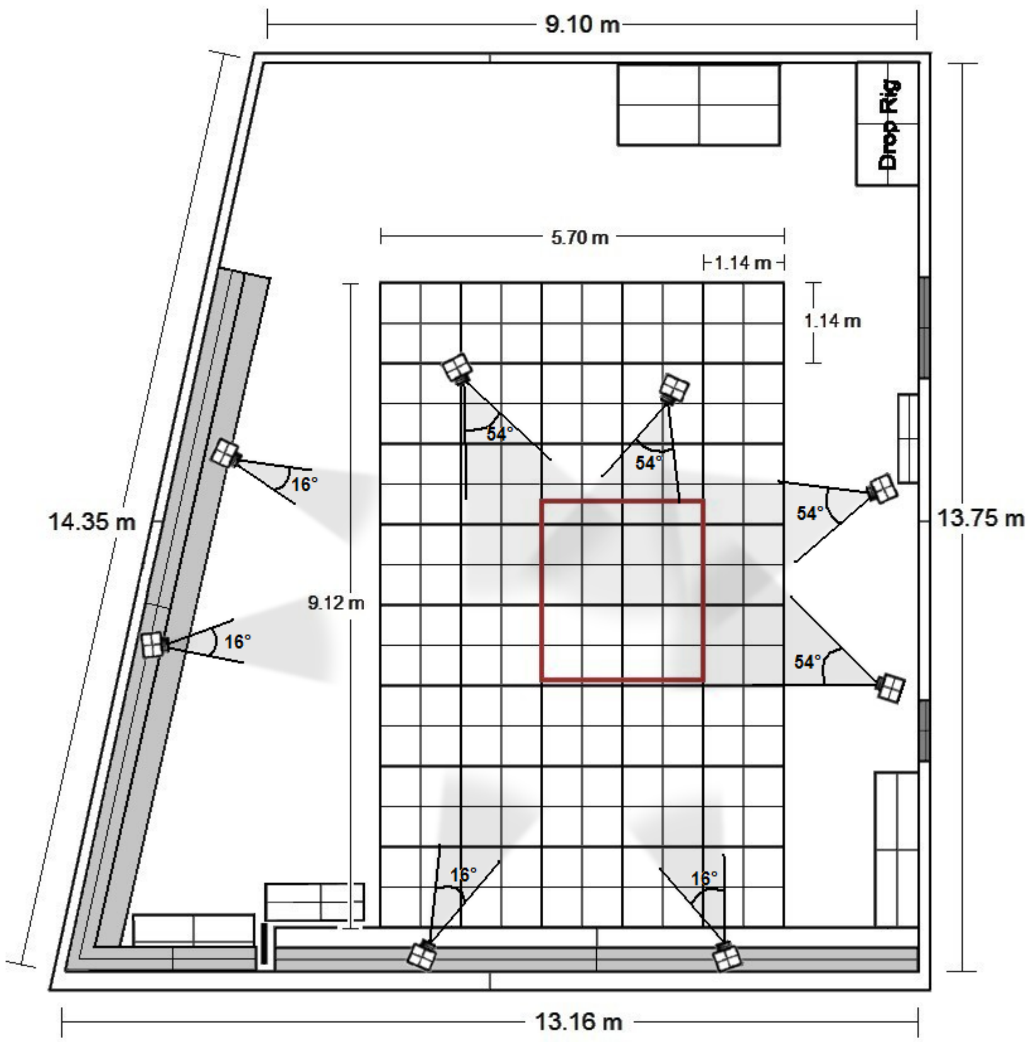

Figure 3. An overhead schematic of the capture area with camera locations and view angles noted. The red square indicates the location of the active capture area.

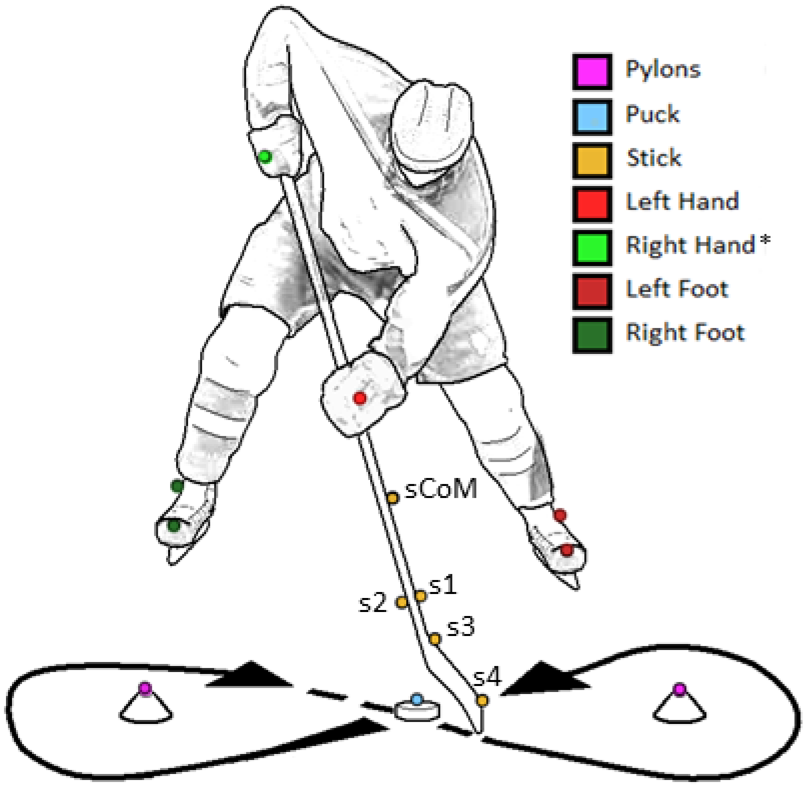

Figure 4. The locations of the retroreflective markers on the subject, stick, puck and pylons. Not shown are the heel markers on the heel of each skate. NB: skates were the only hockey specific equipment worn during each trial. *In the case of a left hand shooter (pictured above) the right hand marker was considered to represent the butt of the stick

Two markers 's1' and 's2' were attached to the shaft at the top of the hosel (figure 4). While a third marker 's3' was placed at the inflection point between the hosel and the blade of the stick (figure 5).

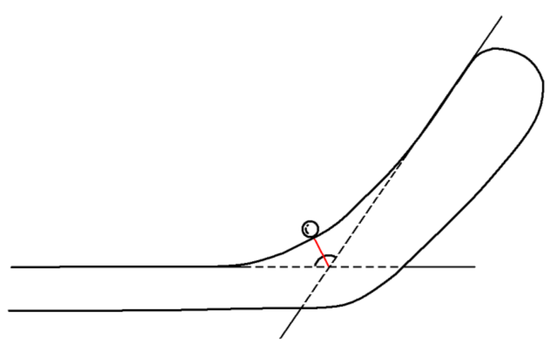

Figure 5. Stick marker s3 location: crux mid-point on top of shaft-blade lie angle.

The fourth marker ('s4') was placed on the toe of the blade. Finally, one marker was placed at the stick's balance point ('scom'). In the case of the 'dist' and 'prox' sticks, the scom marker was placed at the balance point when the mass was affixed. These locations were 6 cm below the unweighted balance point and 7 cm above the unweighted balance point respectively (figure 2).

Protocol

Pre-experimental Measurements

Informed consent was obtained from each subject prior to data collection. Upon giving consent, subject descriptive information was obtained: age, shot preference, preferred stick length (in metres), preferred player position (Forward Center, Forward Left Wing, Forward Right Wing, Defence), skill level, competitive experience (in years) and laterality (as determined using a modified version of the Cambridge Handedness Questionnaire) (Appendix A).

Equipment Calibration

Prior to each testing session, the Vicon® MX3+ cameras were aimed at the active capture area and calibrated using the Vicon® Nexus (v1.8.2) software interface. The residual error was set at less than 0.2 mm.

Experimental Task

In 1999, Hockey Canada introduced a skill testing program consisting of six standardized test stations. A modified version of the stickhandling aptitude test (station four) is the experimental task tested in this study (Hockey Canada, 2010b). Subjects are required to guide a puck around two stationary obstacles as quickly as possible without loss of control of the puck or hitting either obstacle (i.e. without sacrificing accuracy). In this study, the subjects were instructed to "navigate a puck through a figure-8 circuit five consecutive times as quickly and accurately as possible". Trials started with the puck centered between the obstacles. The trial began with the subject standing in a "game-ready" stance, centered in and square to the obstacle plane, with his stick on the ice surface beside the puck. During each trial the subject was permitted to pivot about their toes but not to lift their feet off the surface. Left-handed shooters guided the puck from the centre of two obstacles around the right hand obstacle crossing over the starting point before going around the left hand obstacle and returning back to the starting point (figure 4). Right handed shooters proceeded in the opposite direction. A trial ended when the puck was returned to its starting point after 5 loops. Distance between obstacles was normalized to 2/3 of the subject's height. For example, a 183 cm (6 ft) tall subject would have to navigate obstacles 122 cm (4 ft) apart. Subjects wore their personal skates during testing. Skates and the stick were the only hockey-specific equipment used by the subject in each trial.

Stick order was randomized order for each subject. Subjects were encouraged to practice stickhandling on the surface before data collection began. Subjects were required to practice for no less than 2 minutes or until they were comfortable with the ice surface. For each of the four stick conditions three successful trials were collected. A successful trial was not necessarily an error free trial; if the subject needed to modify the path of the puck to avoid an obstacle it was noted that a correction was required and if the puck stooped motion but a loop could still be completed it was noted that an error had occured. A trial was considered failed for one of the following reasons: 1) The stick or puck made contact with either obstacle; 2) the subject lost control such that he could not continue without moving his feet to retrieve an errant puck; or 3) the played puck flipped over such that the retro-reflective marker was not visible to the cameras.

Data Processing

Several steps were required to process the captured data. First, data was reconstructed and auto-labelled in Vicon® Nexus (v1.8.2) and then inspected to ensure accurate marker identification with ViconiQ 2.5® software. Data was then exported to MATLAB (vR2012a) routines to obtain kinematics data for each marker. Raw data was filtered using a Butterworth (4^{th} order) filter with a cutoff frequency of 8Hz. Then data for the right handed (shot) players was mirrored to appear as a left handed player. Each of the five loops were divided into four time phases: forehand, right, backhand and left (figure 6; figure 9) by puck position about the loop. First and fifth loop trials were discarded due to starting and stoping anomalies.

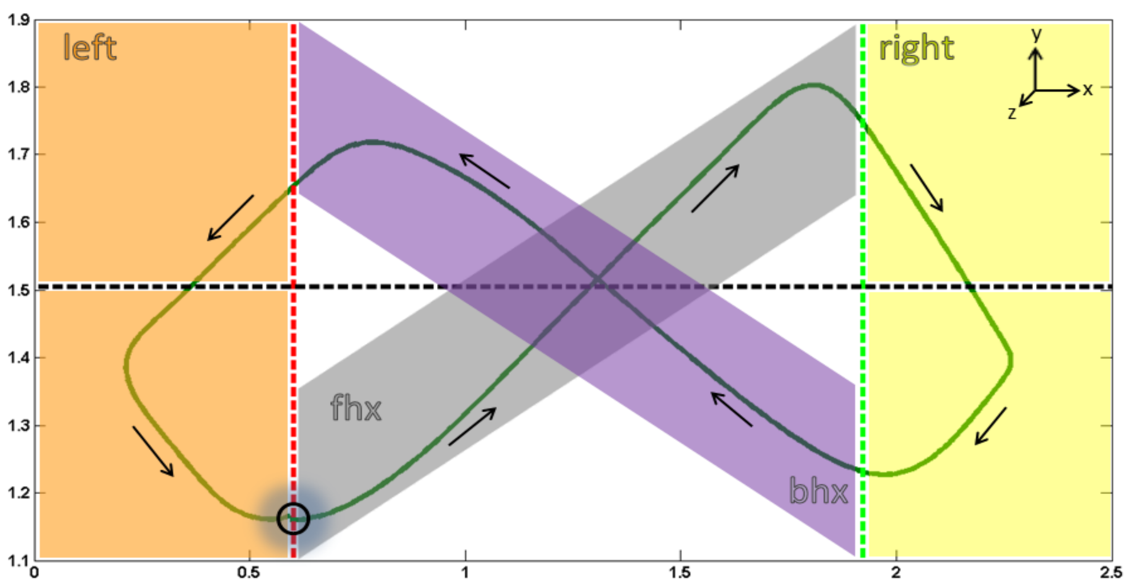

Figure 6. Overhead view showing the path the puck traced out on the floor. The black circle found at the left-fhx phase transition indicates the functional starting and finishing point of a loop. The intersections of the red and black, and green and black dotted lines are the locations of the obstacles. Distances are in metres.

Displacement of two stick markers (s3 and butt) and the puck marker were evaluated in the x, y, and z directions (side-to-side, front-to-back, up-down, respectively). In the x-direction, maximum lateral stick and puck excursion beyond the obstacles were evaluated (figure 7; figure 9, right and left panel). In the y-direction, maximum forward and backward stick and puck excursion beyond the obstacles were evaluated (figure 7; figure 9). In terms of “minima” to describe position 3 and 4 (figure 7) the puck and s3 positions are presented as positive values. And in the z-direction maximum vertical excursion of the stick over the puck was evaluated within each of the four phases (figure 8; figure 9).

Similarly, velocity, acceleration and timing were also evaluated in the x -, y -, and z – directions (see Table 3: *Dependent and Independent Variables)*. The timing was evaluated with respect to both the phase that the peak occurred in and the entire loop in both absolute (in seconds) and normalized (percentage of completion time) frames of reference.

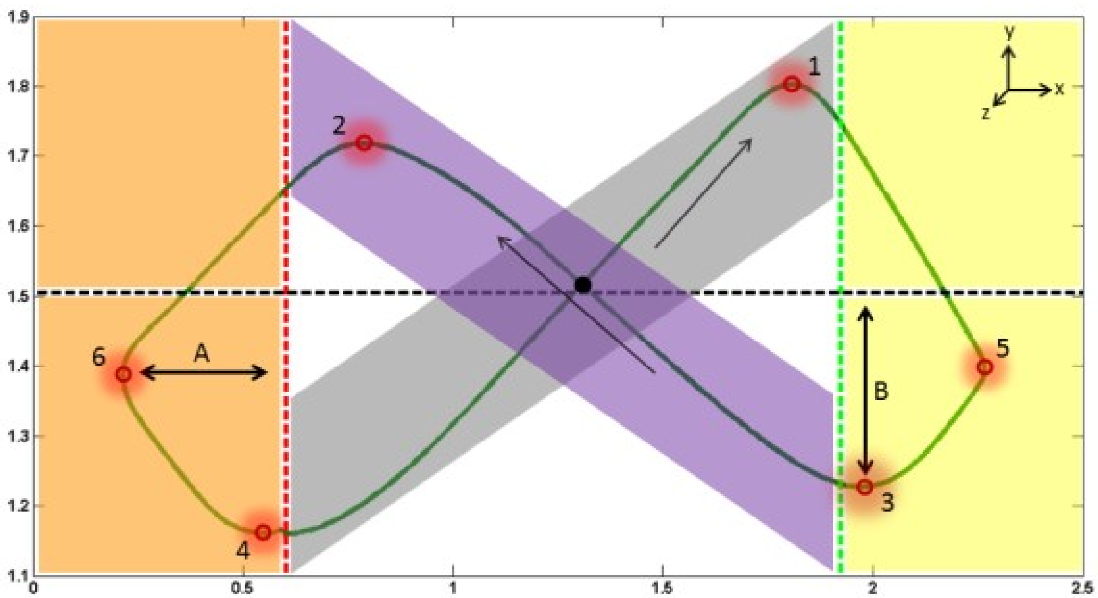

Figure 7. Overhead view of a sample trial showing the x-y displacement pattern of the puck. Peak x-excursion of the stick and puck (A) and peak y-excursions (B) were evaluated. Labels 1 to 4 indicate the right y-maximum, left y-maximum, right y-minimum, left y-minimum. Labels 5-6 indicate (in numerical order) the right x-maximum and the left x-maximum. The intersections of the red and black, and green and black dotted lines are the locations of the obstacles. Distances are in metres

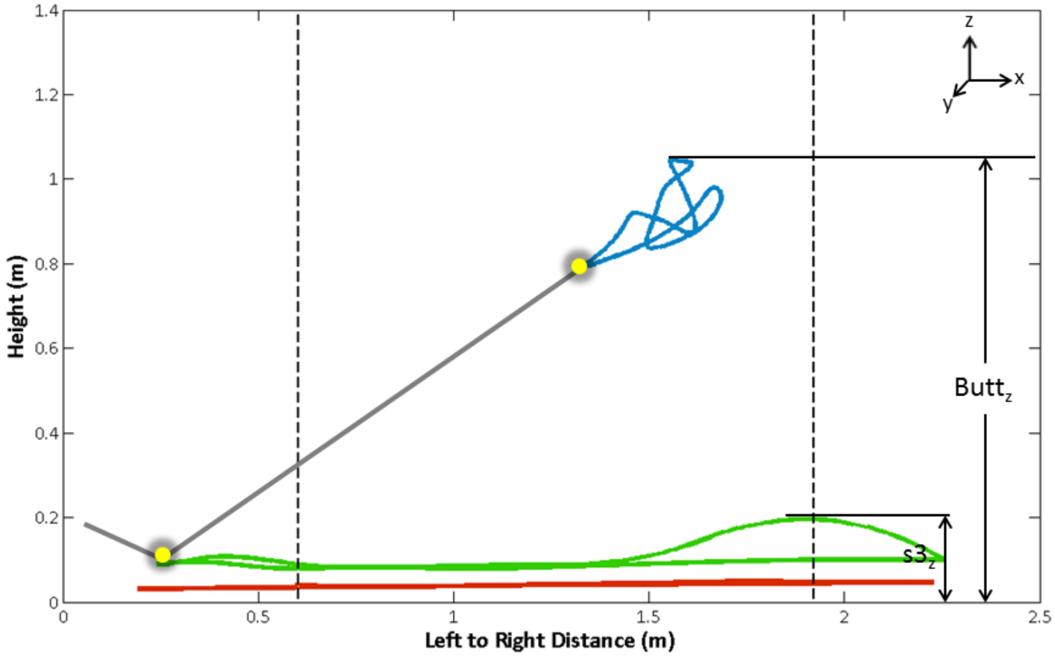

Figure 8. A sample trial (rear view) of the x-z plane (vertical-side-to-side) depicting how the vertical lifting height of the stick was determined. Maximum lifting height was recorded between stick markers (yellow dots) and the floor. Blue – path of the butt during one loop; Green – path of s3 during one loop; Red - puck

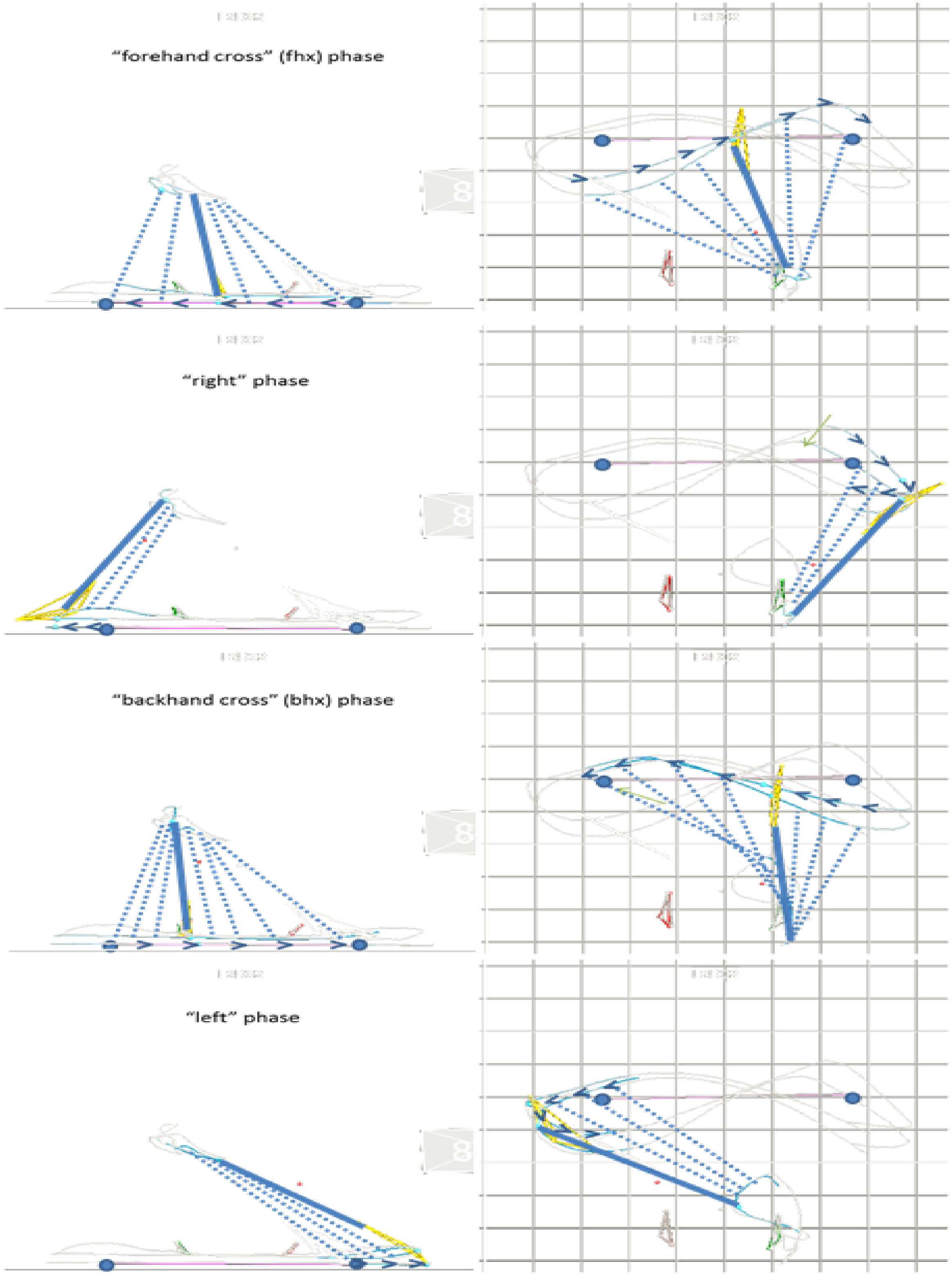

Figure 9. Each of the four consecutive phases of a sample trial (left panels: rear view; right panels: top view). Dotted lines represent successive positions of the shaft of the stick.

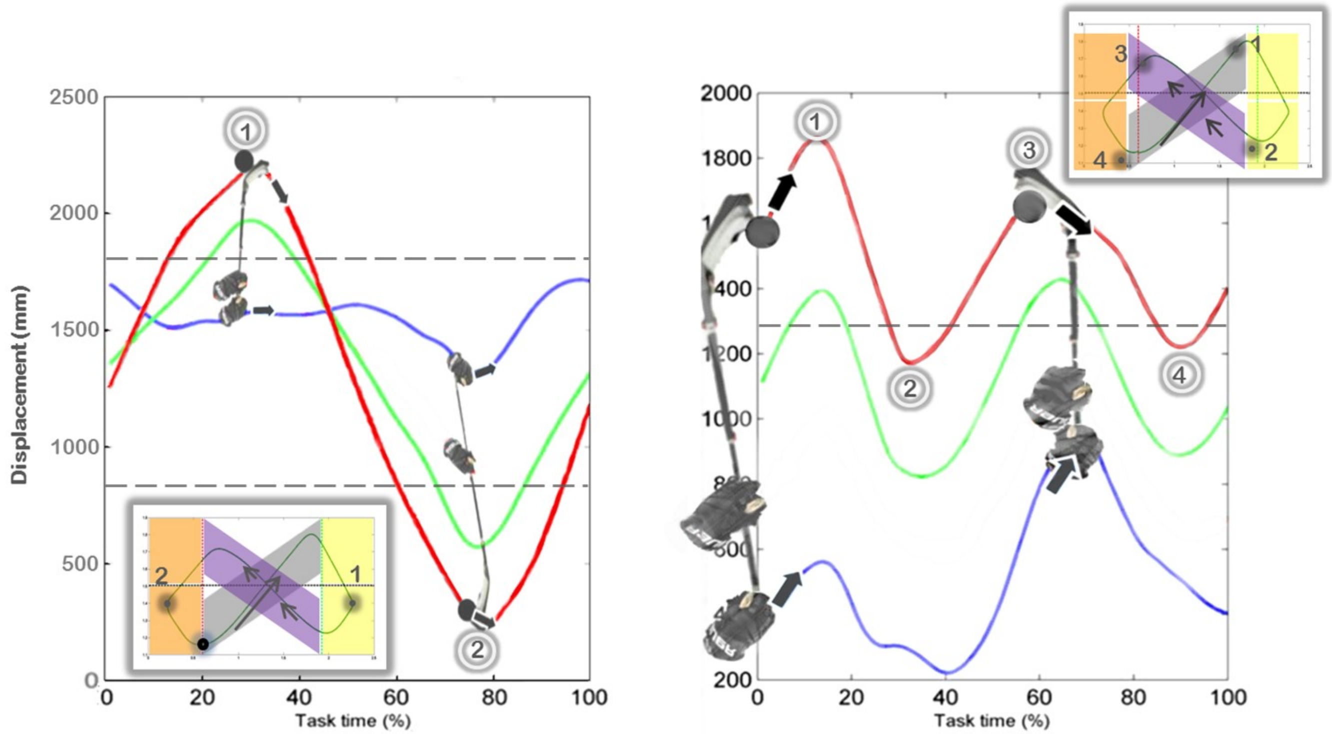

Figure 10. Sample x-displacement (left) and y-displacement (right) data diagraming the approximate paths the puck (red), s3 (green) and butt (blue) markers took during the completion of one loop. Labelled are the respective points of maximal and minimal excursion in each direction. Indicated in horizontal, black dashed lines are the approximate locations of the obstacles about which the subject guided the puck. Inset: shown are the locations about the figure-8 pattern where the points in maximal excursion were recorded

Table 3: Dependent and Independent Variables

		Specific descriptor		
Independent Variables				
	Calibre	High, Low		
	Stick	Control, CoM, Prox, Dist		
Dependent variables				
		directions:	with respect to:	
Task Proficiency	**Corrections**	N/A	total number, number per loop and number per trial	
	Errors	N/A		
	Failures	N/A		
Blade (crux)	**Displacement**	x, y, z	peak magnitude, normalized timing (@ peak magnitude) and absolute timing (@ peak	**Mean ± SD**
	Velocity	x, y, z		**Mean ±**

			magnitude)	SD
	Acceleration	x, y, z		Mean ± SD

	Displacement	x, y, z	peak magnitude, normalized timing (@ peak magnitude) and absolute timing (@ peak magnitude)	Mean ± SD
Shaft (butt)	Velocity	x, y, z		Mean ± SD
	Acceleration	x, y, z		Mean ± SD

	Displacement	x, y	peak magnitude, normalized timing (@ peak magnitude) and absolute timing (@ peak magnitude)	Mean ± SD
Puck	Velocity	x, y		Mean ± SD
	Acceleration	x, y		Mean ± SD

Statistical Analyses

A 2 (skill level) by 4 (stick condition; repeated measure) factor analysis of variance (ANOVA) was carried out on the means of each dependent variable. All statistical analyses were carried out using SPSS (IBM® SPSS® Statistics, Version 21.0, 2012) statistical software. The main effects of both calibre and stick condition on means from more than one dependent variable as well as the interaction of skill and stick condition were considered. When evaluating the main effects of stick condition, as well as any interaction effects, post-hoc analyses of means were performed to determine the specific directionality of significant differences. A Tukey HSD analysis was chosen for this purpose.

Results

In general, there were limited main effects of skill and no main effects of stick condition. In turn, there was no significant interactions between skill level and stick condition. There were no significant differences ($p > 0.05$) with respect to the number of corrections, errors and failures, although the magnitude of these events varied loop to loop (figure 10). Subjects demonstrated repeatable movement pattern “signatures” and correction occurances (figure 11).

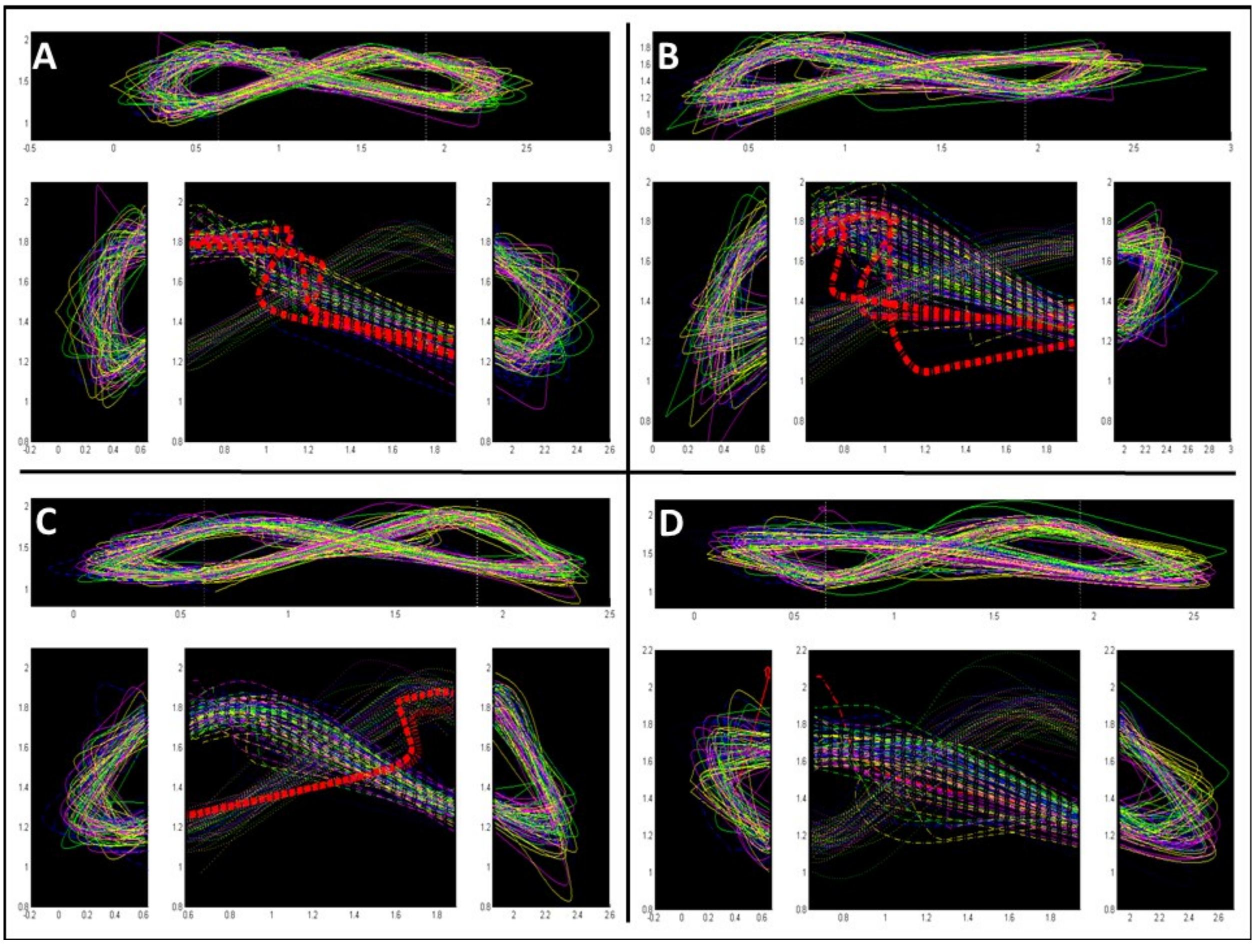

Figure 11. Examples of corrective maneuvers and errors observed during task completion. A) Varsity subject making several corrective maneuvers on the backhand cross. B) Recreational subject making several corrective maneuvers on the backhand cross. C) Varsity subject making corrective maneuvers on the forehand cross. D) Recreational subject commiting an error on the backhand to left transition.

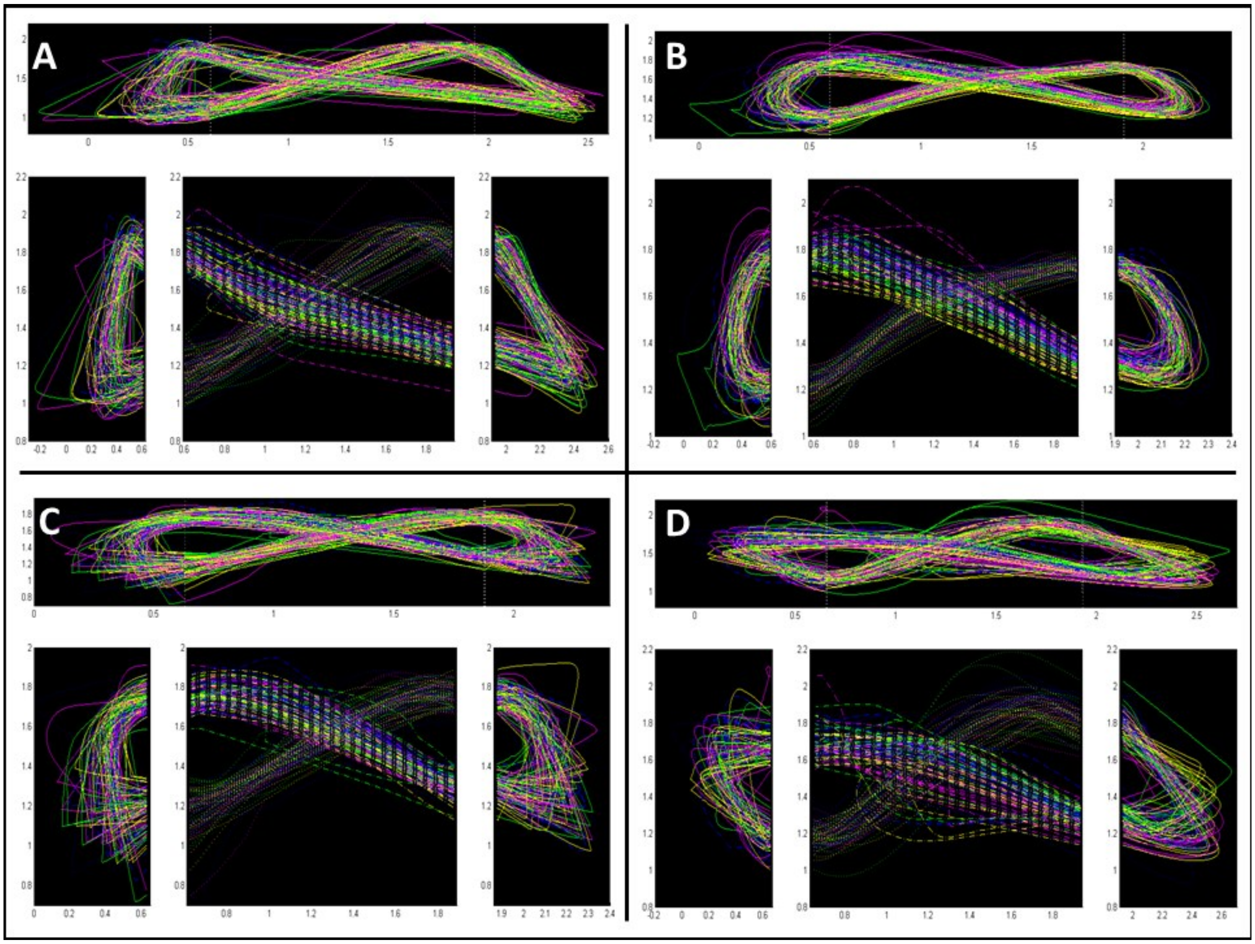

Figure 12. Examples of different task completion styles. Each panel is the cumulative traces of the trajectory of marker s3 for a selection of varsity and recreational subject for the control stick condition. A) elite subject B) Elite subject C) Recreational subject D) Recreational subject

Time

Skill level was found to have a significant main effect ($p < 0.05$) on task completion time. Varsity players took significantly less time to complete one loop compared to recreational level players (2.24 ± 0.30s vs. 2.76 ± 0.52s). Overall, Varsity players completed one loop 18% (T_{rec} - T_{var} = 0.52s) faster than recreational players. In addition, each phase of a loop was completed significantly faster by varsity players than by recreational players (Figure 12). The fhx phase was completed 10% (T_{rec} - T_{var} = 0.06s) faster, the right phase was completed 25% (T_{rec} - T_{var} = 0.18s) faster, the bhx phase was completed 20% (T_{rec} - T_{var} = 0.14s) faster and the left phase 20% faster (T_{rec} - T_{var} = 0.15s). Similarly, normalized phase times showed skill main effects however, in this case only the fhx phase and right phase were sources of divergence. Recreational players showed a significantly shorter fhx phase (23.0 ± 4.8% vs 25.4 ± 3.9%) and a significantly longer right phase than varsity players (24.1 ± 3.2% vs. 26.2 ± 3.9%).

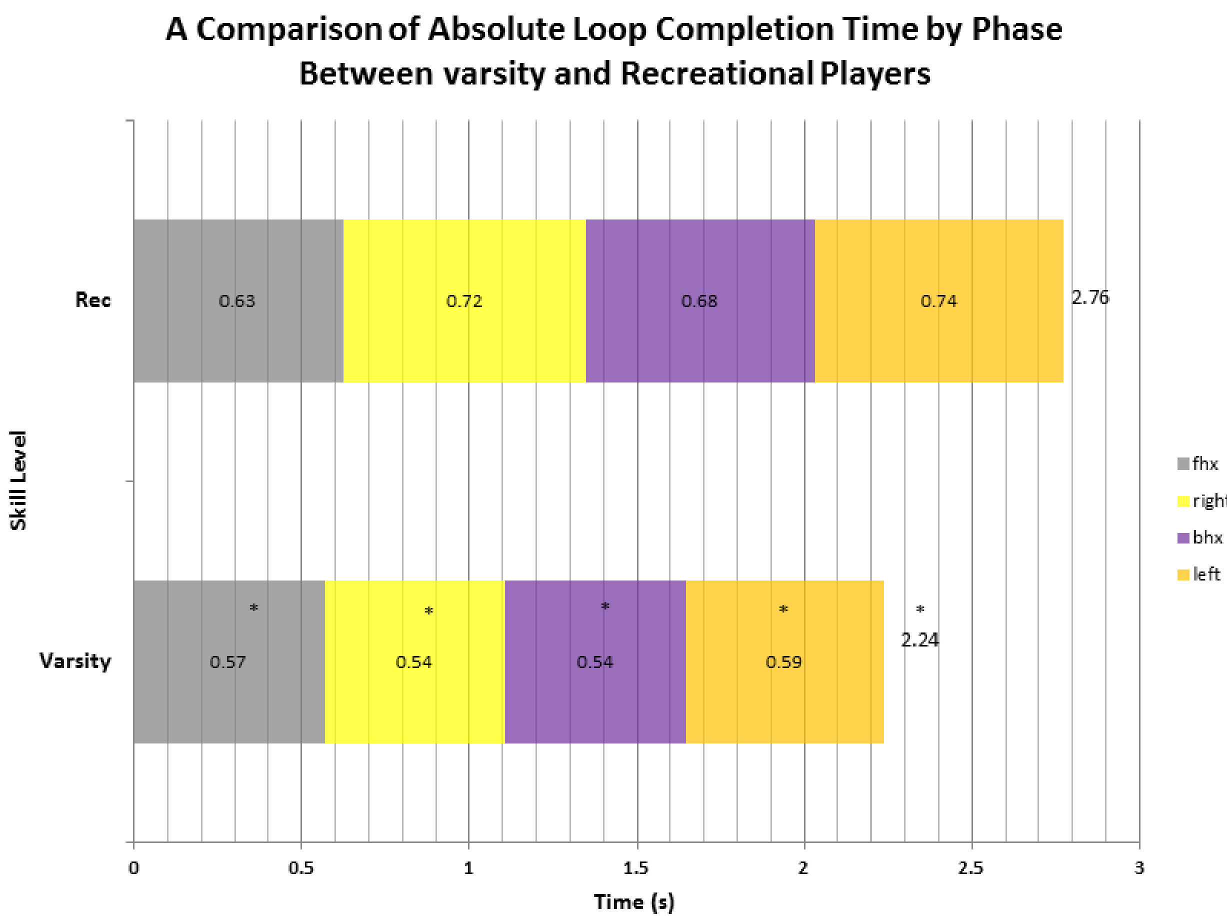

Figure 13. A comparison of the completion time for one loop. Varsity players completed the loop significantly faster than recreational players. In addition, varsity players also completed each phase of the loop significantly faster than recreational players ($p<0.05$).

Stick condition showed some differences ($p < 0.05$), particularly with regards to both absolute and normalized completion times for the bhx phase. Post-hoc anaylsis revealed longer times with the Control stick and shortest with the CoM stick ($p<0.05$; $T_{cont} = 0.65 \pm 0.45$s, $T_{CoM} = 0.58 \pm 0.14$s). The phase completion time with the prox and dist conditions were similar ($T_{prox} = 0.62 \pm 0.17$s, $T_{dist} = 0.61 \pm 0.18$s) and not significantly different from either the Control or CoM stick. Similarly, normalized completion time for the bhx phase was longest with the

Control stick and shortest with the CoM stick ($p<0.05$; $T_{cont} = 25.1 \pm 10.7\%$, $T_{CoM} = 23.6 \pm 3.6\%$). The phase completion time with the prox and dist conditions were similar ($T_{prox} = 24.2 \pm 3.9\%$, $T_{dist} = 24.3 \pm 3.7\%$) and not significantly different from either the cont or CoM stick. There were no significant interactions ($p < 0.05$) with respect to completion time in either frame of timing reference.

Displacement

Displacement: X-direction (side-to-side)

There was a significant main effect ($p < 0.05$) of skill in side-to-side displacement. On the right hand side of the pattern stick marker s3 and the puck travel approximately 4 cm less when a varsity player is controlling the stick than a recreational player ($var_{Puck} = 0.33 \pm 0.11$m, $rec_{Puck} = 0.37 \pm 0.14$m; $var_{s3} = 0.40 \pm 0.18$m, $rec_{s3} = 0.45 \pm 0.17$m) (figure 13). There was no consistent effect of skill on the left hand side of the pattern.

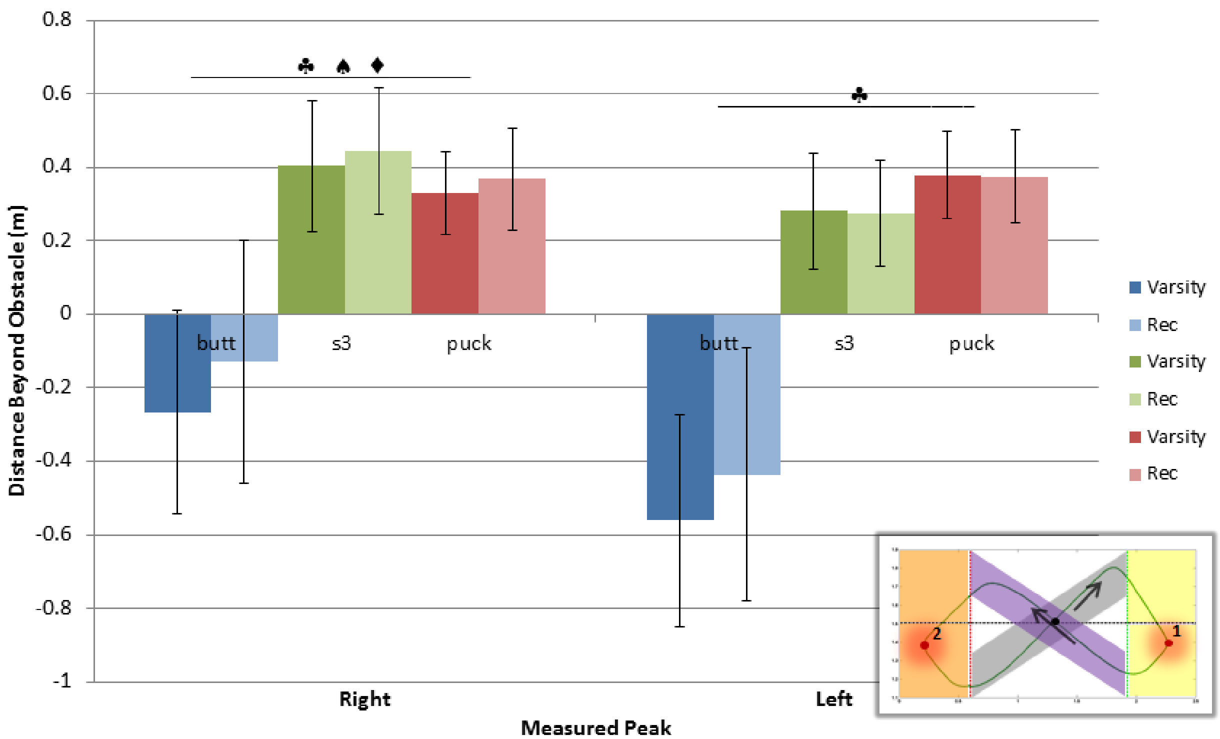

Figure 14. A comparison of the maximum left and right excursion of the stick and puck between varsity and recreational players. On the right varsity players realized significantly less excursion than recreational players. On the left there were no telling differences between varsity and recreational players (Significant differences between skill groups ($p<0.05$); ♣ butt; ♠ s3; ♦ puck). Inset: Grey – fhx phase; yellow – right phase; purple – bhx phase; orange – left phase.

There was also a significant main effect ($p < 0.05$) of skill in phase timing at peak excursion. Peak excursion was always realized sooner by the varsity players (Appendix B, section 1). For both skill groups, there was a noticeable proximal-to-distal sequence in the timing of the stick and puck reaching their maximal excursion (i.e. butt-s3-puck). There were similar significant differences ($p < 0.05$) in the loop times (seconds and %) at peak excursion. Peak excursion was always realized sooner by varsity players (Appendix B, section 1) (figure 14) and there was a noticeable proximal-to-distal sequence in the timing.

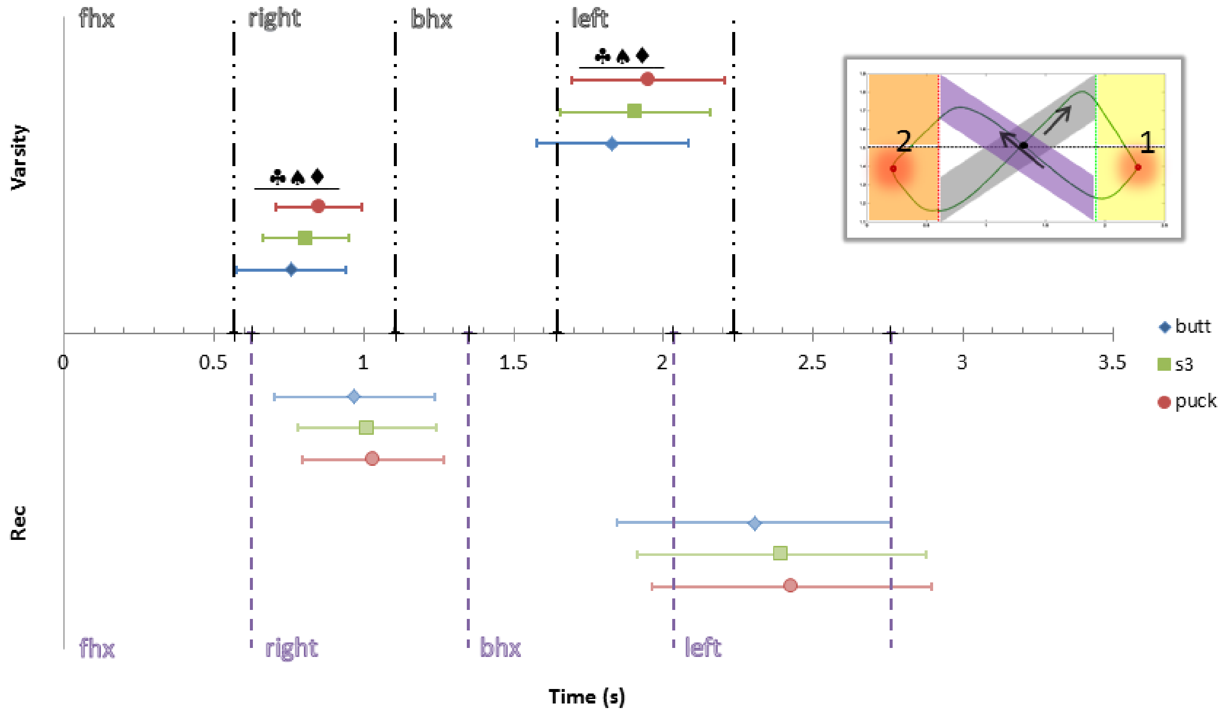

Figure 15. A comparison of the absolute timing of peak excursion events between varsity and recreational players. On both the left and right varsity players realized peak excursion sooner than recreational players (Significant differences between skill groups ($p<0.05$); ♣ butt; ♠ s3; ♦ puck). Inset: Grey – fhx phase; yellow – right phase; purple – bhx phase; orange – left phase.

There was a significant main effect ($p < 0.05$) of condition with respect to the puck on the right side. Post-hoc analyses of means found a significant difference in the peak excursion beyond the right pylon between the prox and CoM and dist conditions ($D_{prox} = 0.38 \pm 0.13$m > $D_{CoM} = 0.34 \pm 0.12$m > $D_{dist} = 0.33 \pm 0.12$m). The distance the puck travelled beyond the right pylon when the Control stick was used was not significantly different from any of the other three conditions ($D_{cont} = 0.36 \pm 0.13$m). There were no significant interactions ($p < 0.05$) of skill and stick condition with respect to x-displacement.

Displacement: Y-Direction (forward-backward)

There was a significant main effect ($p < 0.05$) of skill with respect to all the markers and the four important front-to-back peaks – right side maximum, left side maximum, right side minimum and left side minimum (figure 15). With respect to the right side maximum there were significant differences ($p < 0.05$) between each marker between skill levels. When a varsity player was controlling the stick, the maxmimum excursion of stick marker s3 and the puck were larger than when a recreational player was ($D_{var\ puck} = 0.29 \pm 0.08$m, $D_{rec\ puck} = 0.28 \pm 0.08$m; $D_{var\ s3} = 0.19 \pm 0.08$m, $D_{rec\ s3} = 0.18 \pm 0.07$m). However, the maximum excursion of the butt marker was less than for a recreational player ($D_{var\ butt} = -0.86 \pm 0.08$m, $D_{rec\ butt} = -0.77 \pm 0.10$m). Skill level differences ($p < 0.05$) were observed in the right side minimum as well. Varsity players moved the puck and marker s3 less than recreational players ($D_{var\ puck} = 0.29 \pm 0.09$m, $D_{rec\ puck} = 0.33 \pm 0.10$m; $D_{var\ s3} = 0.45 \pm 0.07$m, $D_{rec\ s3} = 0.49 \pm 0.08$m). As well, the largest excursion for the butt was less for a varsity player than for a recreational player ($D_{var\ butt} = 1.18 \pm 0.09$m, $D_{rec\ butt} = 1.23 \pm 0.08$m).

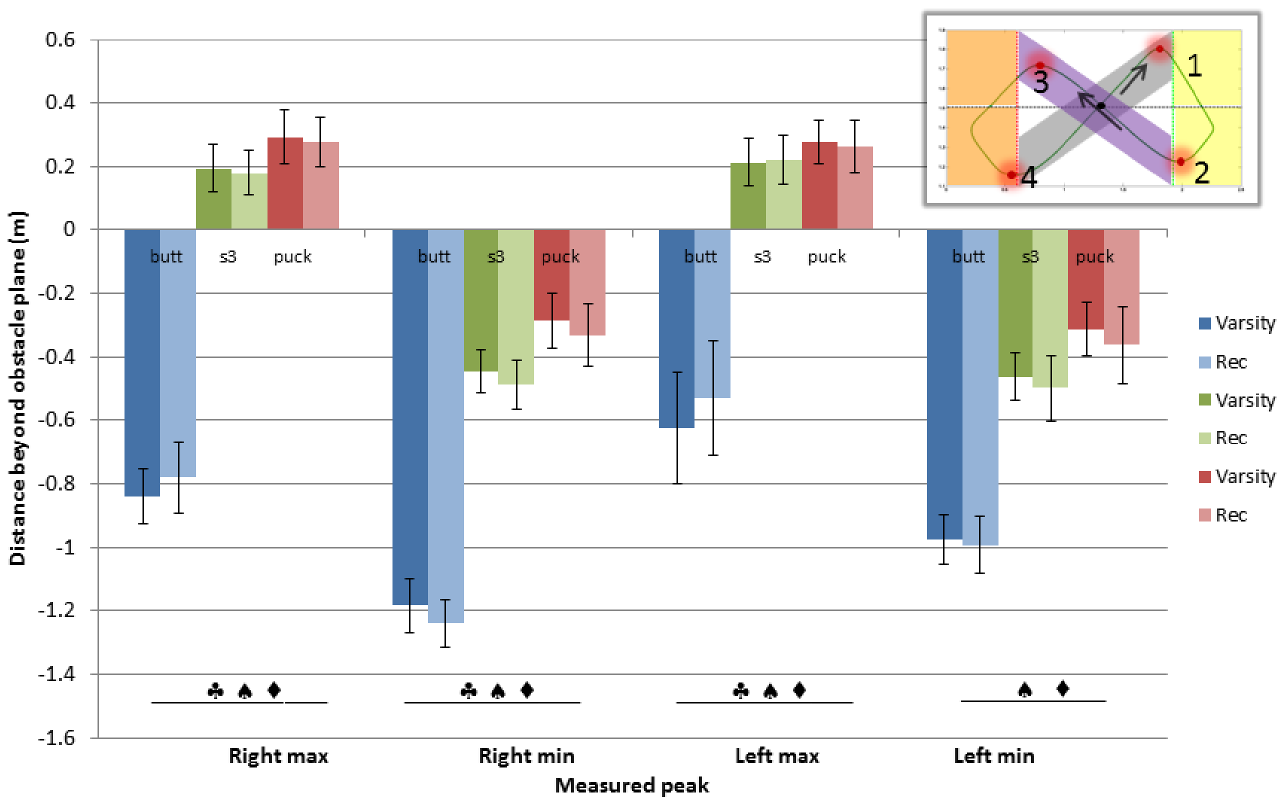

Figure 16. A comparison of the maximum forward and backward excursion of the stick and puck between varsity and recreational players. Differences in excursion with respect to the distal end of the stick and puck were

consistent at all four points of measurement (Significant differences between skill groups ($p<0.05$); ♣ butt; ♠ s3; ♦ puck). Inset: Grey – fhx phase; yellow – right phase; purple – bhx phase; orange – left phase.

Similar trends were observed on the left side ($p < 0.05$) (figure 15). Varsity players moved the puck farther forward (i.e. more) than recreational players ($D_{var\ puck} = 0.28 \pm 0.07$m, $D_{rec\ puck} = 0.26 \pm 0.08$m). The top stick marker (butt) moved less than by recreational players ($D_{var\ butt} = -0.61 \pm 0.19$m, $D_{rec\ butt} = -0.52 \pm 0.18$m). Stick marker s3 only exhibited marginal differences between varsity and recreational players. Similar trend for left side minimum were observed ($D_{var\ puck} = 0.32 \pm 0.09$m, $D_{rec\ puck} = 0.36 \pm 0.12$m; $D_{var\ s3} = 0.46 \pm 0.07$m, $D_{rec\ s3} = 0.50 \pm 0.10$m).

Analyses of the timing of peak excursions (absolute phase timing) revealed skill differences ($p < 0.05$). Varsity players generally reached right maxima sooner than recreational players (Appendix B, section 2). A proximal-to-distal sequence in timing was observed, especially for varsity players. Similar trends were observed in absolute loop timing as well as in the normalized times (figure 16). The sequential pattern of peak realization was less evident for recreational players (Appendix B, section 2). There were no consistent significant effects ($p < 0.05$) of stick condition on peak magnitude or timing of peak magnitude. In addition, there were no consistent significant interactions ($p < 0.05$) of condition and skill level.

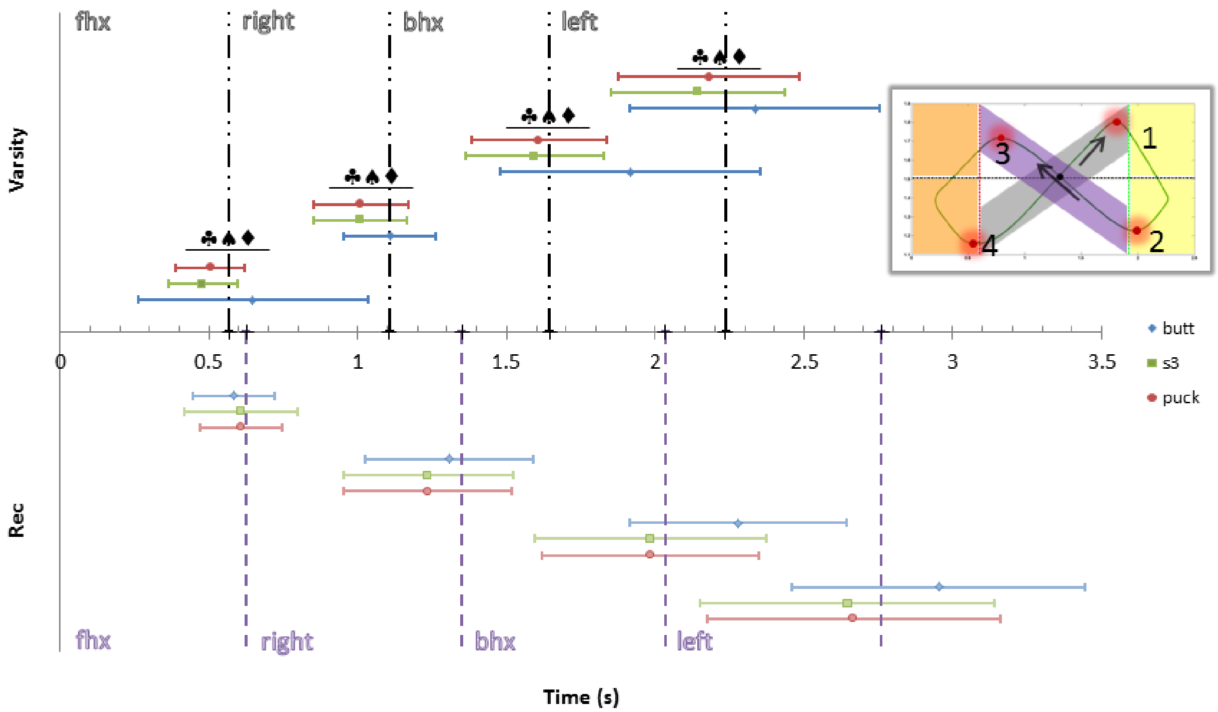

Figure 17. A comparison of the absolute timing of forward and backward peak excursion events between varsity and recreational players. In all four phases varsity players realized peak excursion sooner than recreational players (Significant differences between skill groups ($p<0.05$); ♣ butt; ♠ s3; ♦ puck). Inset: Grey – fhx phase; yellow – right phase; purple – bhx phase; orange – left phase.

Displacement: Z-Direction (vertical)

There was a main effect of skill ($p < 0.05$) in the right, bhx and left phases when players lifted the stick (figure 17). In the right phase the blade of the stick was lifted higher by recreational players ($p < 0.05$) ($D_{rec\ s3} = 0.21 \pm 0.04$m, $D_{var\ s3} = 0.18 \pm 0.02$m). Conversely, the butt of the stick top was lifted higher by varsity players ($D_{rec\ butt} = 1.10 \pm 0.09$m, $D_{var\ butt} = 1.15 \pm 0.08$m). The same trends were observed during bhx phase. Recreational players lifted the blade of the stick higher (i.e. marker s3) ($D_{rec\ s3} = 0.19 \pm 0.03$m, $D_{var\ s3} = 0.18 \pm 0.04$m) whereas the butt was lifted higher by varsity players ($D_{rec\ butt} = 1.11 \pm 0.11$m, $D_{var\ butt} = 1.13 \pm 0.10$m). In the left phase, a different trend emerged. Recreational players lifted higher the blade and the stick butt ($p < 0.05$) ($D_{rec\ s3} = 0.18 \pm 0.03$m, $D_{var\ s3} = 0.16 \pm 0.04$m; $D_{rec\ butt} = 1.01 \pm 0.07$m, $D_{var\ butt} = 1.06 \pm 0.13$m).

Skill affected the timing of lifts in reference to both the phases and the entire loop. Differences in the absolute timing of lifts with respect to the entire loop were seen in the right, bhx and left phases ($p < 0.05$)(figure 18), wherein varsity players lifted their stick sooner (Appendix B, section 3). In the normalized frame of reference, the bhx phase was the only phase where consistent differences were found.

There were no significant differences between stick conditions in lift height or the normalized timing measures. However, absolute timing differences ($p < 0.05$) were found in the right and bhx phases. In the right phase, post-hoc analyses of the butt marker found that timing for lifting the blade was significantly less for the CoM stick condition compared to the other three stick conditions ($T_{CoM} = 31.77 \pm 6.07$s, $T_{prox} = 32.63 \pm 6.79$s, $T_{dist} = 32.91 \pm 6.98$s, $T_{cont} = 34.01 \pm 7.33$s).

In the bhx phase, CoM stick marker s3 moved sooner ($p < 0.05$) than the cont and proximal sticks. The CoM stick butt marker reached peak height earliest particularly with respect to the prox condition. There were no significant interactions ($p < 0.05$) of skill and condition.

Velocity

Varsity players were expected to show larger peak velocities in stick and puck motions and earlier times to peaks. Normalizing the cycle time would eliminate skill-based timing differences. In addition, there was an expectation that peaks in velocity would become larger as accessory mass moved away from the butt of the stick. The timing of these peaks would be later but when normalized by cycle time there would be no stick differences.

Velocity: X-direction (side-to-side)

Player skill affected peak velocity measures ($p < 0.05$). Varsity players demonstrated higher stick and puck peak velocities in both fhx and bhx phases (figure 19). Peak velocities ranking between markers from least to greatest was butt – puck – s3 (Appendix B, section 4).

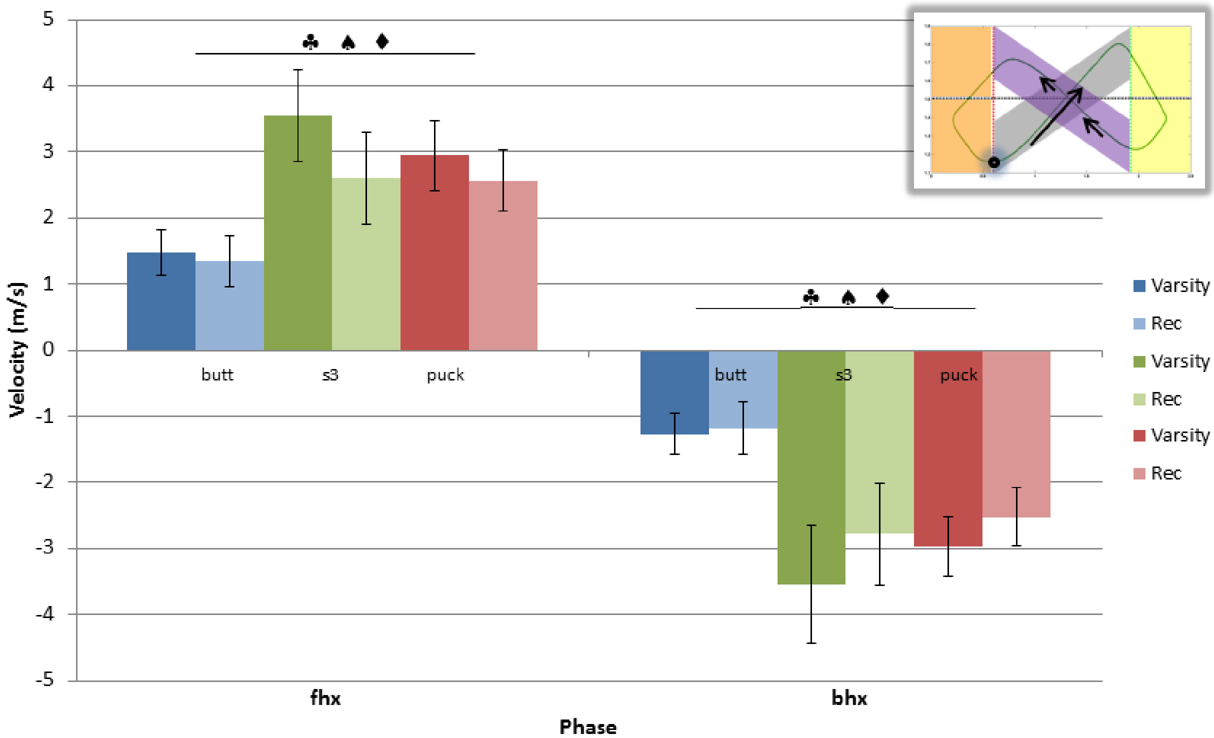

Figure 18. A comparison of the maximum left and right velocity of the stick and puck between varsity and recreational players. Differences in velocity were consistent across directions where varsity players always realized higher peak velocity than recreational players (Significant differences between skill groups ($p<0.05$); ♣ butt; ♠ s3; ♦ puck). Inset: Grey – fhx phase; yellow – right phase; purple – bhx phase; orange – left phase.

A main skill effect ($p < 0.05$) was found for peak velocities events in absolute time. For varsity players, the order of peak velocities was butt, puck and stick marker s3; for recreational players, the order was butt, s3 and puck. Varsity players reached stick peak velocity later ($T_{var\ butt} = -0.09 \pm 0.13s$, $T_{rec\ butt} = -0.16 \pm 0.12s$; $T_{var\ s3} = 0.27 \pm 0.19s$, $T_{rec\ s3} = 0.18 \pm 0.21s$) and puck peak velocity sooner ($T_{var\ puck} = 0.18 \pm 0.18s$, $T_{rec\ puck} = 0.24 \pm 0.20s$) (Note: negative timing indicates that the peak actually occurred before the start of the fhx phase). The skill effect was also seen in the bhx phase. Both skill groups showed the same order of peak velocity timing:

puck, s3 then butt. Different from the trends in the fhx phase, but congruent with predictions, varsity players always realized peak velocity sooner than recreational players (Appendix B, section 4).

Skill affected the timing (normalized to phase) of the peak velocities events ($p < 0.05$) for all three markers in the fhx phase. Mixed trends were observed such that varsity players reached peak velocities later with the stick (Appendix B, section 4) and earlier with the puck. In the bhx phase, varsity players reached peak velocities sooner for both the puck and s3 ($T_{var\ puck} = 35.2 \pm 25.5\%$, $T_{rec\ puck} = 40.1 \pm 26.6\%$; $T_{var\ s3} = 51.4 \pm 24.9\%$, $T_{rec\ s3} = 56.6 \pm 27.4\%$). There were no main skill differences in the normalized timing of peak velocities referenced to the start of a loop. No stick condition effects ($p < 0.05$) were found for peak velocity measures. As well there were no skill x stick interactions.

Velocity: Y-Direction (forward-backward)

There was a main effect ($p < 0.05$) of skill with respect to peak forward-backward velocities. Peak velocity was always significantly higher when the stick and puck were controlled by varsity players (figure 20). In the fhx phase the order of peak velocity between markers from least to greatest was butt – puck – s3 (Appendix B, section 5). In the bhx phase the order of peak velocity between markers from least to greatest was puck - butt – s3 (Appendix B, section 5). Significant differences ($p < 0.05$) were found in the right and left phases, but did not demonstrate any reliable trends.

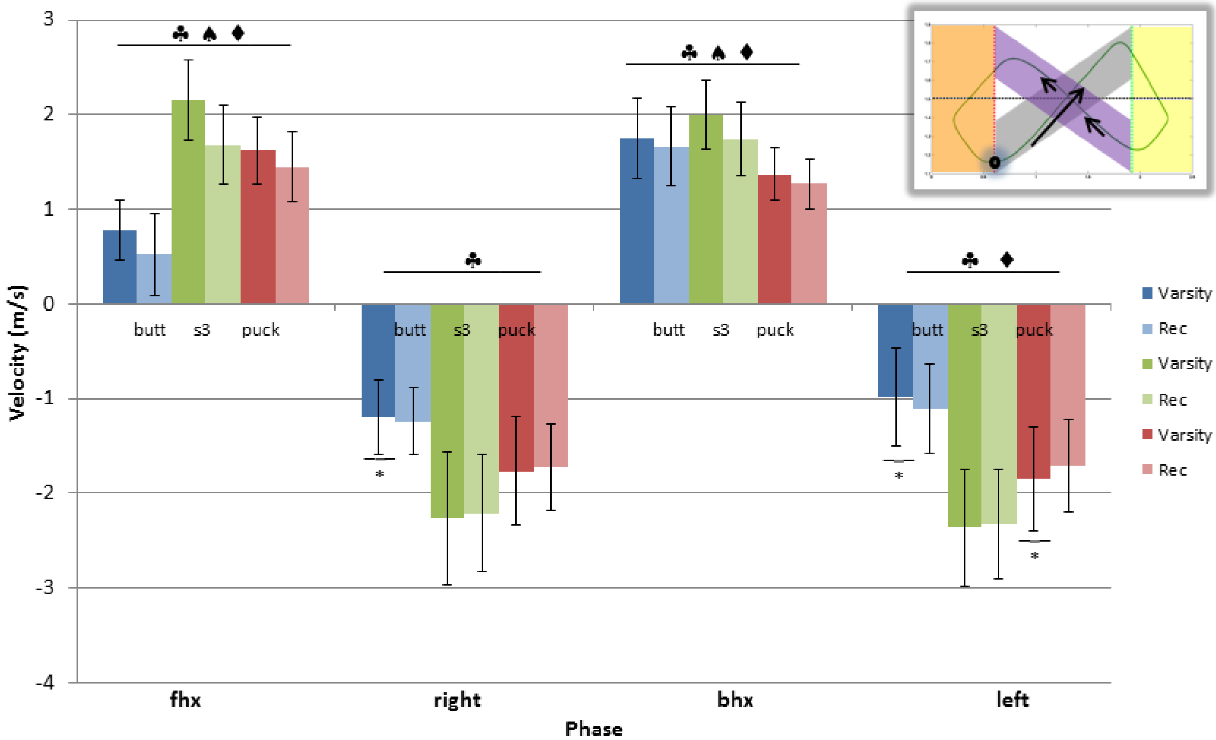

Figure 19. A comparison of the maximum forward and backward velocity of the stick and puck between varsity and recreational players. Differences in velocity were consistent in the positive direction (away from the player) where varsity players always realized higher peak velocity than recreational players. Differences were not as apparent in the negative direction (Significant differences between skill groups ($p<0.05$); ♣ butt; ♠ s3; ♦ puck). Inset: Grey – fhx phase; yellow – right phase; purple – bhx phase; orange – left phase.

There was a main effect ($p < 0.05$) of skill on normalized timing. Significant differences in normalized timing of peak velocities events (with respect to when they occurred in the phase) were identified for marker s3 in all four phases. Varsity players reached peak velocity sooner (Appendix B, section 5). In addition, in the left phase all three markers reached peak velocity sooner when a varsity player performed the task (Appendix B, section 5). There is a distal-to-proximal sequence of timing of peaks in the left phase.

A main effect ($p < 0.05$) of skill on absolute timing of peak velocity was noted. The results for the timing of the peaks in velocity followed hypothetical expectations. In each phase except for the fhx phase, the stick and puck controlled by varsity players reached peak velocity sooner (Appendix B, section 5). The sequence of timing was puck – s3 – butt. The sequential timing of the peaks in velocity was remarkably consistent across the four phases for varsity players, but not for recreational players. There were no main effects ($p < 0.05$) of stick condition with respect to the magnitude of peak velocity or the normalized timing of peak velocity. No noteworthy skill x stick interactions were noted ($p < 0.05$).

Velocity: Z-Direction (vertical)

There was a skill main effect ($p < 0.05$) with respect to the magnitude of peak lifting velocity. Results were mixed; there were three instances when recreational players reached significantly higher peak velocity than varsity players (s3: right and bhx; butt: bhx) and there were four instances when varsity players reached significantly higher peak velocity than recreational players (s3: fhx; butt: fhx, right, left) (Appendix B, section 6) (figure 21).

There was a mixed effect of skill with respect to the normalized timing of peaks in velocity. There were three instances where varsity players reached peak velocity sooner than recreational players ($p < 0.05$) (s3: fhx, left; butt: right). There were four instances when recreational players reached peak velocity sooner than varsity players ($p < 0.05$) (s3: right; butt: fhx, bhx, left) (Appendix B, section 6). The same mixed findings were seen in normalized timing with respect to the loop.

There was a significant main effect ($p < 0.05$) of skill with respect to the absolute timing of peaks in velocity in the bhx and left phases. Varsity players realized peak velocity significantly sooner than recreational players in the bhx phase (Appendix B, section 6). In the left phase, results were mixed.

There were a few main effects ($p < 0.05$) of stick condition detected, however post-hoc analysis found inconsistent trends between the markers. Post-hoc analysis indicated that peak velocity of the butt of the stick in the bhx phase was significantly higher when the cont stick was used (V_{butt} = 0.31 ± 0.27 m/s). The order from second highest to lowest peak velocity was as follows: prox (V_{butt} = 0.23 ± 0.15 m/s), CoM (V_{butt} = 0.20 ± 0.12 m/s), dist (V_{butt} = 0.20 ± 0.16 m/s). In the absolute timing reference there was a significant difference ($p < 0.05$) in the timing of peaks in velocity for both the butt and s3 markers. There were no consistent trends that indicated meaningful interactions between skill and stick condition ($p < 0.05$).

Acceleration

Varsity players were expected to show larger peak accelerations in stick and puck motions and earlier times to peak. Normalizing the cycle time would eliminate these skill differences. In addition, there was an expectation that peaks in acceleration would become larger as accessory mass moved away from the butt of the stick. The timing of these peaks would be later, but when normalized by cycle time there would be no stick differences.

Acceleration: X-Direction (side-to-side)

A skill main effect ($p < 0.05$) for peak acceleration was detected. Varsity players always realized higher peak acceleration of the puck and s3 (figure 22). In the fhx phase the order of peak acceleration magnitude increased from butt – s3 – puck (Appendix B, section 7). A similar trend was observed in the bhx phase.

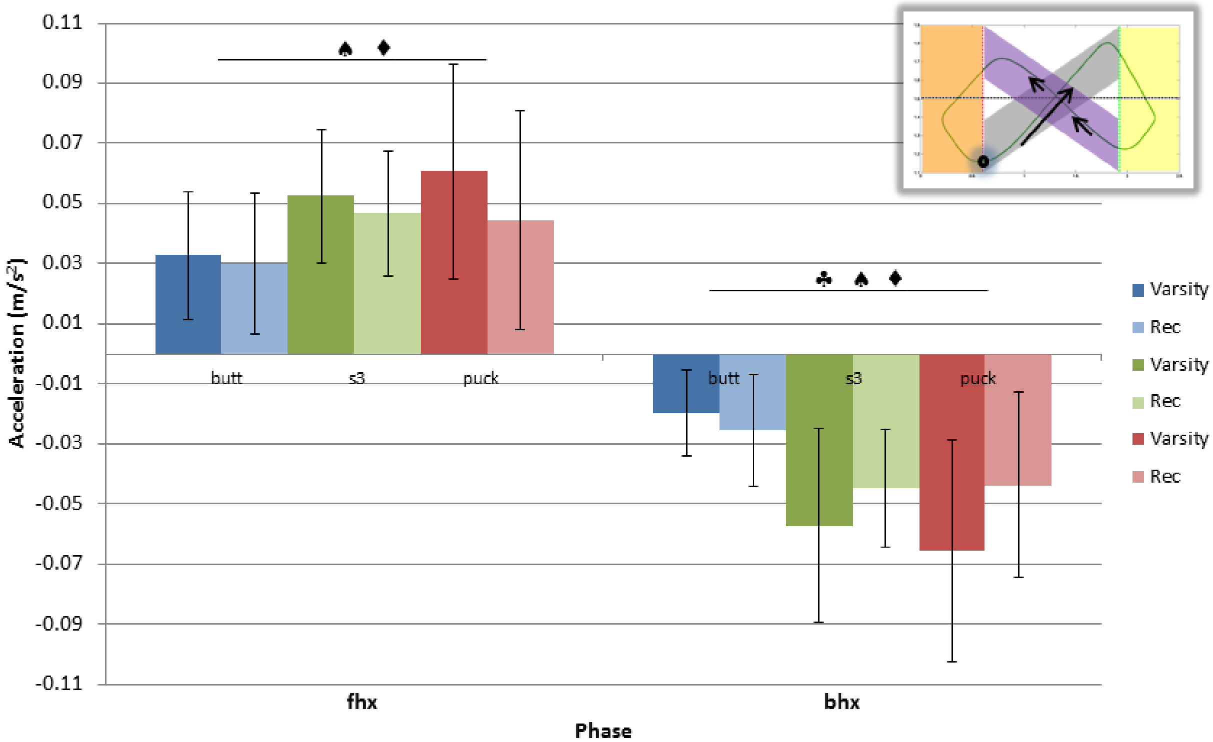

Figure 20. A comparison of the maximum left and right acceleration of the stick and puck between varsity and recreational players. Differences in acceleration were consistent across directions for the distal end of the stick and the puck where varsity players always realized higher peak acceleration than recreational players (Significant differences between skill groups ($p<0.05$); ♣ butt; ♠ s3; ♦ puck). Inset: Grey – fhx phase; yellow – right phase; purple – bhx phase; orange – left phase.

There were significant differences ($p < 0.05$) between varsity and recreational players with respect to normalized timing of the peaks in velocity. When referenced to the entire loop, the butt reached peak acceleration first, followed by s3 and the puck. That trend was consistent between fore and back hand. Examining the data more closely indicated that marker s3 consistently reached peak acceleration sooner under the control of a recreational player than under the control of a varsity player in both the fhx ($T_{var\ s3} = 92.7 \pm 6.8\%$, $T_{rec\ s3} = 91.7 \pm 7.0\%$) and bhx phases ($T_{var\ s3} = 42.6 \pm 5.2\%$, $T_{rec\ s3} = 41.7 \pm 5.0\%$). Other differences were not consistent between the fore and back hand or between varsity and recreational players.

Skill differences ($p < 0.05$) were seen in absolute timing of the peaks in acceleration such that varsity players peaked sooner (Appendix B, section 7). Differences ($p < 0.05$) between stick conditions were seen in terms of the absolute timing of peaks in acceleration but not with respect to the magnitude of peak acceleration or the normalized timing of peaks in acceleration. Thus, no main stick effect was observed. There were no significant ($p < 0.05$) interactions between skill level and stick condition detected.

Acceleration: Y-Direction (forward-backward)

There was a significant main effect ($p < 0.05$) of skill level with respect to magnitude of acceleration. In nine out of twelve measured peaks varsity players reached significantly higher peak acceleration than recreational players (figure 23). There were two instances when the acceleration of the butt of the stick was not statistically different between skill levels and one instance where the puck as piloted by recreational players reached statistically higher acceleration (Appendix B, section 8).

A skill main effect ($p < 0.05$) with respect to the normalized timing of peaks in acceleration was found in particular, with respect to s3 in the right and bhx phases. Marker s3 reached peak acceleration sooner by varsity players in the right and left phases (right: $T_{var\ s3}$ = 27.3 ± 3.9%, $T_{rec\ s3}$ = 26.6 ± 3.8%; left: $T_{var\ s3}$ = 76.4 ± 5.4%, $T_{rec\ s3}$ = 77.0 ± 5.9%). In the fhx and bhx phases, s3 reached peak acceleration sooner by recreational players (fhx: $T_{var\ s3}$ = 97.7 ± 5.5%, $T_{rec\ s3}$ = 96.8 ± 6.2%; bhx: $T_{var\ s3}$ = 47.1 ± 4.5%, $T_{rec\ s3}$ = 45.6 ± 4.1%). With respect to the whole loop, in the right phase, the stick reached peak acceleration sooner by varsity players (right: $T_{var\ s3}$ = 27.3 ± 3.9%, $T_{rec\ s3}$ = 26.6 ± 3.8%; $T_{var\ butt}$ = 29.0 ± 4.2%, $T_{rec\ butt}$ = 28.7 ± 3.8%). Conversely, during the the bhx phase the stick, reached peak acceleration sooner by recreational players (: $T_{var\ s3}$ = 47.1 ± 4.5%, $T_{rec\ s3}$ = 45.6 ± 4.1%; $T_{var\ butt}$ = 54.1 ± 4.8%, $T_{rec\ butt}$ = 53.0 ± 5.6%). No differences in puck peak timing were noted.

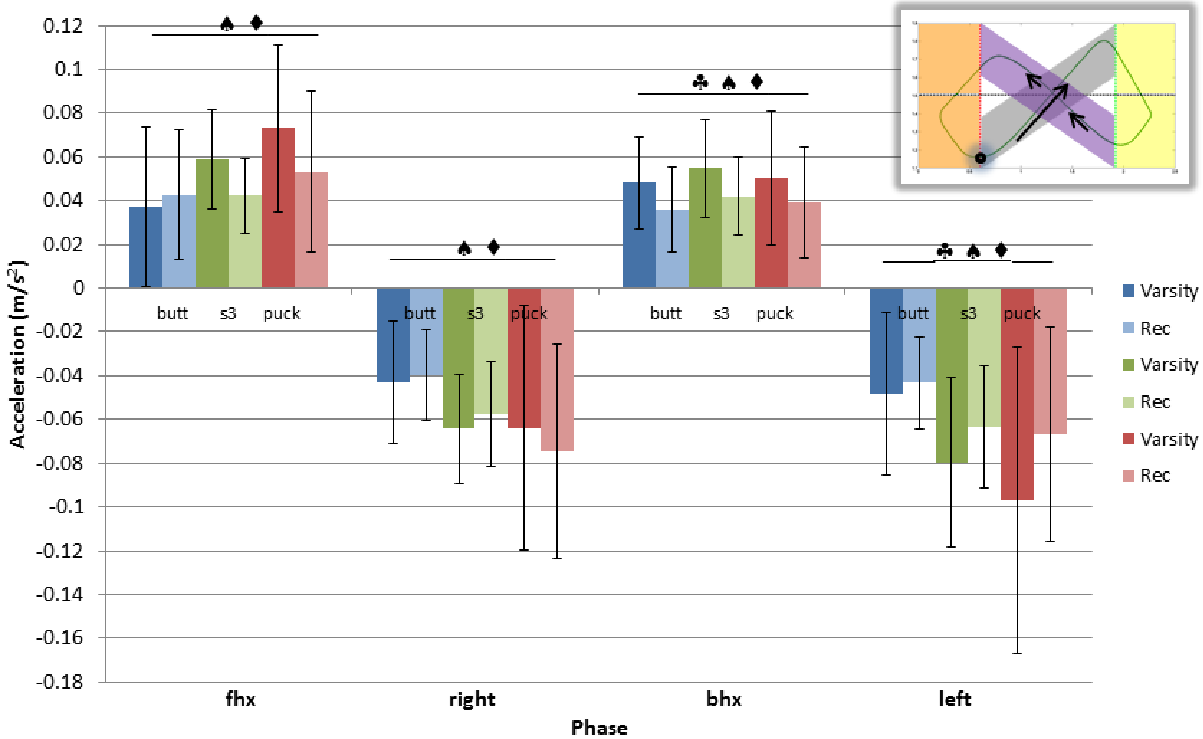

Figure 21. A comparison of the maximum forward and backward acceleration of the stick and puck between varsity and recreational players. Differences in acceleration were consistent across all directions at the distal end of the stick where varsity players always realized higher peak acceleration than recreational players (Significant differences between skill groups ($p<0.05$); ♣ butt; ♠ s3; ♦ puck). Inset: Grey – fhx phase; yellow – right phase; purple – bhx phase; orange – left phase.

A skill main effect ($p < 0.05$) with respect to the absolute timing of peaks in acceleration was observed such that varsity players realized peak acceleration sooner (Appendix B, section 8) except for the stick butt. When referenced to phases, varsity players in general realized peak acceleration sooner (Appendix B, section 8).

Stick differences were found in terms of the normalized and absolute timing of peaks in acceleration but not with respect to the magnitude of peak acceleration. No main effects ($p < 0.05$) were identified. There were no significant interactions ($p < 0.05$) between skill level and stick condition detected.

Discussion

The primary objective of this study was to evaluate the effect of skill level on stick motion during a repetitive figure-8 stickhandling task. Differences in several kinematic parameters were expected. As a result, differences in the style of stick usage were expected between varsity and recreational players, however it was not certain how those nuances might be manifested; a "plough-push" (PP) and "volley-and-catch" (VAC) technique were anticipated. The PP technique would be characterized primarily by linear stick translation with the puck's kinematics being almost identical to the stick. It was presumed that this technique would be exhibited primarily by recreational players.The VAC technique would be characterized by accentuated pendular stick motion kinematics and the puck's velocity and acceleration would less closely match the stick. This technique would primarily by exhibited primarily by the varsity players. The secondary objectives of this study were to evaluate the effect of changing the inertial properties of the stick on the same task and to identify if there was any interaction between skill level and stick condition. To my knowledge this has been the first comprehensive, quantitative study of an ice hockey stickhandling task.

Contrary to our expectations, there were four major observable motion patterns that presumably arose from at least four different techniques. There was a rectilinear pattern (figure 12, panel A) which was characterized by four straight "bee-line" paths joined by tightly angled curves that were the result of abrupt changes in direction. The second major pattern (figure 12, panel B) was a curvilinear pattern. This pattern was characterized by straight "bee-line" paths crossing the pattern joined at the left and right periphery by smooth, semi-lunar curves which resulted from gradual changes in direction. The third major pattern (figure 12, panel C) was a combination of the rectilinear and curvilinear patterns. "Bee-line" cross phases where connected by smooth, semi-lunar curves which were abbreviated by abrupt changes in direction at the left and right peripheral minima. The final major style (figure 12, panel D) was another hybrid of the rectilinear and curvilinear patterns. In this strategy a prominent "bee-line" bhx phase was connected by a swooping and curvilinear left, fhx and right phase which traced out a generally sinusoidal path. This strategy resulted in a slightly misshapen figure-8 pattern which seemed to be drawn out at the lower left and upper right corners. It would seem reasonable to expect that a purely VAC technique would produce a linear pattern as seen in pattern A and a PP technique a curvilinear style as in pattern B. However, when the traces for each subject were compared against the four major patterns identified, recreational players tended to exhibit pattern A and C most frequently and varsity players tended to exhibit pattern B most frequently and pattern A next most frequently. Pattern D was interspersed between both groups. In roughly one third of the cases, the patterns exhibited were hybrid patterns. It is unclear how each of the observed patterns aligns with the VAC and PP techniques introduced earlier. In addition, several of the recreational level subjects were quite experienced, but not necessarily accomplished players; they had a number of years of playing experience but none at an extremely high level. This is perhaps why there seems to be a continuum of patterns rather than two distinct subsets of groups. Perhaps if the groups were more stringently selected there would be two distinct and separate groups of patterns. It seems that we were wrong in the stick motion styles we anticipated or stick motion is more individually nuanced than assumed prior to data collection. It is also potentially a combination of the two reasons.

In general, varsity subjects were expected to be more proficient in task completion and commit less corrections, errors and failures. Varsity players were expected to exhibit shorter completion times per cycle due to a combination of lower overall puck displacement and higher velocity and acceleration peaks. Furthermore, it was expected that the timing of peaks (in kinematic measures) would differ in absolute time (seconds) and in normalized (%) timing within a loop cycle. Thus varsityplayers were predicted to finish the task faster, with the aforementioned peaks occurring sooner than for recreational players. The changes in the inertial properties of the stick were expected to substantially perturb the stick motion task. Specifically it was hypothesized that as the accessory mass moved down the stick larger displacements and larger peaks in velocity and acceleration would occur. It was expected that the time per cycle would increase.

Skill level and Task Completion

Performance Descriptors

As Myers noted, better golfers had lower handicaps and as Ranganathan noted better baseball batters were more adept at selecting "hitable" pitches and adjusting their swing kinematics to pitches. Using this to guide our predictions, it was presumed that varsity players would more deftly complete the task than recreational players (Myers et al., 2008; Ranganathan & Carlton, 2007). Contrary to expectations, the evaluation of task completion statistics showed no significant differences between varsity and recreational players. Varsity players showed a very slight tendency to make more corrections (per loop and per trial) than recreational players while committing fewer errors. Furthermore, no skill difference in the percentage of failed trials was noted. Rated on a categorical scale, varsity players are no more adept than recreational players in terms of task execution. This might have been because our subject pool represented a continuum of skill levels rather than two distinct subsets. As already noted, more stringently selected groups might have demonstrated more definite differences between skill levels. Another potential reason is the nature of the task; the figure-8 motion chosen might not be truly representative of an in-game task. As a result, both groups of subjects were completing it as best they could and subject to similar obstacles or hardships with respect to task completion. It is unclear precisely the nature of this finding.

Time

In their study of field hockey players, Lopez de Subijana and colleagues demonstrated differences in the timing of key execution events. Something similar was noted in this study; as expected, varsity players completed the task faster than recreational players and with more equal duration between the four phases of the loop. In the absolute time frame there is a trend for recreational players to proceed more slowly in the right and left phase than in either the fhx or bhx phase (figure 12). The right phase was of particular interest because the varsity players completed the phase in 25% less time than recreational players: a substantial disparity in completion time. The bhx and left phases were also completed in substantially less time by varsity players: 20% less time for each. Important events took place in the right (yellow shaded) and left (orange shaded) phases (figure 22). In the right phase, the player must maneuver their stick blade from a fore to backhand orientation and in the left phase, from a back to forehand orientation. Our loop and phase duration data indicates that task speed was sacrificed and we presume that was to maintain puck trajectory accuracy while completing the fore- and back-hand transitions, especially for recreational players. Presumably the transition between the fore and back hand compromised co-ordination, and to optimize the integration of hard and soft constraints recreational players executed the task at a slower speed so the task could be completed with an acceptable level of accuracy and stability (Swinnen & Wenderoth, 2004; Temprado et al., 2001). Greater difficulty for recreational players to complete the fore to back hand transition, may be related to the challenge in controlling the puck with the convex, backhand face of the blade. When transitioning from the back to forehand in the left phase, the puck can be cradled in the concave forehand face of the blade to complete the maneuver (figure 22); that is, there is less chance that the puck will roll off or lose contact with the blade. However, in the right phase the player must switch to the back side of the blade to control the puck. The puck cannot be cradled in the blade and thus the puck is presumably more difficult to control (figure 22). Consequently, recreational players proceed more cautiously through the right phase and into the early stages of the bhx phase. While direct causal evidence has not been identified, it seems that in completing the task more quickly than recreational players, varsity players are better adept at managing the soft constraints of the task through practice.

Displacement

Qualitative inspection of the spatial patterns of movement suggested that subjects demonstrated good inter-trial variability; that is, each subject demonstrated unique spatial pattern movement styles (or signatures). As a result, greater inter-subject variability in stick and puck motion were qualitatively evident (Figure 11). This occurred across both skill levels. Nonetheless, general differences in gross kinematic amplitudes were observed between skill groups. These basic features offered insight into differences in task completion between the skilled and unskilled players.

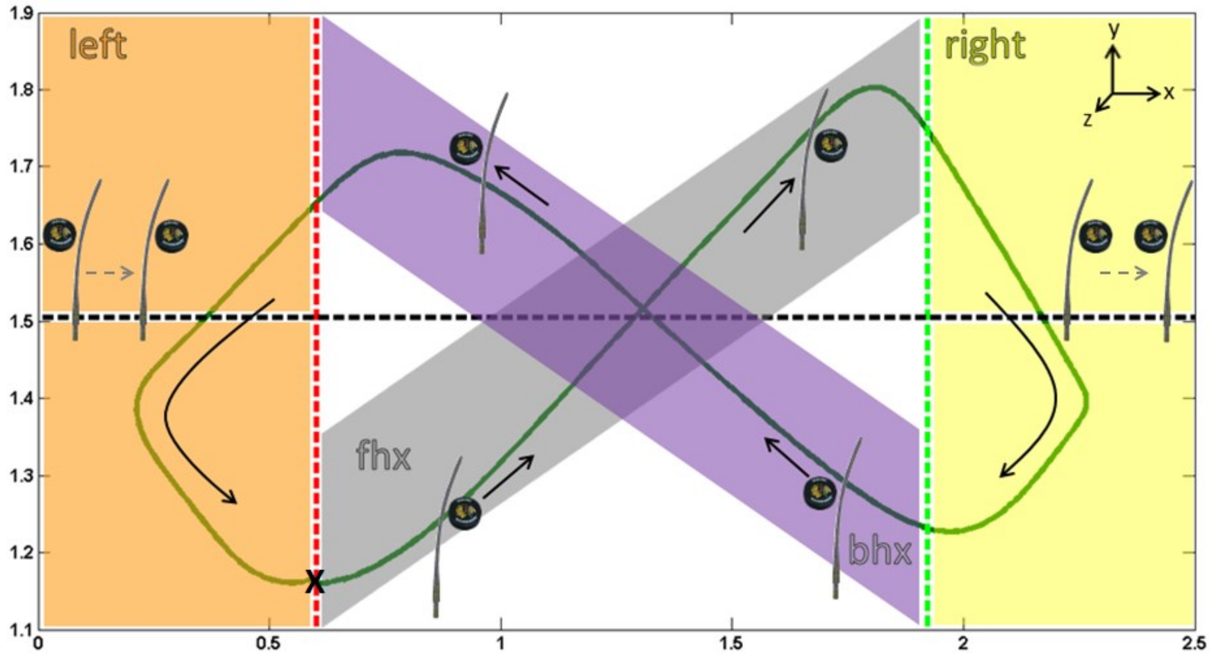

Figure 22. A schematic of one loop showing the orientation of the puck with respect to the blad of the stick. Cross phases (fhx,bhx) are labelled with respect to the position of the puck to the blade. The left and right phases are where major back- to forehand and fore- to backhand transitions occur respectively. The bold 'X' at the left-fhx transition marks the functional start of a loop.

In the right phase the lower stick (i.e. marker s3) and the puck travelled approximately 4cm less by varsity players ($Puck_{var}$ = 0.33 ± 0.11m, $Puck_{rec}$ = 0.37 ± 0.14m; $s3_{var}$ = 0.40 ± 0.18m, $s3_{rec}$ = 0.45 ± 0.17m) and the stick top (i.e. butt) travelled approximately 14cm less by a varsity player ($butt_{var}$ = -0.267 ± 0.277m, $butt_{rec}$ = -0.129 ± 0.330m; Note: a larger negative number means the stick marker was further to the right of the obstacle than the other). In proportion to the average magnitude of maximum excursion for all subjects (approximately 35cm) 4cm represents about 11 percent difference in the maximum excursion. Furthermore, a 14 cm disparity in excursion when the average maximum magnitude of excursion of the butt of the stick is 19cm represents an enormous proportion of the average. These data suggest that varsity players might execute the fore to backhand transition (in the right phase) differently than recreational players. There was no consistent effect of skill on the magnitude of excursion on the left hand side of the pattern.

The front-to-back displacements differed marginly between skill groups. For left and right side maximums varsity players tended to play the puck 1.5 cm farther away from the obstacles than recreational players (marker s3 followed a similar trend). Interestingly, the maximum forward excursion of the stick top (butt) of a varsity player was about 9 cm further behind the obstacles (i.e. further in the negative direction). Differences in the left and right side front-back minimum displacements were also observed. Varsity players played the puck approximately 4.5 cm closer to the obstacle (s3 ~ 4 cm; and stick butt ~5cm closer to the obstacle). These differences average about 7 percent of the total excursion but can reach up to 16 percent. Of note, the puck displacement was shifted forward with respect to the two obstacles. Potentially the varsity players may have stood closer to (or more "on top" of) the obstacles making obstacle avoidance easier. In support, Bongers found that when subjects had to move objects with a long tool, the limb was held closer to the trunk of the body which they asserted was to maintain closer control of the tool (Bongers et al., 2003). Furthermore, Lopez De Subijana noted differences in drag flick technique between expert and novice field hockey players that were manifested in physical spatial differences in task completion (López De Subijana et al., 2010). Further data analysis or subsequent whole-body analysis is warranted to determine the exact nature of this spatial difference. Because the average player height between the groups was so similar, stick length or player height do not seem to be the cause of the differences noted.

In addition, it appears that varsity players might realize different stick angles than recreational players. The spatial differences between the blade and butt of the stick at maximal displacement suggest that at certain points during the task the frontal and sagittal angle of the stick are different between varsity and recreational players. Despite only minor differences in the actual displacement of the stick, how the stick moves in the time between maxima might be different. Differences in stick angle between maximum might be what defines varsity from recreational level players. For example, realizing a different stick angle during the fore to back hand transition might facilitate a more efficient transition and reduce the overall time to completion of a loop. The data do not conclusively confirm that varsity players use the stick any differently, however, the near-simultaneous nature of the absolute timing of the maxima within each subject group suggest that at peak y-displacement stick angles might be different between subject groups. Further research might reveal a difference, but for now it is merely a suspicion that the stick action is different when the stick is controlled by a varsity player.

The timing of peaks in displacement might also indicate differences in execution between skill levels. On the right, when referenced to the start of the phase, there is a marked difference in realizing the side-to-side maxima between varsity and recreational players; that is, varsity players moved the stick to maximal excursion between 30 and 53% into the phase compared to a later time by recreational players (46 and 55%). In absolute terms (i.e. seconds), variablity in peak timing was much greater for recreational players. Furthermore, timing sequences were similar for both skill groups. Right maxima occurred in proximal to distal order whereas all other sequences occurred in distal to proximal order. In absolute time, varsity players reached peak displacement sooner. Noteable differences occurred in the right phase. When a varsity player was controlling the stick, maximal excursion to the right occurred between 0.471s and 0.506s into the phase and loop. In normalized terms, this represents approximately 80 - 89% of the way through the phase and approximately 21 - 23% of the way through the loop. When a recreational player was controlling the stick, maximal excursion to the right occurred between 0.338s and 0.607s into the phase and loop. In normalized terms, this represents approximately 40 - 96% of the way through the phase and 9 - 22% of the way through the loop. As Shaffer and colleagues noted in baseball, a distinct difference in the sequence of muscle activation separated skilled from unskilled batters (Shaffer et al., 1993). Similarly, Lopez De Subijana found differences in the timing of key events in the drag-flick technique between expert and novice players (López De Subijana et al., 2010). Our findings are analogous to this; this timing disparity in reaching peak excursion could be an indication of a difference in execution between skill levels. Further analysis of this data set related to the fore-backhand transition in the right phase should reveal skill technique differences, for example, with regards to angular kinematics. However, the exact nature of these differences is not completely apparent from within the context of this analysis.

Furthermore, the coefficient of variation (temporal data) of the right hand minima (Puck: CV_{var} = 0.24 CV_{rec} = 0.57; s3: CV_{var} = 0.22 CV_{rec} = 0.57; Butt: CV_{var} = 0.79 CV_{rec} = 2.57) and left hand maxima (Puck: CV_{var} = 0.22 CV_{rec} = 0.50; s3: CV_{var} = 0.24 CV_{rec} = 0.51; Butt: CV_{var} = 1.25 CV_{rec} = 1.16) are quite large for recreational players; generally in the order of two times the value of the coefficient of variation of the right side maxima (Puck: CV_{var} = 0.24 CV_{rec} = 0.23; s3: CV_{var} = 0.29 CV_{rec} = 0.32; Butt: CV_{var} = 0.28 CV_{rec} = 0.88) and left side minima (Puck: CV_{var} = 0.29 CV_{rec} = 0.29; s3: CV_{var} = 0.28 CV_{rec} = 0.29; Butt: CV_{var} = 0.44 CV_{rec} = 0.64). The nature of this anomaly in the data is immediately unclear; however, data from Button and his colleagues has helped us speculate what the cause is. They demonstrated that less skilled shooters exhibited more erratic, and differently shaped arm trajectories than skilled shooters. Furthermore, they also demonstrated differences in the timing of peak angular joint motion between skilled and unskilled shooters; unskilled shooters synchronously reached peak angular joint motion of the wrist and elbow where there was a latency period of 0.5 seconds for skilled shooters (Button, MacLeod, Sanders, & Coleman, 2003). This may indicate that the backhand phase was more erratic than the forehand motion as a result of different stick kinematics and potentially upper body kinematics between skilled and unskilled ice hockey players. Figure 11 demonstrates an observable manifestation of this phenomenon.

Loosely, one could surmise that maneuvers on the forehand (i.e. from the middle of the left phase through the fhx phase and to the middle of the right phase) are less stringently controlled since displacement through this portion of the loop maneuver is systematically higher than on the backhand (figure 11). One also might loosely surmise that maneuvers on the backhand are the less stringently controlled ones because of the increased temporal variability between varsity and recreational players. Two important factors are confounding the interpretation of this data. First, the way the stick is wielded and second, the shape of the blade of the stick. It is counterintuitive that the right maxima are systematically higher than the left maxima because of the way the stick is held with the hands several centimetres apart. The trail hand in this case is the left hand and one would intuitively think that the right maxima would be the smaller one based on the physical awkwardness of pivoting the stick to the right while maintaining an appropriate grip on the stick. Also pertinent to this discussion is to note that in the bhx phase the puck is controlled with the convex backhand face of the blade. Combined with the round puck profile control is decidedly more difficult and might help to explain some of these observed differences. Perhaps control on the forehand is a simpler task which affords less stringent tolerances on spatial distribution to maintain proper timing for achieving quality performance. More research is warranted to assess the nature of these peculiarities in the data.

Though the puck movement task was two-dimenional, stick motion involved changes in stick elevation and orientation to the ground during transitions about the obstacles. Varsity players do not lift the blade of the stick as high in order to clear the puck on transtions from the forehand to the backhand. Skill level differences were shown in the vertical displacement of the stick; particularly in the left, right and bhx phases with respect to the blade (1 to 2cm) and butt (4 to 5.5cm). Recreational players tended to lift the blade higher (and later) in the bhx phase while varsity players tended to lift the stick the highest in the right phase. Recreational players were substantially slower in the bhx phase (~8% phase timing) which translated into a 4 to 5% delay throughout the loop. Peak timing differences between the blade and butt indicate changes in stick orientation as it pivots from left to right and front to back in the loop. Further investigation into the angular kinematics of the sticks motion, and/or whole-body kinematics is warranted.

Velocity

Given the combination of displacement and timing skill differences, it is not surprising to have found skill group differences in puck and stick velocities. As expected, from side-to-side varsity players moved the stick and puck faster in both the fhx and bhx phases. In the front-to-back direction of the fhx and bhx phases, all stick markers and puck peak velocities were greater for varsity players. Differences contrary to expectations were noted in the left and right phases; higher stick butt velocity was shown by recreational players. There are no research studies to help us glean definitive insight into the nature of this finding. It is possible that the relationship of the velocity of the blade compared to the velocity of the butt might be indicative of differences in execution style between varsity and recreational hockey players. In the side-to-side direction, there was an increasing disparity in peak velocity between skill groups moving distally along the length of the stick (butt: $V_{var} – V_{rec}$ = 0.13m/s; puck: $V_{var} – V_{rec}$ = 0.41m/s; s3: $V_{var} – V_{rec}$ = 0.94m/s). The same observation was made in the bhx phase (butt: $V_{var} – V_{rec}$ = 0.09m/s; puck: $V_{var} – V_{rec}$ = 0.45m/s; s3: $V_{var} – V_{rec}$ = 0.75m/s). Recreational players exhibited velocities which were more similar between all markers than varsity players. Another interesting and related observation was the amount of inconsistency in velocity in the fhx phase between the puck and s3 (i.e. $x = V_{s3} - V_{puck}$) between skill groups (Var = 0.61m/s; Rec = 0.08m/s). This trend was also observed in the bhx phase (Var = 0.57m/s; Rec = 0.26m/s). This observation demonstrates that the blade of the stick moved much more quickly than the puck did at peak velocity for varsity players but not recreational players. Finally, the inconsistency in velocity between s3 and the butt (i.e. V_{s3}-V_{butt}) between skill groups in both the fhx (var: 2.08m/s; rec: 1.26m/s) and bhx (var: 2.27m/s; rec: 1.61m/s) phases. In addition, the sequence in which markers reached peak velocity in the fhx phase was different between varsity and recreational players (butt-puck-s3 compared to butt-s3-puck).

In the front-to-back direction blade velocities were greater than the stick butt by upwards of 1.4 m/s and 1.1 m/s for varsity and recreational players, respectively. This observation could be an indication that varsity players employ a different technique to complete the task than recreational players.

Varsity players might employ a “volley-and-catch” technique rather than a “plough-push” technique. The above anomalies can not be fully explained within the scope of this report. Three measures which were not considered in this study but might help to provide corroborating evidence are the length of time the stick is lifted for, the proximity of the puck to the blade of the stick and the location of the centre of rotation of the shaft of the stick. Understanding the spatial separation between the puck and the stick and how the stick pivots with respect to the hands will help interpret the cross pattern movement dynamics.

In the vertical direction, findings were mixed and no trends were consistently observed with respect to the magnitude of peak velocity, normalized timing of peaks in velocity or absolute timing of peaks in velocity. It seems that lifting velocity is not a variable in which clear distinctions between skill levels can be reliably made.

Acceleration

There was found to be less reliable distinctions between skill levels by examining the acceleration data. Because the peaks in acceleration often straddled phase divisions it was difficult to assess any differences other than those based on the magnitude of acceleration.

In the side-to-side directions, there were several significant results. In accordance with hypothetical expectations, varsity players reached higher peak acceleration with the blade end of the stick, but not with the butt. There was a consistent proximal-to-distal sequence in the realizing of peak acceleration. In the forward and backward directions there were several important results. In general varsity players reached significantly higher peak acceleration than recreational players.

In conclusion, there is a skill based difference in task execution. It seems that the difference is explained largely by spatial parameters. The discovery that there is differences in excursion on the right but not the left and that traces are systematically shifted forward with respect to the pylons are the flagship findings of this study. They suggest that angular kinematics might help to further explain skill based differences and that a full-body analysis is warranted to investigate postural differences between the two skill groups.

Stick Condition and Task Completion

Several sources of data from multiple disciplines of research guided the hypothesis that changing the inertial properties of the stick would influence usage. Hove and his colleagues demonstrated that naïve subjects could detect differences in inertial properties of hockey sticks and that they rated differently weighted sticks as being suitbale for different tasks. They also asserted that it might be feasible to develop sticks for different levels of players based on those findings (Hove et al., 2006). In a series of experiments Bongers and colleagues demonstrated evidence that the haptically perceived properties of a tool affected the spatially observable usage for a reaching task (Bongers et al., 2004; Bongers et al., 2003). In multiple investigations, Johansson and colleagues have demonstrated that neuromuscular activation was modulated in a task-based manner (Johansson & Flanagan, 2009a, 2009b; Johansson & Westling, 1984, 1987). Despite compelling evidence, few kinematic differences due to stick mass and mass location were found. Sporadic and inconsistent differences where limited to the right and bhx phases.

In conclusion, altering the stick's centre of mass or inertial properties does not seem to exert any meaningful effect on skill execution. All subjects reported being able to detect the inertial change in the stick, but it appears that visual cues overruled the haptic cues imparted by the stick. The experimental conditions may have pre-disposed subjects to this response. In this experiment, the external weight increased the moment of inertia of the stick to a maximum of about 25%; The stick would have felt about 110 grams heavier; a small magnitude change which while detectable, would probably not sufficiently challenge the musculature of the arms controlling the stick. In addition, subjects were privy to the location of the applied weight – that is they could see where on the stick the external weight was attached. According to classical research, tactile input serves to modulate descending motor patterns that were activated based on initial visual cues (Johansson & Flanagan, 2009a; Johansson & Westling, 1988). In the case of this research, initial visual cues likely provided enough information to the central nervous system to release proper commands for muscle activation to successfully complete the task. That is, despite weight being added the physical dimensions of the stick were still the primary sensory guide to its useage.

The change in the weight distribution might serve to improve puck control when vision is compromised, for example, when visual attention is directed to monitoring the positions of teammates and opponents on the ice. However, the current experimental protocol makes it impossible to draw any definitive conclusions. While it is possible to develop an experimental protocol to assess the effect vision has on task completion, translating those findings to actual in-game scenarios would be increasingly difficult. There are many differences between a laboratory setting and and in-game scenario that isolating and monitoring them all is not realistic.

Contribution to the Field

Despite the limited nature of the findings in this research, there is still applicable information to be gained. Stickhandling is identified as a major category of essential stick skills a hockey player must possess, and very little research has investigated the nuances of this skill (Pearsall, 2000). A deep knowledge of precisely how the stick is manipulated by the player during stickhandling tasks has implications for the advancement and progression of the game. The information in this report has the potential to initiate a paradigm shift in coaching, scouting and skill assessment strategies. The information might also be used to direct research and design programs. Placing tangible values to temporal and spatial stick parameters has the potential to advance the game of hockey in the same way science has advanced the game of golf or baseball.

For example, in hockey culture, the terms “hands” is often used as a descriptor of a player’s stickhandling ability. Young players are encouraged to work on “quick” or “soft” hands without specific instruction on the body postures or stick motions that are equated with these terms. A better understanding of the biomechanical foundations of stickhandling will help improve the teaching of technique to minor players. Many sports have already benefitted from the information that scientific research has made available to coaches and trainers. Consider the sport of golf and the advances the game experienced once scientific literature began to infiltrate coaching strategies. In 1995, Bechler and his colleagues investigated the temporal activation of several lower limb muscles during an expert golf swing (Bechler, Jobe, Pink, Perry, & Ruwe, 1995). The results confirmed what professional coaches had long preached about leading the swing with the hips. In addition, by elucidating the order in which muscles were activated during a "proper" swing, coaches had the ability to better diagnose and correct dysfunctional swings. Similar findings were outlined for the baseball batter's swing in the introduction. For example, if further research confirms that standing closer to the obstacles improves performance, coaches can instruct players learning the skill to keep the puck closer to their body to improve their performance in the skill.

Furthermore, the information gathered from this study also has the potential to make the assessment of talent much more objective and unbiased. Compare the National Football League (NFL) and NHL scouting combines for example; in both, draft-eligible players are assessed on many levels to determine worthiness of being awarded lucrative contracts in each sport. The NFL assesses potential players on many different levels including cardiovascular fitness, strength, agility as well as in a battery of position-specific skills (NFL Enterprises, 2012). Currently the NHL does not assess position specific talent at their annual prospect combine; Assessments of aerobic fitness, endurance, strength, agility and flexibility are the parameters used to evaluate and assess each candidate's 'worthiness' (Skahan, 2011). Historically in ice hockey, position-specific skill level has been assessed from afar by scouts observing the game from the confines of arena bleachers. Perhaps this is because there is a lack of benchmark data to compare prospective players too. For example, the information in this report has helped to identify that potentially varsity players are more adept at completing the stickhandling task because they keep the puck closer to their body where they're able to maintain a higher level of control over it. By quantifying the variables associated with stickhandling, skill-specific testing protocols might be developed and introduced into the combine agenda to more accurately identify hockey-specific strengths and weaknesses of each prospect. Coaches and scouts alike will have the luxury of objectively separate players of higher skill from those with less skill or identifying players which might fit into niche roles in their rosters.

Finally, we return to stick design. Composite sticks have largely replaced traditional wooden ice hockey sticks, however, the pros and cons of their performance has been a hot topic of debate. With the ability reduce the variability in the mechanical properties (i.e stiffness, bend node location) of composite sticks with more consistent materials and construction techniques (i.e. carbon fibre layering processes), it is easy to presume that they definitively offer a performance advantage over wooden sticks (Stein & Kopper, 2010). In a 2008 experiment, Anderson wished to determine if there were any detectable performance differences between wooden and composite sticks. Six wooden and 11 composite sticks of various quality (ranging from low quality wooden to elite quality composite) and brand were all compared on the basis of puck exit velocity during a simulated slap shot. The average puck exit velocity across the selection of wooden sticks was 45.9 ± 3.1 mph and peaked at 51.15 mph (Anderson, 2008). The average puck exit velocity across the selection of composite sticks was 54.1 ± 4.3 mph and peaked at 59.92 mph (Anderson, 2008). In this laboratory-controlled experiment, the difference in puck exit velocity was statistically significant. Furthermore, by evaluating the exit velocity of the puck at different locations along the length of the blade it was possible to locate a distinct "sweet spot" for each stick. Only one of the six wooden sticks (the highest quality model which had a carbon-insert blade) was found to have a definite "sweet spot" on the blade. That is, a specific location which showed markedly higher puck exit velocity. The other five wooden models showed “erratic performance curves” with no specific location exhibiting higher exit velocities (Anderson, 2008). Of the composite sticks tested, only two were said to have erratic performance curves and were both described as low-end composite models (Anderson, 2008). The data seem to demonstrate that at least theoretically, composite sticks yield an increase in performance as some suggest. Perhaps further studies might clarify more nuances of stickhandling technique and a stickhandling sweet spot might be designed into stick blade to give the player an advantage when playing the puck. However, more research is needed to investigate the stickhandling task before this is a feasible pospect. Further to this, Hove and his colleagues suggested that it might be feasible to develop “novice” and “expert” stick models that take advantage of the action-relevant inertial properties (Hove et al., 2006). That is, sticks could be developed for different players based on experience/skill level to enhance the adoption of ice hockey skills. The results of this study suggest that this is not the case. There were no significant interactions of skill and stick conditon in any displacement, velocity or acceleration variable evaluated. No one stick condition was utilized more effectively by either skill group. Furthermore, the weight that was used in the current study was beginning to compromise the weight advantages offered by high end models of hockey sticks. Adding more weight might suffice to create a measurable effect of condition but at the sacrifice of overall weight; the primary advantage of high end sticks.

Conclusions

Within the game of ice hockey, stickhandling and puck control are an essential skill. The manner and context of stick-puck movement tasks are quite varied making quantitative analysis difficult. Hence, to begin to address these shortcomings in knowledge, this study examined one controlled task situation commonly used in training development: puck cycling through a figure-8 route about two static obstacles. The purpose of this research is to address how skill level and the properties of the stick, specifically weight distribution, might influence a repetitive stickhandling task. To our knowledge, there is no available data concerning the kinematic variables during stickhandling tasks in ice hockey. Twenty-seven healthy, male subjects were recruited in order to evaluate the difference between skill and if stick condition impinged on this relationship. A "volley-and-catch" (rectilinear) and "plough-push" (curvilinear) technique were expected to be manifested in two clearly different patterns. Four patterns were identified which suggests that there are more than two distinct techniques that can be used for task completion. Results indicate that variation in stick mass and inertial properties had a negligible effect on the gross movement patterns of the stick. Not surprisingly, varsity players complete the skill faster than recreational players as well as achieving higher peak velocities and accelerations. This data indicate that recreational players had the most difficulty completing the right (25% slower) and backhand cross (20% slower) phases compared to varsity players. I believe that speed was sacrificed in order to maintain the puck's trajectory to fulfill the task requirement to complete each loop as accurately as possible. Controlling the puck with the backhand face of the blade was a larger obstacle to completing the task quickly for recreational players. In addition, varsity players also exhibited different forwards and backwards translation. While the range of translation was similar between groups, the puck patterns were shifted 5cm further forward. It was speculated that this was a result of varsity players standing closer to the obstacle in order to position themselves more "on top" of the obstacles and limit the degree to which their movements would exceed their range of motion. In side-to-side movements recreational players had greater right side obstacle clearance (approximately 30%) than varsity players which contributed to their longer phase time and slower progress into the backhand phase. This study has demonstrated a need for further research on the topic of stickhandling and puck control in order to continue to elucidate the nuances of the task. Whole-body kinematics will help to identify the specific body postures that can be observed during stickhandling and highlight differences in task completion between varsity and recreational players. In terms of the stick, lie angle has a major unknown effect on the completion of the task. The data demonstrates differences in execution technique (namely how far a player stands from the obstacles) that might be affected by the lie angle. This might be a key stick property which helps to dictate success in stickhandling tasks.

References

Anderson, R. L. (2008). *Experimental Characterization of Ice Hockey Sticks and Pucks.* Master of Science, Washington State University. Retrieved from http://www.dissertations.wsu.edu/Thesis/Spring2008/R_Anderson_042308.pdf

Bechler, J. R., Jobe, F. W., Pink, M., Perry, J., & Ruwe, P. A. (1995). Electromyographic analysis of the hip and knee during the golf swing. *Clinical journal of sport medicine: official journal of the Canadian Academy of Sport Medicine, 5*(3), 162.

Bongers, R. M., Michaels, C. F., & Smitsman, A. W. (2004). Variations of Tool and Task Characteristics Reveal That Tool-Use Postures Are Anticipated. *Journal of Motor Behavior, 36*(3), 305 - 315. doi: 10.3200/JMBR.36.3.305-315

Bongers, R. M., Smitsman, A. W., & Michaels, C. F. (2003). Geometries and Dynamics of a Rod Determine How It Is Used for Reaching. *Journal of Motor Behavior, 35*(1), 4 - 22. doi: 10.1080/00222890309602117

Button, C., MacLeod, M., Sanders, R., & Coleman, S. (2003). Examining movement variability in the basketball free-throw action at different skill levels. *Research Quarterly for Exercise and Sport, 74*(3), 257.

Carson, R. G., Chua, R., Byblow, W. D., Poon, P., & Smethurst, C. J. (1999). Changes in posture alter the attentional demands of voluntary movement. *Proceedings of the Royal Society of London. Series B: Biological Sciences, 266*(1421), 853-857.

Easton Hockey. (2011a, Last update not indicated). Product Tech: Stick Technology Retrieved August 30, 2011, from http://eastonhockey.com/the-difference/stick-tech

Easton Hockey. (2011b, Last update not indicated). Products: One Piece: Sticks: Synergy: EQ50 Retrieved August 30, 2011, from http://eastonhockey.com/eq50-2.html

Hockey Canada. (2010a). *Hockey Canada Referee's Case Book/Rule Combination 2010 - 2012* (8th ed.). Ottawa: Hockey Canada.

Hockey Canada. (2010b). National Skills Standards and Testing Program Handbook (pp. 11). Calgary Alberta: Hockey Canada.

Hove, P., Riley, M. A., & Shockley, K. (2006). Perceiving Affordances of Hockey Sticks by Dynamic Touch. *Ecological Psychology, 18*(3), 163 - 189. doi: 10.1207/s15326969eco1803_2

Johansson, R. S., & Flanagan, J. R. (2009a). Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience, 10*(5), 345-359. doi: 10.1038/nrn2621

Johansson, R. S., & Flanagan, J. R. (2009b). Sensory control of object manipulation. *Sensorimotor control of grasping: physiology and pathophysiology. Cambridge University Press, Cambridge*, 141-160.

Johansson, R. S., & Westling, G. (1984). Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects. *Experimental Brain Research, 56*(3), 550-564. doi: 10.1007/bf00237997

Johansson, R. S., & Westling, G. (1987). Signals in tactile afferents from the fingers eliciting adaptive motor responses during precision grip. *Experimental Brain Research, 66*(1), 141-154. doi: 10.1007/bf00236210

Johansson, R. S., & Westling, G. (1988). Coordinated isometric muscle commands adequately and erroneously programmed for the weight during lifting task with precision grip. *Experimental Brain Research, 71*(1), 59-71. doi: 10.1007/bf00247522

Lomond, K., Turcotte, R., & Pearsall, D. (2007). Three-dimensional analysis of blade contact in an ice hockey slap shot, in relation to player skill. *Sports Engineering, 10*(2), 87-100.

López De Subijana, C., Juárez, D., Mallo, J., & Navarro, E. (2010). Biomechanical analysis of the penalty-corner drag-flick of elite male and female hockey players. *Sports Biomechanics, 9*(2), 72-78. doi: 10.1080/14763141.2010.495414

Magee, P. M. (2009). *Whole-body predictors of wrist shot accuracy in ice hockey: A kinematic analysis.* Master of Science, McGill University, Montreal. Retrieved from http://proquest.umi.com/pqdlink?did=2043553931&Fmt=7&clientId=10843&RQT=309&VName=PQD (AAT MR61645)

Michaud-Paquette, Y., Pearsall, D., & Turcotte, R. (2009). Predictors of scoring accuracy: ice hockey wrist shot mechanics. *Sports Engineering, 11*(2), 75-84. doi: 10.1007/s12283-008-0009-9

Morrison, S., Hong, S., & Newell, K. (2009). Upper frequency limits of bilateral coordination patterns. *Neuroscience Letters, 454*(3), 233-238.

Myers, J., Lephart, S., Tsai, Y.-S., Sell, T., Smoliga, J., & Jolly, J. (2008). The role of upper torso and pelvis rotation in driving performance during the golf swing. *Journal of Sports Sciences, 26*(2), 181-188. doi: 10.1080/02640410701373543

National Hockey League. (2010). Official Rules 2010 - 2011 Retrieved from http://www.nhl.com/league/ext/rules/2010-2011_Rulebook.pdf

NFL Enterprises. (2012, Not Indicated). What Goes on at the Combine Retrieved March 26, 2012, from http://www.nfl.com/combine/workouts

Pearsall, D. J. (2000). Biomechanics of ice hockey. *Exercise and sport sciences reviews, 1*, 675.

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*, 3-12.

Ranganathan, R., & Carlton, L. G. (2007). Perception-Action Coupling and Anticipatory Performance in Baseball Batting. *Journal of Motor Behavior, 39*(5), 369-380. doi: 10.3200/jmbr.39.5.369-380

Shaffer, B. E. N., Jobe, F. W., Pink, M., & Perry, J. (1993). Baseball batting: An electromyographic study. *Clinical orthopaedics and related research, 292*, 285.

SI.com. (2005). A Whole New World. [Article]. *Sports Illustrated, 103*(13), 56-59.

Skahan, S. (Producer). (2011, March 26 2012). From NEHJ: Scouting the Scouting Combine. *New England Hockey Journal*. Retrieved from http://hockeyjournal.com/news/players/2011-12/From_NEHJ-_Scouting_the_Scouting_Combine

Stein, H., & Kopper, D. E. (Writers) & H. Stein (Director). (2010). Factory Made: Hockey Sticks [Television]. In Discovery Studios (Producer), *Factory Made*. Silver Spring MD: Discovery Communications USA.

Summers, J. (2002). Practice and Training in Bimanual Coordination Tasks: Strategies and Constraints. *Brain and Cognition, 48*(1), 166-178. doi: 10.1006/brcg.2001.1311

Swinnen, S. P., & Wenderoth, N. (2004). Two hands, one brain: cognitive neuroscience of bimanual skill. *Trends in Cognitive Sciences, 8*(1), 18-25. doi: 10.1016/j.tics.2003.10.017

Temprado, J. J., Chardenon, A., & Laurent, M. (2001). Interplay of biomechanical and neuromuscular constraints on pattern stability and attentional demands in a bimanual coordination task in human subjects. *Neuroscience Letters, 303*(2), 127-131. doi: 10.1016/s0304-3940(01)01650-0

USA Hockey. (2011). The Official Rules of Ice Hockey *2011-2013 Official Rules of Ice Hockey*

Woo, T., Loh, J., Turcotte, R., & Pearsall, D. (2004). *The ice hockey slap shot, elite versus recreational*.

Wu, T. C., Pearsall, D., Hodges, A., Turcotte, R., Lefebvre, R., Montgomery, D., & Bateni, H. (2003). The performance of the ice hockey slap and wrist shots: the effects of stick construction and player skill. *Sports Engineering, 6*(1), 31-39.

Appendicies

Appendix A: Sample data collection sheet for recording descriptive information, handedness and trial-by-trial performance data for each subject

Stick random order: ___, ___, ___, ___, ___

PARTICIPANT CODE: ___________

The Kinematic Characteristics of Stickhandling Tasks in Ice Hockey:

Subject Information Sheet

Test Date: ______________________________ Age: _________

Day Month Year

Years Playing:	_____________	Position:	__________
Previous Team:	_____________	League:	__________

Height (mm): _________

Weight (kg): _________

Shot Preference:	__________
Preferred Stick Length:	__________
Everyday Handedness:	__________

Handedness Questionnaire

Which hand do you use for the following tasks:		Always Left	Usually Left	Either	Usually Right	Always Right
1	To Write Legibly					
2	To throw a ball to hit a target					
3	To play a game requiring the use of a racquet					
4	At the top of a broom to sweep the floor					
5	At the top of a shovel					
6	To hold a match while you light it					
7	To hold scissors when cutting a sheet of paper					
8	To hold the thread while threading a needle					
9	To hold the pack while dealing cards					
10	To hold the nail while hammering it into a board					
11	To hold your toothbrush when brushing your teeth					
12	To hold the jar when unscrewing the lid					
13	To draw a picture					
14	To hold a potato while peeling it					
15	To hold a jug when pouring a glass of water					

Which hand do you use for the following tasks:		Always Left	Usually Left	Either	Usually Right	Always Right
16	To hold a knife when cutting a slice of bread					
17	To hold a knife when also eating with a fork					
18	To hold a glass for drinking					
19	To hold a dish when drying it					
20	To hold the comb while combing your hair					
21	To hold the deck of cards while sorting them					
22	To hold the body of a pocketknife when opening it					
23	To hold a watch when setting the time					
24	To reach for an object on a high shelf					
25	To strum the strings of a guitar					
26	To pull the trigger of a rifle					
27	To hold a scrub brush while washing the floor					
28	To rub writing off a blackboard with an eraser					

Totals					

Handedness score:

Always Left	Usually Left	Either	Usually Right	Always Right	Cumulative Total

Overall Handedness: __________

Trial #	Stick					Trial outcome			
	Cont	CoM	Dist	Prox	Ovi	Clean	# Error	Fail	Details/Reason for failure

Appendix B: Compiled Results Summary Table

Section 1: Skill-wise X-displacement

Measure		Magnitude (m) Var. mean (SD)	Magnitude (m) Rec. mean (SD)	Event Phase Timing (s) Var. mean (SD)	Event Phase Timing (s) Rec. mean (SD)	Event Loop Timing (s) Var. mean (SD)	Event Loop Timing (s) Rec. mean (SD)
Puck	left min.	0.378 (0.118)	0.374 (0.126)	0.302 (0.095)*	0.405 (0.163)	1.948 (0.256)*	2.428 (0.468)
	right max.	0.329 (0.112)*	0.368 (0.139)	0.284 (0.064)*	0.399 (0.145)	0.850 (0.142)*	1.030 (0.237)
s3	left min.	0.280 (0.143)	0.273 (0.145)	0.262 (0.094)*	0.371 (0.158)	1.906 (0.251)*	2.394 (0.482)
	right max.	0.403 (0.179)*	0.445 (0.171)	0.241 (0.066)*	0.379 (0.140)	0.806 (0.145)*	1.010 (0.232)
Butt	left min.	-0.562 (0.288)*	-0.437 (0.344)	0.190 (0.112)*	0.280 (0.151)	1.830 (0.255)*	2.305 (0.457)
	right max.	-0.267 (0.277)*	-0.129 (0.330)	0.174 (0.102)*	0.346 (0.188)	0.758 (0.182)*	0.970 (0.269)

Measure				Event Phase Timing (%) Var. mean (SD)	Event Phase Timing (%) Rec. mean (SD)	Event Loop Timing (%) Var. mean (SD)	Event Loop Timing (%) Rec. mean (SD)
Puck	left min.			51.606 (13.553)*	54.397 (17.161)	87.191 (6.208)	87.737 (7.348)
	right max.			52.895 (10.364)*	55.342 (15.334)	38.070 (4.848)*	37.360 (5.543)
s3	left min.			44.563 (13.077)*	49.227 (15.354)	85.363 (5.996)*	86.325 (7.022)
	right max.			44.707 (10.595)*	52.145 (13.693)	36.112 (5.040)	36.556 (4.981)
Butt	left min.			32.060 (17.337)*	37.144 (17.405)	81.813 (6.792)*	83.018 (7.403)
	right max.			30.126 (16.528)	46.267 (22.504)	32.242 (5.998)*	34.751 (6.319)

Section 2: Skill-wise Y-displacement

Measure		Magnitude (m) Var. mean (SD)	Magnitude (m) Rec. mean (SD)	Event Phase Timing (s) Var. mean (SD)	Event Phase Timing (s) Rec. mean (SD)	Event Loop Timing (s) Var. mean (SD)	Event Loop Timing (s) Rec. mean (SD)
Puck	right max.	0.293 (0.082)*	0.277 (0.077)	0.506 (0.116)*	0.607 (0.137)	0.506 (0.116)*	0.607 (0.137)
	right min.	0.285 (0.087)*	0.331 (0.100)	0.443 (0.105)*	0.621 (0.357)	1.010 (0.159)*	1.234 (0.281)
	left max.	0.278 (0.069)*	0.264 (0.082)	0.504 (0.111)*	0.645 (0.321)	1.607 (0.227)*	1.985 (0.363)

	left min.	0.317 (0.086)*	0.363 (0.121)	0.533 (0.154)*	0.645 (0.184)	2.178 (0.303)*	2.666 (0.493)
s3	right max.	0.193 (0.075)*	0.179 (0.071)	0.479 (0.116)*	0.608 (0.193)	0.479 (0.116)*	0.608 (0.193)
	right min.	0.448 (0.068)*	0.489 (0.079)	0.441 (0.097)*	0.622 (0.354)	1.001 (0.157)*	1.236 (0.286)
	left max.	0.212 (0.074)*	0.221 (0.077)	0.492 (0.119)*	0.647 (0.333)	1.594 (0.232)*	1.983 (0.390)
	left min.	0.462 (0.074)*	0.499 (0.105)	0.500 (0.138)*	0.625 (0.179)	2.144 (0.292)*	2.645 (0.493)
Butt	right max.	-0.859 (0.078)*	-0.769 (0.096)	0.471 (0.131)*	0.338 (0.298)	0.471 (0.131)*	0.338 (0.298)
	right min.	1.176 (0.089)*	1.225 (0.076)	0.038 (0.030)*	0.087 (0.224)	1.076 (0.141)*	1.451 (0.383)
	left max.	-0.609 (0.185)*	-0.515 (0.182)	0.315 (0.394)	0.287 (0.335)	1.950 (0.461)*	2.325 (0.509)
	left min.	0.978 (0.078)	0.982 (0.072)	0.268 (0.119)*	0.446 (0.284)	0.268 (0.119)*	0.446 (0.284)
				Event Phase Timing (%)		**Event Loop Timing (%)**	
Puck	right max.			89.292 (12.910)*	96.514 (16.175)	22.561 (4.022)*	22.022 (3.728)
	right min.			81.977 (14.943)	84.178 (28.720)	45.135 (4.630)*	44.477 (5.157)
	left max.			95.019 (16.948)	94.731 (19.412)	72.199 (5.742)	71.656 (6.303)
	left min.			90.445 (18.661)	87.171 (17.747)	95.119 (15.394)*	96.446 (7.115)
s3	right max.			84.477 (14.002)*	96.328 (22.854)	21.355 (4.260)*	21.960 (4.859)
	right min.			81.673 (13.156)*	84.413 (28.092)	45.042 (4.565)	44.543 (5.186)
	left max.			91.828 (19.551)*	94.364 (18.243)	71.303 (6.154)	71.582 (6.143)
	left min.			84.698 (16.870)	84.509 (17.186)	95.883 (6.395)	95.744 (6.937)
Butt	right max.			80.077 (23.135)*	40.642 (37.729)	20.616 (6.431)*	9.281 (8.642)
	right min.			7.323 (5.886)	7.946 (14.706)	49.946 (4.699)	49.630 (5.849)
	left max.			24.978 (23.135)	26.835 (37.729)	79.913 (6.431)	80.033 (8.642)
	left min.			46.869 (17.010)*	59.071 (25.852)	11.883 (4.480)*	13.237 (5.483)

Section 3: Skill-wise Z-dislpacement

Measure	Magnitude (m)	Event Phase Timing (s)	Event Loop Timing (s)

		Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)
s3	fhx	0.171 (0.034)	0.174 (0.022)	0.317 (0.175)	0.305 (0.128)	0.317 (0.175)	0.305 (0.128)
	right	0.180 (0.023)*	0.207 (0.035)	0.187 (0.182)*	0.252 (0.161)	0.813 (0.231)*	0.898 (0.236)
	bhx	0.175 (0.035)*	0.185 (0.031)	0.269 (0.172)*	0.463 (0.367)	1.391 (0.256)*	1.743 (0.360)
	left	0.164 (0.038)*	0.176 (0.027)	0.224 (0.222)*	0.294 (0.199)	1.893 (0.276)*	2.379 (0.517)
Butt	fhx	1.151 (0.069)	1.138 (0.064)	0.272 (0.131)	0.292 (0.075)	0.272 (0.131)	0.292 (0.075)
	right	1.153 (0.083)*	1.099 (0.085)	0.293 (0.150)*	0.350 (0.142)	0.916 (0.213)*	0.994 (0.220)
	bhx	1.127 (0.102)*	1.105 (0.108)	0.241 (0.182)*	0.342 (0.187)	1.362 (0.263)*	1.625 (0.329)
	left	1.012 (0.069)*	1.060 (0.1270	0.224 (0.222)	0.294 (0.211)	1.871 (0.297)*	2.249 (0.324)

				Event Phase Timing (%)		**Event Loop Timing (%)**	
s3	fhx			53.811 (23.549)	54.603 (21.916)	13.569 (6.596)*	12.380 (4.373)
	right			31.796 (28.023)	33.456 (18.511)	34.791 (7.941)*	31.809 (5.933)
	bhx			46.944 (27.561)*	62.205 (27.672)	60.619 (7.758)*	63.384 (9.086)
	left			36.203 (34.736)	36.575 (21.742)	83.371 (10.196)	82.877 (8.341)
Butt	fhx			51.234 (23.263)	54.746 (17.260)	12.771 (6.066)	12.563 (3.473)
	right			51.850 (24.140)*	48.449 (19.504)	39.349 (7.568)*	35.657 (6.347)
	bhx			42.826 (31.596)*	56.796 (31.287)	59.516 (8.851)*	62.216 (9.733)
	left			35.063 (39.213)	33.408 (20.923)	83.039 (11.195)	81.960 (8.071)

Section 4: Skill-wise X-velocity

Measure		**Magnitude (m/s)**		**Event Phase Timing (s)**		**Event Loop Timing (s)**	
		Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)
Puck	fhx	2.944 (0.535)*	2.531 (0.460)	0.181 (0.184)*	0.242 (0.200)	0.181 (0.184)*	0.242 (0.200)
	bhx	-2.971 (0.454)*	-2.521 (0.433)	0.193 (0.148)*	0.278 (0.338)	1.296 (0.253)*	1.609 (0.363)
s3	fhx	3.556 (0.689)*	2.607 (0.698)	0.267 (0.195)*	0.179 (0.208)	0.267 (0.195)*	0.179 (0.208)
	bhx	-3.536 (0.888)*	-2.783 (0.763)	0.279 (0.143)*	0.388 (0.383)	1.373 (0.258)*	1.708 (0.371)

Butt	fhx	1.477 (0.349)*	1.352 (0.382)	-0.094 (0.127)*	-0.162 (0.121)	-0.094 (0.127)*	-0.162 (0.121)
	bhx	-1.269 (0.312)*	-1.177 (0.388)	0.432 (0.107)*	0.578 (0.485)	1.534 (0.252)*	1.870 (0.359)
				Event Phase Timing (%)		**Event Loop Timing (%)**	
Puck	fhx			30.720 (28.311)*	37.317 (27.698)	57.625 (8.006)	58.629 (7.994)
	bhx			35.181 (25.549)*	40.112 (26.614)	57.625 (8.006)*	58.629 (7.994)
s3	fhx			48.045 (30.221)*	30.110 (33.394)	11.639 (7.618)*	6.822 (7.498)
	bhx			51.407 (24.852)*	56.570 (27.406)	61.373 (7.888)	62.373 (8.322)
Butt	fhx			-16.555 (22.281)*	-25.543 (17.041)	-4.102 (5.478)*	-5.921 (3.961)
	bhx			79.695 (14.232)	80.914 (18.977)	68.045 (5.832)	68.504 (6.287)

Section 5: Skill-wise Y-velocity

Measure		**Magnitude (m/s)**		**Event Phase Timing (s)**		**Event Loop Timing (s)**	
		Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)
Puck	fhx	1.619 (0.362)*	1.443 (0.368)	0.140 (0.078)*	0.187 (0.095)	0.140 (0.078)*	0.187 (0.095)
	right	1.766 (0.569)	1.728 (0.455)	0.157 (0.091)*	0.214 (0.153)	0.719 (0.126)*	0.843 (0.229)
	bhx	1.371 (0.280)*	1.265 (0.266)	0.158 (0.098)*	0.219 (0.336)	1.259 (0.196)*	1.538 (0.348)
	left	-1.844 (0.556)*	-1.710 (0.483)	0.192 (0.133)*	0.256 (0.144)	1.837 (0.276)*	2.273 (0.444)
s3	fhx	2.154 (0.425)*	1.676 (0.414)	0.193 (0.091)*	0.243 (0.101)	0.193 (0.091)*	0.243 (0.101)
	right	-2.262 (0.697)	-2.212 (0.620)	0.192 (0.082)*	0.309 (0.140)	0.757 (0.130)*	0.938 (0.228)
	bhx	1.997 (0.367)*	1.739 (0.386)	0.192 (0.084)*	0.285 (0.348)	1.295 (0.199)*	1.602 (0.369)
	left	-2.364 (0.621)	-2.329 (0.582)	0.198 (0.116)*	0.300 (0.138)	1.843 (0.265)*	2.316 (0.467)
Butt	fhx	0.791 (0.296)*	0.562 (0.405)	0.368 (0.131)	0.384 (0.177)	0.368 (0.131)	0.384 (0.177)
	right	-1.199 (0.391)*	-1.244 (0.354)	0.212 (0.132)*	0.271 (0.175)	0.776 (0.173)*	0.896 (0.241)
	bhx	1.749 (0.421)*	1.657 (0.422)	0.273 (0.076)*	0.370 (0.129)	1.373 (0.197)*	1.709 (0.352)
	left	-0.992 (0.507)*	-1.113 (0.472)	0.236 (0.142)*	0.342 (0.161)	1.878 (0.272)*	2.358 (0.498)

Event Phase Timing **Event Loop Timing**

				Event Phase Timing (%)		Event Loop Timing (%)	
Puck	fhx			24.308 (12.441)*	29.237 (11.920)	6.188 (3.325)*	6.742 (2.943)
	right			29.161 (16.105)	28.975 (17.696)	32.172 (4.320)*	30.452 (5.187)
	bhx			29.454 (17.890)	28.219 (17.135)	56.338 (6.089)	55.583 (6.861)
	left			32.814 (21.374)*	35.348 (19.872)	82.235 (7.553)	82.570 (7.987)
s3	fhx			34.082 (13.884)*	38.842 (14.501)	8.594 (3.633)	8.920 (3.393)
	right			35.594 (13.957)*	42.271 (15.121)	33.888 (4.480)	34.031 (4.875)
	bhx			35.689 (15.885)*	38.260 (18.718)	57.813 (6.070)	58.062 (6.920)
	left			33.462 (17.968)*	40.335 (16.414)	82.461 (6.808)*	83.999 (7.253)
Butt	fhx			64.962 (15.177)	62.377 (27.308)	16.325 (4.501)*	14.405 (6.186)
	right			39.429 (24.032)	37.517 (20.967)	34.789 (6.628)*	32.735 (6.108)
	bhx			51.427 (14.749)*	56.448 (16.406)	61.557 (5.991)	62.185 (6.781)
	left			38.092 (19.189)*	44.829 (17.320)	83.544 (6.868)*	84.751 (6.797)

Section 6: Skill-wise Z-velocity

Measure		Magnitude (m/s)		Event Phase Timing (s)		Event Loop Timing (s)	
		Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)
s3	fhx	0.745 (0.335)*	0.632 (0.210)	0.264 (0.210)*	0.347 (0.205)	0.264 (0.210)	0.347 (0.205)
	right	0.514 (0.181)*	0.563 (0.225)	0.169 (0.172)	0.173 (0.149)	0.773 (0.196)*	0.829 (0.231)
	bhx	0.807 (0.228)*	0.862 (0.227)	0.340 (0.189)*	0.438 (0.373)	1.447 (0.322)*	1.669 (0.378)
	left	0.623 (0.269)	0.632 (0.249)	0.139 (0.160)*	0.257 (0.167)	1.797 (0.262)*	2.357 (0.481)
Butt	fhx	0.898 (0.310)*	0.698 (0.251)	0.250 (0.230)	0.181 (0.204)	0.250 (0.230)	0.181 (0.204)
	right	1.088 (0.368)*	0.931 (0.247)	0.151 (0.118)*	0.229 (0.143)	0.766 (0.161)*	0.871 (0.222)
	bhx	0.206 (0.170)*	0.265 (0.212)	0.448 (0.082)*	0.605 (0.476)	1.562 (0.178)*	1.828 (0.353)
	left	0.753 (0.334)*	0.588 (0.265)	0.336 (0.176)*	0.276 (0.216)	1.958 (0.235)*	2.347 (0.435)
				Event Phase Timing (%)		Event Loop Timing (%)	

Measure		Magnitude Var. mean (SD)	Magnitude Rec. mean (SD)	Event Phase Timing Var. mean (SD)	Event Phase Timing Rec. mean (SD)	Event Loop Timing Var. mean (SD)	Event Loop Timing Rec. mean (SD)
s3	fhx			44.505 (31.879)*	58.688 (31.644)	11.206 (8.547)*	13.387 (7.321)
	right			31.312 (32.525)*	22.324 (17.745)	34.196 (8.492)*	29.015 (5.356)
	bhx			57.219 (28.157)	62.188 (27.621)	63.160 (8.678)	63.899 (8.735)
	left			22.315 (22.601)*	32.027 (18.976)	79.495 (7.866)*	81.715 (7.345)
Butt	fhx			42.692 (36.807)*	30.048 (30.832)	10.505 (9.293)*	7.286 (7.726)
	right			27.470 (21.163)*	30.300 (16.457)	33.454 (5.964)*	30.912 (5.172)
	bhx			81.819 (13.203)*	76.109 (16.494)	69.890 (5.685)*	66.381 (7.944)
	left			56.090 (29.700)*	36.623 (28.599)	87.264 (8.507)*	82.355 (9.303)

Section 7: Skill-wise X-acceleration

Measure		Magnitude (m/s^2)		Event Phase Timing (s)		Event Loop Timing (s)	
		Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)
Puck	fhx	0.061 (0.036)*	0.045 (0.036)	0.492 (0.124)*	0.578 (0.153)	2.127 (0.280)*	2.590 (0.474)
	bhx	-0.065 (0.037)*	-0.044 (0.031)	0.445 (0.089)*	0.564 (0.154)	1.007 (0.229)*	1.195 (0.252)
s3	fhx	0.052 (0.022)*	0.047 (0.021)	0.425 (0.127)*	0.515 (0.151)	2.063 (0.266)*	2.542 (0.491)
	bhx	-0.057 (0.032)*	-0.045 (0.020)	0.390 (0.148)*	0.518 (0.156)	0.957 (0.143)*	1.153 (0.246)
Butt	fhx	0.033 (0.021)	0.030 (0.024)	0.372 (0.138)*	0.440 (0.136)	1.997 (0.271)*	2.460 (0.474)
	bhx	-0.020 (0.014)*	-0.025 (0.019)	0.276 (0.140)*	0.409 90.241)	0.833 (0.204)*	1.032 (0.302)
				Event Phase Timing (%)		**Event Loop Timing (%)**	
Puck	fhx			81.544 (16.575)*	78.976 (16.155)	94.993 (6.541)	94.109 (7.033)
	bhx			82.527 (12.922)*	77.840 (15.453)	45.007 (4.937)*	43.347 (5.836)
s3	fhx			72.414 (18.400)*	69.374 (15.082)	92.748 (6.761)*	91.673 (6.970)
	bhx			72.437 (15.410)	71.359 (14.725)	42.575 (5.175)*	41.708 (5.008)

Butt	fhx			61.913 (21.129)	60.913 (17.968)	89.629 (7.566)	89.613 (7.675)
	bhx			49.869 (25.026)*	55.277 (28.807)	36.555 (7.267)	37.183 (7.745)

<u>Section 8: Skill-wise Y-Acceleration</u>

Measure		Magnitude (m/s^2)		Event Phase Timing (s)		Event Loop Timing (s)	
		Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)	Var. mean (SD)	Rec. mean (SD)
Puck	fhx	0.083 (0.040)*	0.046 (0.032)	0.560 (0.137)*	0.723 (0.149)	2.176 (0.289)*	2.907 (0.557)
	right	-0.064 (0.056)*	-0.075 (0.049)	0.061 (0.044)*	0.085 (0.069)	0.611 (0.107)*	0.705 (0.160)
	bhx	0.062 (0.028)*	0.044 (0.023)	0.487 (0.085)*	0.624 (0.134)	1.058 (0.163)*	1.265 (0.208)
	left	-0.097 (0.070)*	-0.066 (0.049)	0.074 (0.058)*	0.104 (0.072)	1.685 (0.221)*	2.024 (0.333)
s3	fhx	0.063 (0.025)*	0.040 (0.017)	0.537 (0.101)*	0.675 (0.144)	2.194 (0.277)*	2.749 (0.490)
	right	-0.064 (0.025)*	-0.057 (0.024)	0.056 (0.042)*	0.113 (0.085)	0.615 (0.111)*	0.730 (0.163)
	bhx	0.058 (0.021)*	0.045 (0.019)	0.473 (0.095)*	0.609 (0.127)	1.052 (0.163)*	1.231 (0.225)
	left	-0.080 (0.039)*	-0.063 (0.028)	0.069 (0.052)*	0.123 (0.080)	1.707 (0.225)*	2.083 (0.375)
Butt	fhx	0.037 (0.036)	0.043 (0.030)	0.359 (0.120)	0.384 (0.144)	0.359 (0.120)	0.384 (0.144)
	right	-0.043 (0.028)	-0.040 (0.020)	0.095 (0.073)*	0.169 (0.120)	0.633 (0.137)*	0.777 (0.192)
	bhx	0.048 (0.018)*	0.034 (0.017)	0.118 (0.069)*	0.157 (0.329)	1.191 (0.152)*	1.455 (0.311)
	left	-0.048 (0.037)*	-0.043 (0.021)	0.236 (0.182)*	0.270 (0.172)	1.897 (0.382)*	2.319 (0.439)
				Event Phase Timing (%)		**Event Loop Timing (%)**	
Puck	fhx			92.092 (14.056)	90.588 (12.499)	98.098 (5.644)	97.392 (5.890)
	right			11.595 (8.726)	11.563 (8.095)	27.635 (3.814)*	25.659 (3.379)
	bhx			87.998 (10.568)	85.761 (11.498)	46.399 (3.966)	46.141 (3.953)
	left			12.297 (9.195)*	14.901 (10.442)	75.661 (5.357)	75.868 (5.674)
s3	fhx			90.947 (12.205)*	88.328 (12.162)	97.656 (5.534)	96.824 (6.176)
	right			10.181 (7.506)*	15.596 (10.628)	27.309 (3.872)*	26.604 (3.796)

	bhx		87.474 (11.800)*	85.497 (10.139)	47.113 (4.547)*	45.586 (4.059)
	left		11.693 (8.352)*	17.078 (11.158)	76.374 (5.425)	76.998 (5.855)
Butt	fhx		64.254 (18.334)	63.985 (21.283)	16.162 (4.619)*	14.332 (4.560)
Butt	right		17.364 (12.474)*	23.028 (13.763)	29.041 (4.169)	28.707 (3.825)
Butt	bhx		22.728 (13.796)*	19.347 (12.516)	54.148 (4.808)*	53.036 (5.661)
Butt	left		38.072 (25.870)	35.103 (21.203)	83.571 (7.904)*	82.488 (7.494)