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Skating start propulsion: Three-dimensional kinematic analysis of elite male and female ice hockey players

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Abstract

The forward skating start is a fundamental skill for male and female ice hockey players. However, performance differences by athlete's sex cannot be fully explained by physiological variables; hence, other factors such as skating technique warrant examination. Therefore, the purpose of this study was to evaluate the body movement kinematics of ice hockey skating starts between elite male and female ice hockey participants. Male (*n*=9) and female (*n*=10) elite ice hockey players performed five forward skating start accelerations. An 18-camera motion capture system placed on the arena ice surface captured full-body kinematics during the first seven skating start steps within 15 meters. Males' maximum skating speeds were greater than females. Skating technique sex differences were noted: in particular, females presented ~10° lower hip abduction throughout skating stance as well as ~10° greater knee extension at initial ice stance contact, conspicuously followed by a brief cessation in knee extension at the moment of ice contact, not evident in male skaters. Further study is warranted to explain why these skating technique differences exist in relation to factors such as differences in training, equipment, performance level and anthropometrics.

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Introduction

Rapid forward skating starts are a fundamental ice hockey skill and strategically important in a game situation in order to gain puck possession and limit your opponent's chances to score. However, the challenge to male and female skaters is that the low ice surface friction precludes substantial anteroposterior ground reaction forces: ideal for gliding but detrimental to initiating forward acceleration. Consequently, compared to over ground running starts, skating starts require distinctive locomotion patterns needed to orient the skate blade's edge for push off at an acute angle to the primary forward movement direction (Denny, 2011; Pearsall, Turcotte, Levangie, & Forget, 2014).

Skating starts require substantial movement in the frontal plane (De Koning, Thomas, Berger, de Groot, & van Ingen Schenau, 1995; Lockwood & Frost, 2009; Stidwill, Pearsall, & Turcotte, 2010; Upjohn, Turcotte, Pearsall, & Loh, 2008) and high landing forces (Stidwill, Turcotte, Dixon & Pearsall, 2009). Skating locomotion is a difficult skill to perfect; thus, athletes must train to obtain optimal lower body joint coordination and muscle strength for both body propulsion and dynamic stability (Chang, Turcotte, & Pearsall, 2009; Tyler, Nicholas, Campbell, & McHugh, 2001). Skating's atypical locomotion, however, may place ice hockey players at a greater risk of hip non-contact Femoral Acetabular Impingement injuries compared to other sports such as soccer players (Ayeni et al., 2014; Stull, Philippon, & LaPrade, 2011; Wilcox, Osgood, White, & Vince, 2015). Hence, a better understanding of skating mechanics is relevant in terms of athlete performance and injury prevention.

In addition to the above, with the surge in participation in women's ice hockey (Hockey Canada, 2014), the relevance of understanding male-female differences in skating start techniques is clear from a coaching perspective to guide specific training techniques to enhance skating performance (Abbott, 2014; Bracko, 2001; Bracko & George, 2001; Forward et al., 2014; Geithner, 2009, Thorsen, & Henriksson-Larsen, 2011; Pearsall, Turcotte, & Murphy, 2000). Differences in anthropometrics, fitness and physiological variables between male and female athletes cannot fully explain the performance differences in ice-skating (Bracko and George, 2001; Geithner, 2009, Gilenstam et al., 2011), hence, additional factors such as movement technique differences in skating starts should be examined.

There is limited quantitative analysis of ice hockey skating starts due largely to the technical challenge of using state-of-the-art motion capture technologies (principally reserved for in-lab, controlled environments) in the large, open ice arena setting (De Koning, Thomas, Berger, de Groot, & van Ingen Schenau, 1995). Recent studies have demonstrated the feasibility of using motion tracking cameras in ice arenas to study skating starts in males athletes (Renaud, 2016) and of shooting tasks (Swarén, Soehnlein, Holmberg, Stöggl, & Björklund, 2015). Encouraged by the latter studies, the purpose of this study was to evaluate the body movement kinematics of ice hockey skating starts between elite male and female ice hockey players over a larger continuous skating surface (15 m long). Stride-to-stride kinematic measures of hip and knee movements were recorded during the skate start. It was hypothesised that the kinematic patterns would differ between males and females, with the largest magnitude difference occurring in the frontal plane.

Methods

Participants

Ten elite female and nine elite male ice hockey players performed a skating acceleration task. These elite ice hockey players were university varsity athletes (Canadian Interuniversity Sport league) (Table 1). Participants had no major lower limb injuries. Ethics were obtained from McGill University and informed consent was obtained from participants prior to testing.

Table 1. Participants' Description

Parameter	Female (Mean ± SD)	Male (Mean ± SD)	p-value
Age	21 ± 1	22 ± 1	$p = 0.452$
Years of Hockey Experience	14 ± 1	16 ± 2	$p = 0.016$ *
Body Height (m)	1.72 ± 0.07	1.81 ± 0.08	$p = 0.011$ *
Body Mass (kg)	71.2 ± 10.4	81.5 ± 8.4	$p = 0.031$ *
Lower Limb Length (m)	0.93 ± 0.05	0.97 ± 0.05	$p = 0.148$
Pelvis Width (m)	0.26 ± 0.02	0.27 ± 0.04	$p = 0.773$

*Indicates significant difference between sexes ($p < .05$)

Instrumentation

An 18-camera Vicon ™ Motion Capture System (2 x T40, 8 x T20, 8 x T10 cameras - Vicon ™ Motion Systems Ltd., Oxford, UK) was set up on the arena ice surface for data collection. The calibrated capture volume was approximately 3m wide by 15m long and 2m high. All kinematic data were captured at 240 Hz and processed using Vicon ™ Nexus (Ver. 2.2.1,Vicon ™ Motion Systems Ltd., Oxford, UK).

The participants wore tight fitting compression clothing with sixty-seven 14mm diameter passive reflective markers placed on anatomical landmarks. The markers on the pelvis and legs

(Collins, Ghoussayni, Ewins, & Kent, 2009), thorax (Alberto Leardini, Biagi, Merlo, Belvedere, & Benedetti, 2011) and the skate boot (Leardini et al., 2007) based on previous work (Figure 1).

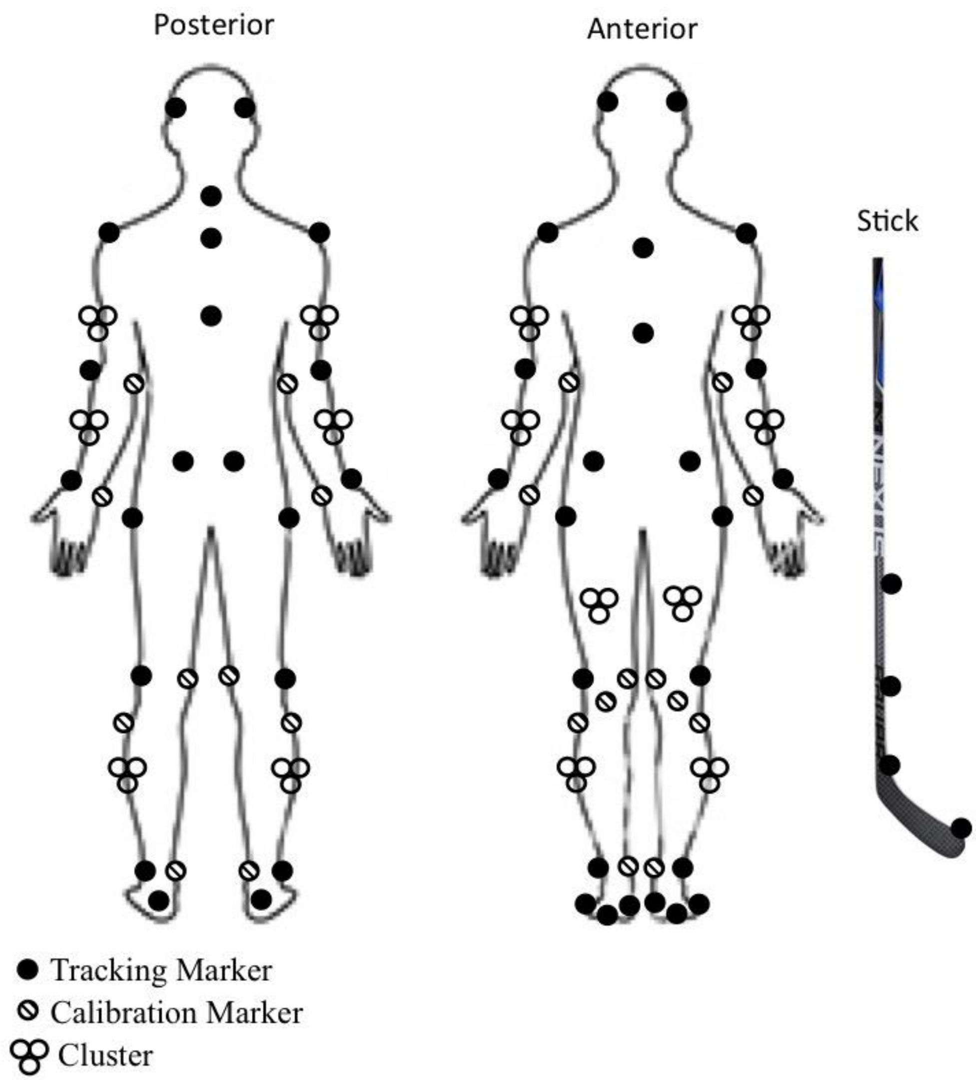

Figure 1: Representation of the 81 passive reflective markers placed on the upper and lower limbs, pelvis, trunk, hockey skate and hockey stick.

Experimental Protocol

Prior to on-ice testing, participants performed a modified version of the Star Excursion Balance Test (SEBT) (Coughlan, Fullam, Delahunt, Gissane, & Caulfield, 2012) to measure the range of motion of the hip in a lunge position in the anterior, posterior-medial and posterior-lateral directions. This test was conducted to confirm subjects' functional movement symmetry prior to skate testing.

Subsequently, each participant performed three single leg-standing long jumps as an estimate of functional unilateral explosive leg strength (Table 2).

Participants used hockey skates (Vapor 1X Model, Bauer Hockey Corp, Exeter, New Hampshire, USA) provided and were given five minutes to warm-up on the ice, to get accustomed to the instrumented hockey skates and ice surface. For the skating trials, participants began at the blue line and were instructed to perform a forward start (without skate cross over) then skate with maximal effort to the next blue line, a distance of 15.3 m. Each participant completed five trials. The capture volume tracked the first seven steps of the acceleration (Figure 2). The participants skated with a hockey stick as to replicate a game context.

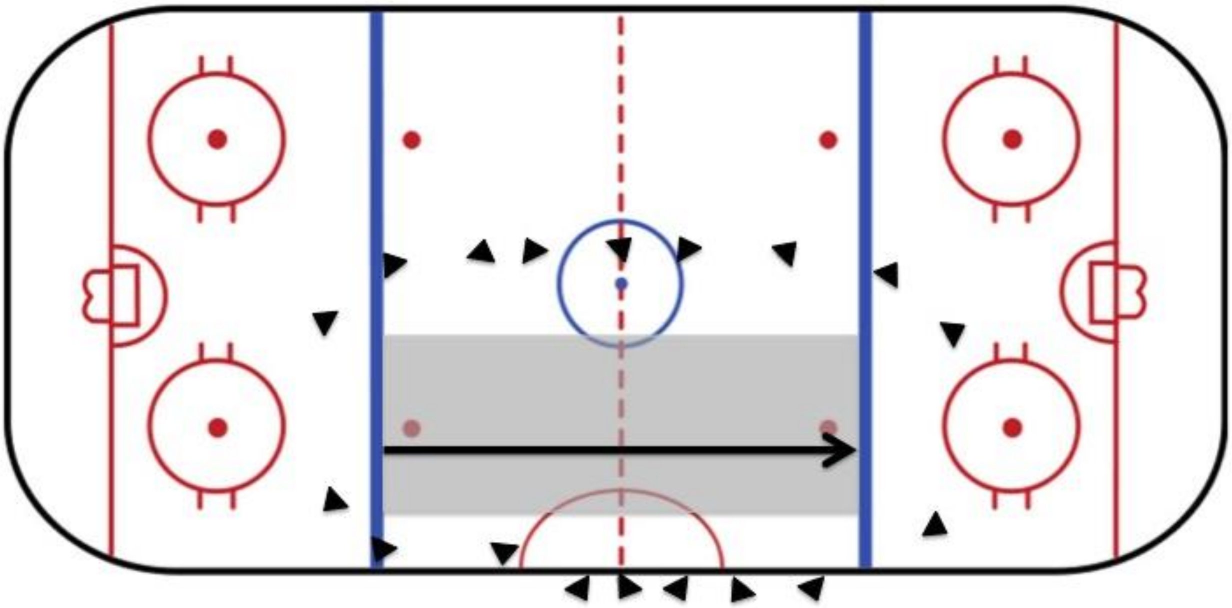

Figure 2: Schematic representation of the on ice camera set-up. Cameras are represented by the black triangles, with the approximate capture volume highlighted in grey. 15 of the 18 cameras were on the ice surface. The black arrow indicates the direction of skating for the trial.

Data Processing

Skating trials were fully labelled using the Vicon™ Nexus software with a combination of rigid body modelling and a Woltring function. A 4th order Butterworth filter with a cut-off frequency of 8Hz was used. In order to evaluate the kinematic and spatiotemporal variables throughout the skating task, locomotion events were detected using Visual3D™ software (Ver 5.01.23, C-Motion, Germantown, Maryland, USA). Skate ON ice placement occurs at the moment of maximum acceleration of the heel marker in the horizontal direction and skate OFF ice occurs at the local maximum vertical acceleration for the toe marker (Hreljac & Marshall, 2000). These ON and OFF events allowed for calculation of step number, stance phase, spatiotemporal events, kinematic parameters and velocity. Step width was calculated as the distance from ipsilateral proximal foot to contralateral proximal foot, which is perpendicular to the direction of primary motion. Additional variables were obtained using custom MATLAB (Mathworks Inc., Natick, MA, USA) scripts based on the BiomechZoo biomechanical toolbox (Dixon, Loh, Michaud-Paquette, & Pearsall, 2017). The most representative skating trial, a captured trial most similar to the mean of the five trials, was determined for each participant (Dixon, Stebbins, Theologis, & Zavatsky, 2013) to analyse a true captured trial, rather than the mean of many trials. Assessment of intra-trial kinematics of the hip and knee measures for six subjects indicated strong repeatability (average ICC r = 0.89, 95% CI 0.95 to 0.84).

Participants were instructed to begin skating with the leg they felt most comfortable for the start. 'Step 1 Leg' referred to the leg side that first stepped forward; 'Step 2 Leg' referred to the contralateral side, regardless of whether this was the right or left leg of the participant. The skate ON and OFF events of that stride delimited the stance phase. A 'Stance 0' phase was identified: this corresponded to the initial push-off phase of the Step 2 Leg (Stull, Philippon, & LaPrade, 2011).

For the kinematic data, the maximum, minimum and range of motion angles were calculated for all Stance phases 0 to 6 for hip flexion/extension, hip adduction/abduction, hip internal/external rotation, and knee flexion/extension (positive/negative angle directions, respectively; zero angle being in standing posture). The lower body angles were calculated in Visual3D™ and derived from YXZ Cardan angles with the following ordered rotations: flexion, abduction, and rotation.

Statistical Analysis

The dependent variables analysed were the three angles of the hip (about the local joint axes) and knee (about local sagittal plane axis), skating speed (at the 4^{th} step and peak), stride length, width and the results of the off-ice testing. From the kinematic time series data, the maximum, minimum and range of motion (maximum-minimum) were extracted for all stance phases. Additionally, the knee kinematics were extracted at ice contact for each step. The data was normally distributed, based on Kolmogrov-Smirnov Test, and spherical, based on Mauchly's Test.

Multiple 2 x 7 mixed-ANOVAs were used to perform tests for interactions between skater sex (M, F) and stance phase (0-6), and the independent variables. A Bonferroni correction was applied. If there was a significant interaction, the difference between groups at each step was examined using the simple main effects. If there was no interaction in the mixed-ANOVA, the main effect (step and group) was interpreted. If there was a significant main effect, pair-wise comparisons show where there were significant differences, using independent T-tests. Significant level for all tests was set at $p < 0.05$. Statistical analysis was performed using SPSS Statistics (Version 19.0, IBM Corp, Somers, USA,).

Results

The males were significantly taller and heavier than the females ($p<0.05$), though lower limb lengths were similar. While male and female subjects did not differ significantly in age, male players had significantly ($p<0.05$) more years of hockey playing experience than female players (Table 1).

The off-ice tests were performed to measure leg strength and balance (Table 2). Males showed significantly longer single leg jump distances ($p<0.05$). For the modified SEBT, the global score did not differ between groups. The posterior-medial reach distance, which most closely resembles a hockey stride motion, showed no significant difference between the sexes.

Table 2: Performance on Off-Ice Tests

Parameter	Female (Mean ± SD)	Male (Mean ± SD)	P-value
Single Leg Jump Right (m)	1.79 ± 0.13	2.06 ± 0.28	$p = 0.015$ *
Single Leg Jump Left (m)	1.77 ± 0.14	2.17 ± 0.21	$p = 0.001$ *
Right Composite Reach Distance	131.26 ± 9.99	133.04 ± 8.77	$p = 0.686$
Left Composite Reach Distance	130.05 ± 8.91	134.05 ± 7.58	$p = 0.310$
Right Posterior-Medial Reach Distance (m)	1.24 ± 0.12	1.30 ± 0.13	$p = 0.320$
Left Posterior Medial Reach Distance (m)	1.23 ± 0.08	1.31 ± 0.09	$p = 0.079$

*Indicates significant difference between sexes (p <.05)

The skating performance and kinematic variables were calculated from the static start until the seventh step (Table 3). Comparing female and male groups, the skating distance (12.88 < 13.43 m), time (1.94 > 1.82 s) and stride rates (1.84 < 1.94 strides/s) covered were not significantly different, respectively; however, the combination of distance and time measures resulted in faster net peak speeds at the seventh step by the male than female skaters (6.98 < 7.60 m/s, $p<0.05$). In terms of stride measures, male and female groups had similar stride lengths but different stride widths (Table 4); that is, the male skaters had significantly wider steps (by 10 to 33 cm) at steps 1, 2, 4 and 6 (p <0.05).

Table 3: Skating Performance Variables of Female and Male Elite Hockey Players

Parameter	Female (Mean ± SD)	Male (Mean ± SD)	P-value
Speed at 4th Step (m/s)	4.65 ± 0.35	5.16 ± 0.50	*p* = 0.019 *
Peak Speed (m/s)	6.98 ± 0.31	7.60 ± 0.28	*p* = 0.001 *
Task Completion Time (s)	1.94 ± 0.18	1.82 ± 0.12	*p* = 0.130
Stride Rate (strides/s)	1.84 ± 0.13	1.94 ± 0.18	*p* = 0.136
Distance Covered in 7 Steps (m)	12.88 ± 1.76	13.43 ± 1.46	*p* = 0.472

*Indicates significant difference between sexes ($p < .05$)

Table 4: Average Step Width and Stride Length (Mean ± SD**)** of Skating Acceleration

Parameter	Gender	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
Step Width (m)	Female	0.16 ± 0.07	0.05 ± 0.03	0.05 ± 0.05	0.07 ± 0.06	0.12 ± 0.08	0.07 ± 0.07
	Male	0.33 ± 0.09	0.18 ± 0.07	0.10 ± 0.06	0.17 ± 0.08	0.18 ± 0.09	0.19 ± 0.07
	P-value	*p* =0.001 *	*p* =0.001 *	*p* =0.089	*p* =0.008 *	*p* =0.168	*p* =0.003 *

*Indicates significant difference between sexes ($p < .05$)

The hip and knee angular movements during skating acceleration were calculated (Figures 3 and 4, respectively). Hip flexion/extension range of motion was significantly greater in males than females during the latter stance phases ($p = 0.05$). As well, there was a significant main effect of sex on hip adduction/abduction angles ($p = 0.05$), such that across all steps, the female skaters were less abducted than the male skaters by 10 degrees. There was a significant Stance*Sex interaction for sagittal plane knee minimum position during Stance 0 ($p = 0.05$) (Figure 4, Panel A). Sex differences were observed for the knee angle at ice contact at Step 4 and

Step 6 (p = 0.05), with the females being more extended at the knee by approximately 10 degrees at both steps.

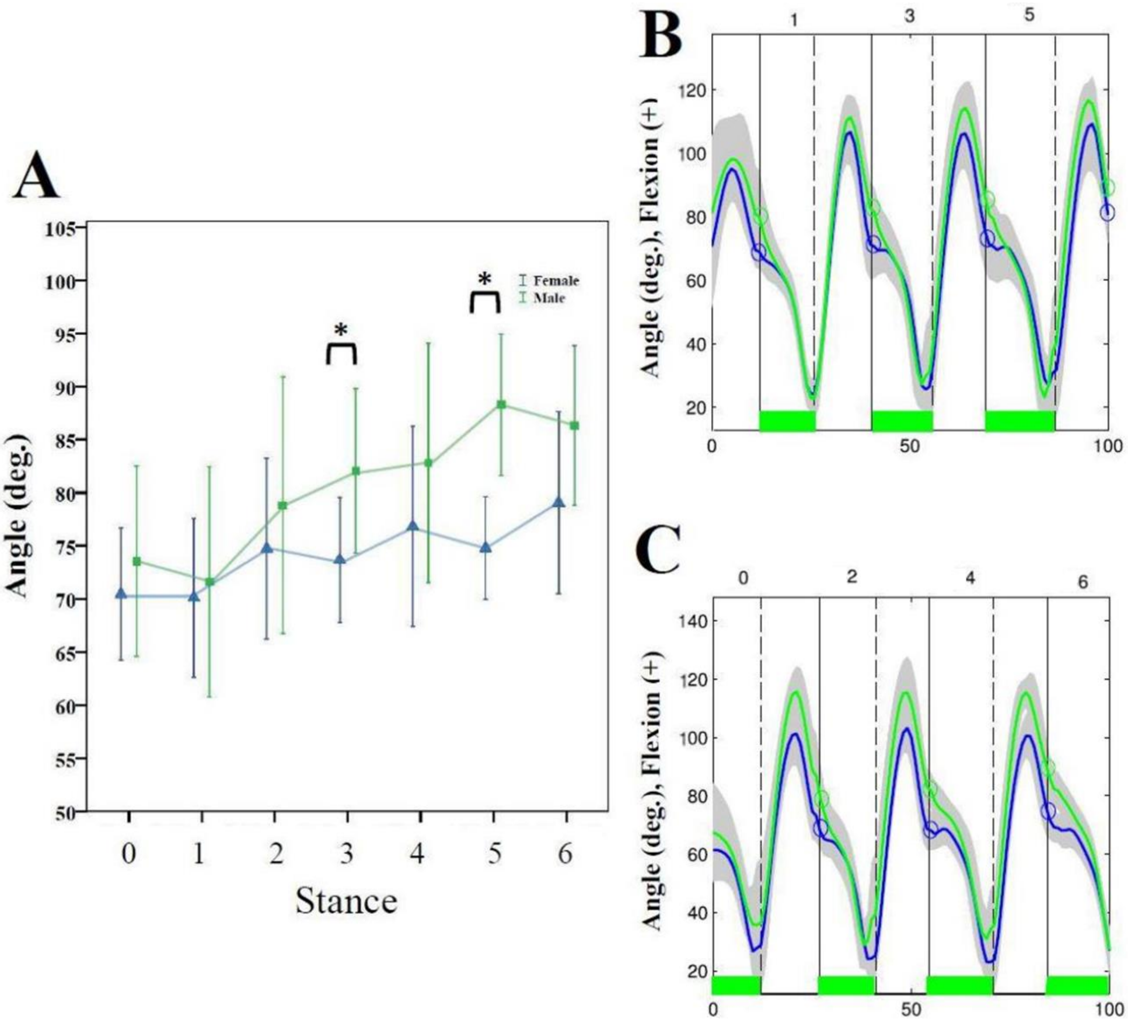

Figure 3: Average maximum and minimum hip angles by sex (female: blue, male: green) during stance phases 0-6 for (A) Flexion *significant effect of stance x sex (p = 0.001), (B) Abduction. * significant main effect of sex (p = 0.006), and (C) External Rotation. Corresponding Range of Motion (ROM) estimated in lower tables.

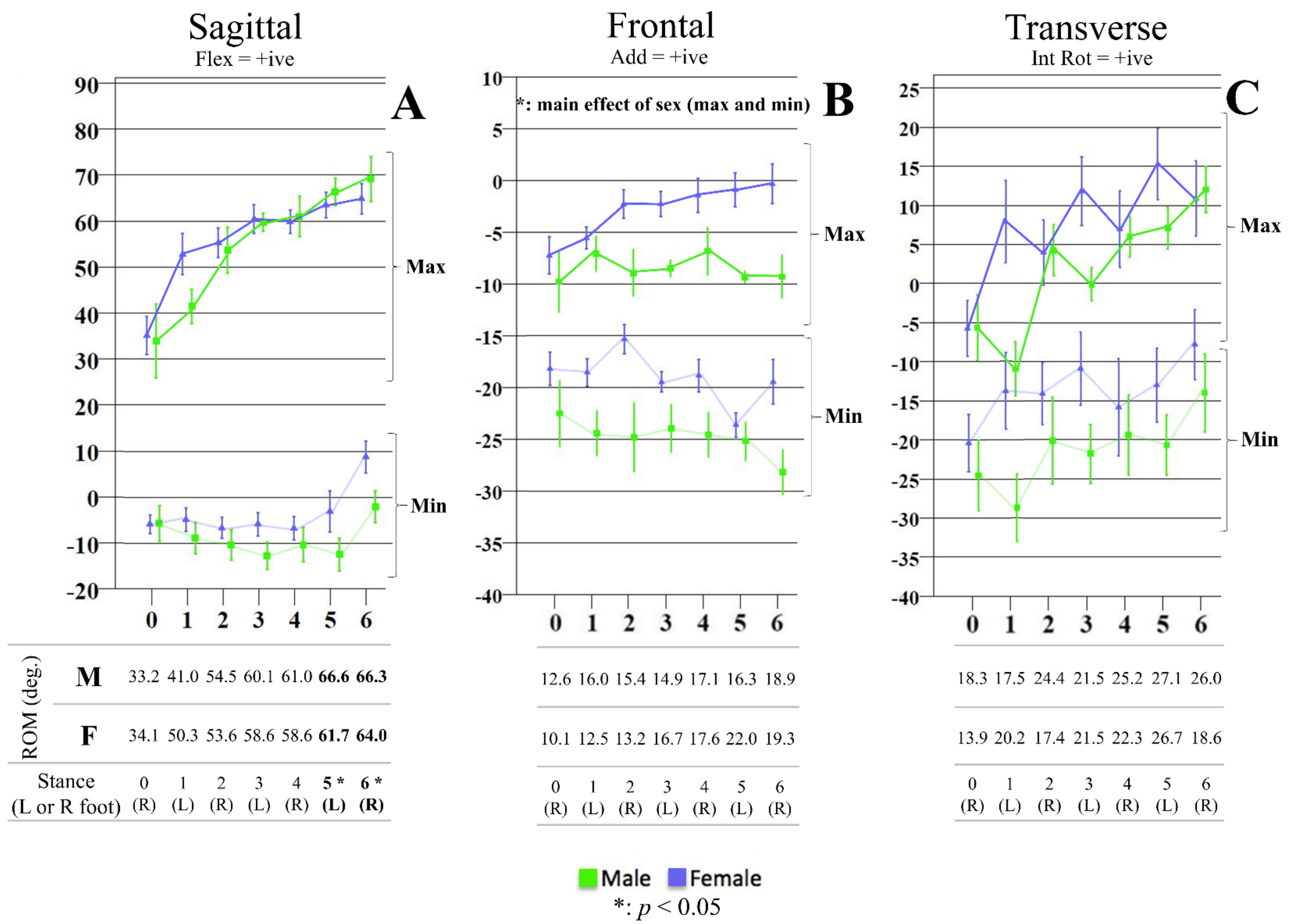

Figure 4: Knee Kinematics (female: blue, male: green).
(A) Average knee flexion angles at ice contact for the stance phase 0-6. There was a significant Stance*Sex interaction at Stance 4 (p = 0.016) and Stance 6 (p = 0.001). Flexion angles were towards positive; squares = males; triangles females. (B) Average knee flexion angle by sex for Step 1 leg (± SD grey bands). (C) Average knee flexion angle by sex for Step 2 leg (± SD grey bands). In Panels B and C, the horizontal green bars represent the stance phases (0-6). The solid vertical lines represent the average skate ON events. Open circles identify the locations of discrete knee flexion measures at ON.

Discussion and Implications

This study conducted a detailed 3D kinematic analysis of the lower limbs during the first six skating strides over a large continuous skating surface for both male and female ice hockey players. While the onice camera set-up and take down was a laborious process, this study represents a major achievement in 3D motion capture, as we were able to calibrate a large (15m*3m*2m) measurement volume on the ice surface so as to record on-ice skating kinematics, with high intra-trial reliability.

Performance differences between male and female skaters were shown in task completion time, peak velocity, as well as hip and knee kinematics and stride width. Over the first seven steps of the skating start, though the male's greater average stride rate and longer step lengths were not significantly different from females (Table 3), they combined and resulted in male skater's average peak skating speed being significantly higher than females. Given similar balance and flexibility profiles between the sexes, the skate start performance difference may well be related to male's greater leg strength as well as power by way of faster stride rates. These strength differences may be related to lean body mass and conditioning differences (Gilenstam et al., 2011).

No differences were noted in range of motion of hip flexion/extension nor internal/external rotation between sexes. However, all skaters presented greater hip abduction and external rotation during skating than typical in running (Ferber, Davis, & Williams III, 2003, Pearsall et al., 2000). Throughout the start, skater's hips were abducted between 5° (during swing phase) to 25° at push-off. Notably, though females had similar hip range of motion, they were less abducted than the males during most of the stance phase, as hypothesized. This may have resulted in the female's smaller step width, affecting their lateral-posterior skate blade push-off forces and stride rate. These findings do not agree with Abbott's (2014) claim that forward skating biomechanics are the same for both male and female hockey players, irrespective of anatomical differences at the hip. Differences in hip strength and pelvis orientation between sex may be responsible, similar to that observed in running (Ferber, Davis, & Williams III, 2003). Given these findings, for female skaters, training interventions focused to increase leg strength and augment hip abduction throughout the skating stance phase is justified.

Male skaters demonstrated significantly more knee flexion during the initial stance (0) and more knee flexion in the subsequent steps (4 and 6, $p<0.05$) than female skaters. At ice contact, skaters showed a momentary knee extension cessation, though significantly more pronounced in female athletes (Figure 4 at stance ON). The reason for this phenomenon is unclear, though one may speculate that the female skaters may have habitually learned protective mechanism so as to avoid high valgus moments and excessive strain to the medial tensile connective structures of the knee. Several studies of jump landing and run cutting manoeuvre tasks repeatedly demonstrate that female athletes exhibited the higher peak knee valgus (Ireland, 1999; Orishimo, Liederbach, Kremenic, Hagins, & Pappas, 2014; Powers, 2010). Further studies of female ice hockey skaters are warranted, particularly given the high non-contact knee injury rates in female competitive hockey (Agel, Dick, Nelson, Marshall, & Dompier, 2007). With the deep knee flexion shown in skating, segment axes cross talk prohibited valid estimates of knee varus-valgus and internal/external rotation angles; additional study is needed to overcome this technical limitation (Freeman & Pinskerova, 2005; Lafortune, Cavanagh, Sommer, & Kalenak, 1992; Piazza & Cavanagh, 2000).

This study's findings are relevant to skating coaching and equipment manufacturing. For example, with the established risk for knee injuries in female athletes (Ireland, 1999), training interventions for females that focus on hip and knee landing, and propulsion mechanics which target hip strengthening exercises (Stastny, Tufano, Golas & Petr, 2016) may be warranted. Female ice hockey coaches may also want to provide cues to their athletes in order to remind them to 'reach out with their legs' and 'extend their knees through contact' to potentially allow for higher forward propulsion. In terms of equipment, skates are currently manufactured in a unisex design and separated into adult (US size 6 and above) and children (US size 5.5 and below). Most female skaters wear children sized skates that do not have the same robust construction of the adult skates; thus the former may lack sufficient medial-lateral support needed for stability during ice contact events and for wider steps during skate starts. Manufacturing of a more stable and robust female specific skate model may provide the proper base of support that female athletes need for a higher level skating performance.

Conclusion

Functional differences in lower limb movement patterns were identified during forward skating starts between elite male and female ice hockey players. Female skaters had significantly less hip abduction and smaller step widths during skating acceleration, compared to male hockey players, as well as conspicuous pauses in knee extension at initial skate ice contact by females were observed.

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