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Ice Hockey Skate Starts: A Comparison of High and Low Calibre Skaters

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Abstract

The forward skating start is a fundamental skill for ice hockey players, yet extremely challenging given the low traction of the ice surface. The technique for maximum skating acceleration of the body is not well understood. The aim of this study was to evaluate kinematic ice hockey skating start movement technique in relation to a skater's skill level. A 10-camera motion capture system placed on the ice surface recorded "hybrid-V" skate start movement patterns of high and low calibre male ice hockey players (n = 7, 8, respectively). Participants' lower body kinematics and estimated body centre of mass (CoM) movement during the first four steps were calculated. Both skate groups had similar lower body strength profiles, yet high calibre skaters achieved greater velocity; skating technique differences most likely explained the performance differences between the groups. Unlike over ground sprint start technique, skating starts showed greater concurrent hip abduction, external rotation and extension, presumably for ideal blade-to-ice push-off orientation for propulsion. Initial analysis revealed similar hip, knee and ankle joint gross movement patterns across skaters, however further scrutiny of the data revealed that high calibre skaters achieved greater vertical CoM acceleration during each step that in turn allowed greater horizontal traction, forward propulsion, lower double support times and, accordingly, faster starts with higher stride rates.

Keywords: Ice Hockey, Ice Skating, Biomechanics, 3D Kinematics, Motion Capture, Hip, Knee, Ankle

1 Introduction

Ice hockey is one of the fastest team sports, with players reaching peak speeds in excess of 40 km/h [1,2]. Such speeds can be sustained due to low ice resistance to forward glide; low surface friction works against the athlete during the skate start, as minimal blade grip can hamper forward propulsion. In a game situation, forward skating acceleration is crucial to a player's overall success. For example, the players with faster starts are more likely to win puck possession, out maneuver their opponents, and achieve tactical separation from defensive players. Consequently, power skating, and in particular skating starts, is emphasized in skill development [3], which involves many repetitions, with skating performance improvement assessed by lower skating drill times. Experienced coaches often stress "correct" body movement technique, yet there is limited information as to what exactly proper technique is and how it leads to better skate start acceleration.

Studies have used different measurement techniques including single and multi-camera (film, video) recording [4-6], direct joint measures using electrogoniometers [7,8], and three-dimensional motion tracking on ice [9], using treadmills [10] and synthetic ice surfaces [11,12]. Using these approaches, some key movement traits of skate starts have been identified. For instance, de Koning et al. [13], using three film cameras of speed skaters' starts, found that male elite skaters displayed "running-like" initial push-offs in order to generate propulsion, then transitioned to a "glide" technique during steady-state skating. Chang et al. [14] and Buckeridge et al. [7], using goniometers placed about the knee and hip, were able to examine differences in joint kinematics corresponding to speed and player calibre, respectively. However, these studies were often limited by one or more factors: low measurement resolution and accuracy [5,6], small measurement field of view with respect to task [4], non-ice testing [12,14] and / or focused description of lower body movements without relation to global body progression [7,14].

Further study is warranted to better understand how the hip, knee, and ankle joints move in the ice hockey skate start technique. Therefore, the purpose of this study was to conduct a comprehensive kinematic analysis of low and high calibre skaters during ice hockey starts using three-dimensional motion capture cameras on the ice surface. This quantitative data may identify key movement patterns for maximal skate start accelerations that coaches and trainers can use as teaching cues for athlete development.

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2 Methods

2.1 Participants and Protocol

Seven high calibre (HC; age 24.7±3.1 years, height 184.2±6.4 cm, mass 87.1±6.0 kg, playing experience 19.7±3.9 years, mean±SD) and eight low calibre (LC; age 23.9±3.1 years, height 179.4±3.4 cm, mass 81.3±8.4 kg, playing experience 9±6 years, mean±SD) male skaters participated in this study. Assumed to be technically superior, HC skaters played at the junior level or higher; LC skaters played at lower than junior level. Groups were similar in age, height and weight ($p > 0.05$, via independent t-test). HC skaters had significantly more playing experience than LC skaters ($p = 0.001$, via independent t-test). Participants also had equivalent leg strength as estimated by the mean average of three dry-land double-support long jump trials (HC; 219.1±17.0 cm, LC; 208.5±18.8 cm, mean±SD) ($p = 0.28$, via independent t-test). Participants who had major lower limb injuries within the last year were excluded from this study. Prior to testing, all participants read and signed the ethics consent form. A research ethics certificate was granted by the McGill University Research Ethics Board II. All participants wore Bauer MX3 skates with standard boots and were sharpened to a 3/8 inch hollow with a 9.5 radius (both standard) by the same technician prior to data collection. They were told to lace their skates as they would in a game; this was decided in order to keep the participants as comfortable as possible in the new skates. They were allotted a five minute warm-up period on the ice surface away from the calibrated capture area. Participants performed three repetitions of a maximum effort forward skating start by listening to the following instructions: "When I yell 'GO!' I want you to skate forward as fast as you can". They were told to keep their skates parallel prior to the "GO!" call, as they started their movement, they were free to choose how to position their skates to allow them to accelerate as quickly as possible. Participants were specifically told not to perform a cross-over start.

2.2 Motion Capture

A 10-camera Vicon MX3+ (eight cameras) and T-Series T40S (two cameras) motion capture system (Vicon Motion Systems Ltd. , Oxford, UK) was setup on the arena ice surface. The system was calibrated prior to each testing session and captured data at a rate of 240 Hz. The approximate calibrated capture area consisted of a volume of 3 m wide x 6.5 m long x 1.5 m high to track the first four skating steps of the start (Fig. 1). Participants wore tight fitting compression clothing in addition to test skates, hockey gloves, helmet, and a hockey stick to carry while skating in order to replicate game situation skating.

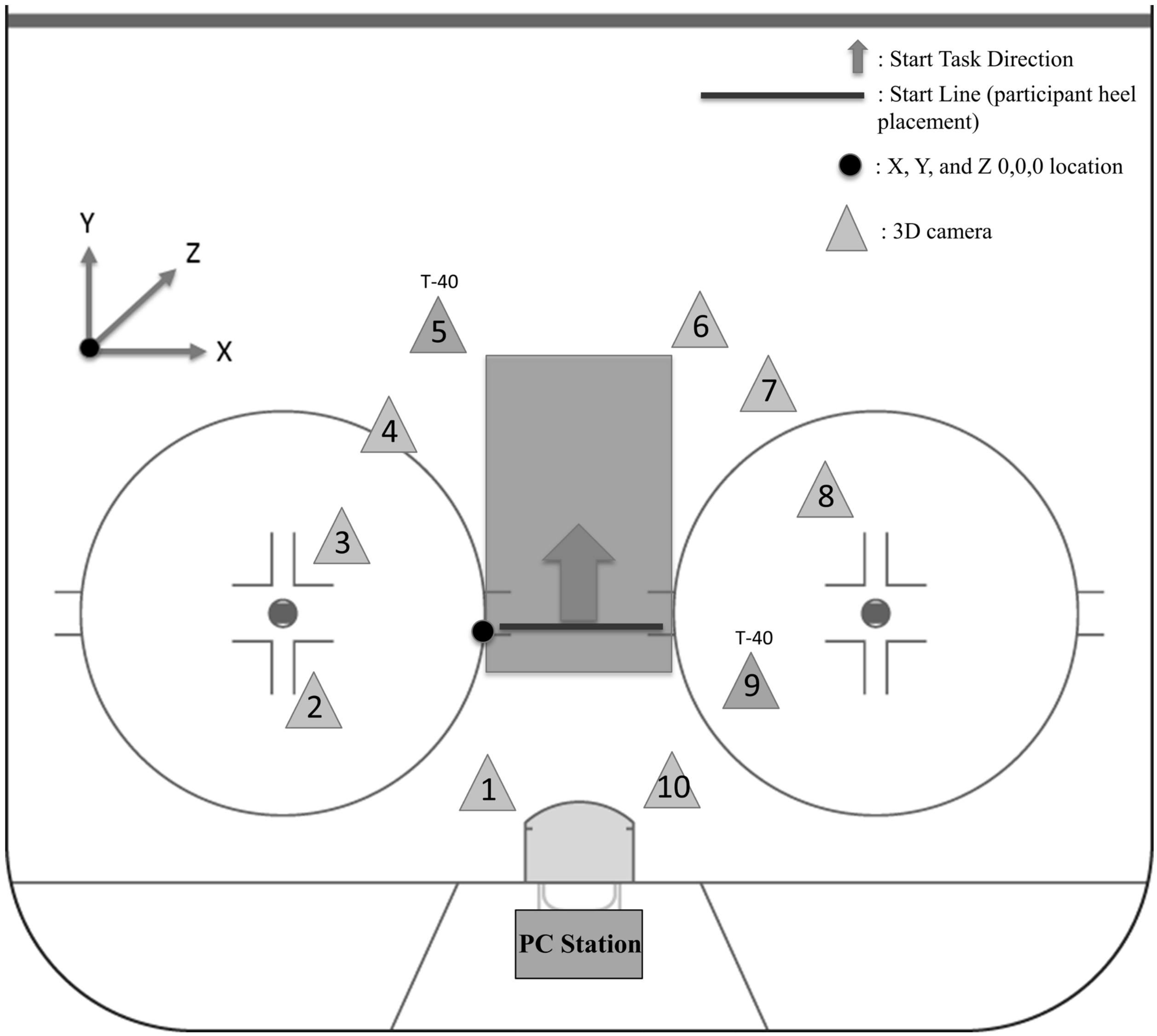

Fig. 1 Diagram of the on ice experimental setup. Camera positions were standardized for all participants. Fixed points on the rink (stars) were used as reference for camera positions. Large shaded rectangle shows camera capture area. Black dot shows the location of the origin of the global coordinate system

2.3 Marker Placement

Each participant had 24 passive retro-reflective markers placed on their lower limbs according to the Vicon™ Plug-in-Gait lower body setup (Vicon Motion Systems Ltd., Oxford, UK., [15]) (Fig. 2). Additional markers were placed on the skates and knees of each participant to allow for accurate ankle joint centre calculations. After participant calibration, the medial knee and medial ankle markers were removed for the dynamic skating trials. The mid-point

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between the left and right posterior superior iliac spine markers was computed and used to estimate the whole body Centre of Mass (CoM) [16,17] position (mid-PSI marker on Fig. 2).

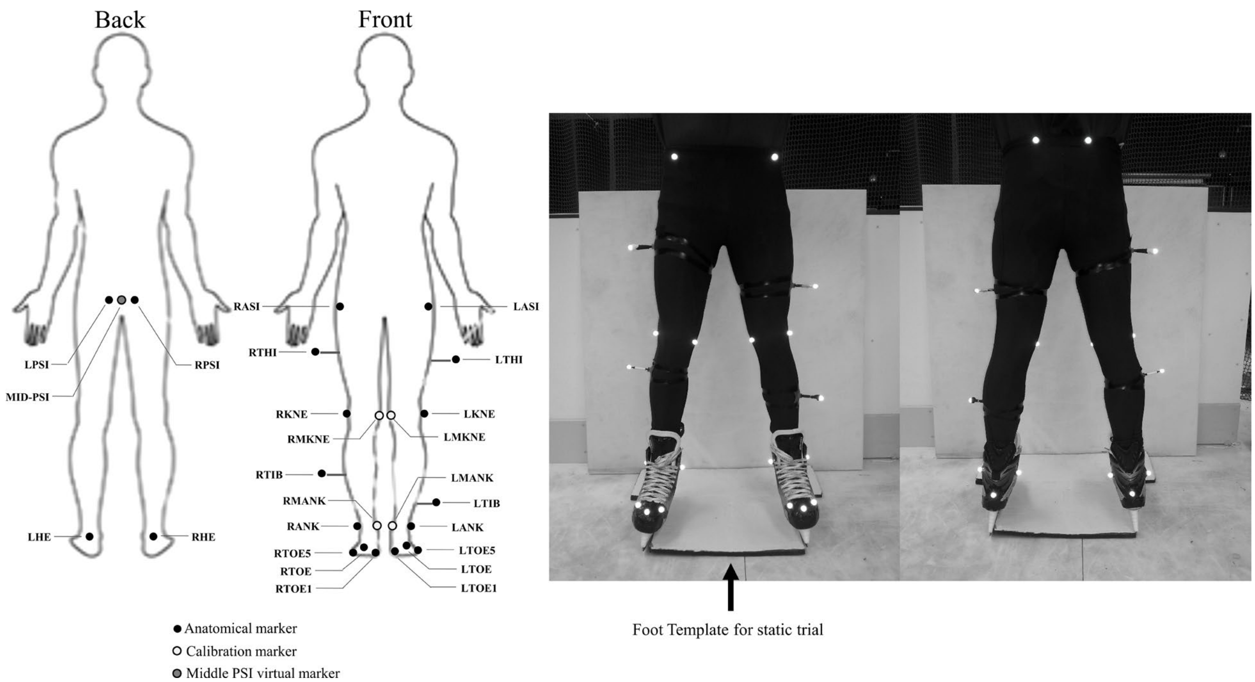

Fig. 2 Modified lower body Plug-in-Gait (Vicon Motion Systems Ltd. UK) calibration marker placement on participant

2.4 Data Analysis

All data from the 10 infrared cameras were collected through the Vicon MX Ultranet and Vicon Giganet connection hubs and Vicon™ Nexus (Ver 1.8.5, Vicon Motion Systems Ltd., Oxford, UK) software. This same software was used to label and extract the kinematics of the lower body including hip (flexion / extension; abduction / adduction; and internal / external rotations), and knee (flexion / extension) angles. The local hip and knee rotation angles were adjusted using the thigh-offset technique as described by Baker et al. [18]. Vicon IQ (Ver 2.5, Vicon Motion Systems Ltd., Oxford, UK) was used to gap fill all of the marker data, while Visual3D (Ver 5.01.23, C-Motion Inc., Germantown, Maryland, United States) was used to estimate CoM velocity, acceleration and position. Visual3D was also used to calculate the ankle kinematics (plantar / dorsi flexion) angles with the modified marker placement on the skates (see Fig. 2). The lower body angles definitions were derived from YXZ Cardan angles with the following ordered rotations: flexion, abduction, and rotation. A fourth order low pass Butterworth [19] filter with a cutoff frequency of 6 Hz was used to filter the data. Data were partitioned from the first to the fourth step of the skating start for all participants.

A representative trial selection method [20] was performed on the three skating start trials for each participant; whereby the root mean squared error between each curve and the mean curve for all dependent variables was calculated. From this calculation, the trial out of the three which had the overall average minimum root mean squared error was chosen as the representative trial. This technique was chosen in order for a true captured trial to be used for data analysis.

2.5 Event and Phase Definitions

For each four steps (S1-S4) of each trial, ice contact events (ON) and end of ice contact events (OFF) were identified through Visual3D by the velocity of the toe marker in the direction of forward progression [21] and the jerk of the heel marker in the vertical direction [22], respectively. Subsequently, these ON and OFF events were used to define the eight kinematic variables: (i) task completion time, (ii) step length and (iii) width, (iv) double support time, (v) angle during ice contact and CoM (vi) position, (vii) velocity and (viii) acceleration.

Each participant was free to select their preferred first step side. To combine results of all participants, left and right terms could not be used; instead, leg sides were defined as Leg 1 (the side and foot that took the first step), and Leg 2 (the contralateral side and foot of the second step) (Fig. 3). Typically, the first step involved either a sliding or stepping motion forward, whereas the second step demonstrated the first substantial forward propulsion and full step motion. The first four steps were identified from S1 to S4. A step sequence began with S1OFF and ended with S4ON (Fig. 4). Two stride phases (cycles) were identified: Stride Phase 1 (SP1) from S1OFF to S3OFF (0 to 50%) and Stride Phase 2 (SP2) from S3OFF to S4ON (51 to 100% of the start trial). These events and phases were used to identify the discrete kinematic variables used for analysis (see Fig. 4). Data analysis steps were performed in MATLAB R2014a (The MathWorks Inc., Natick, Massachusetts, United States) using the biomechZoo toolbox [23] and custom scripts.

Fig. 3 Leg 1 and Leg 2 during the first step of the start. Darker circle shows Leg 1, lighter circle shows Leg 2

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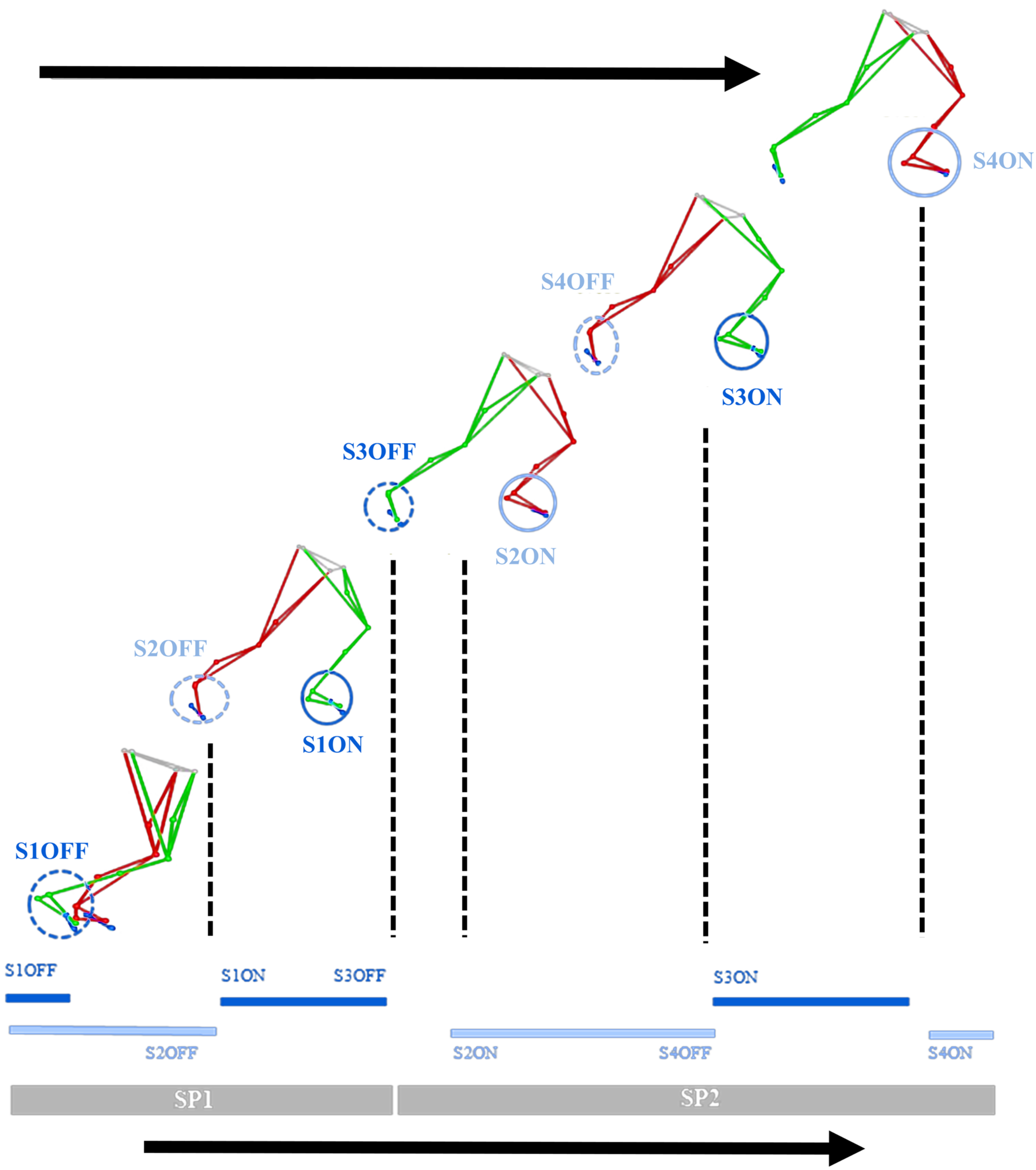

Fig. 4 Sequence of Plug-in-Gait step events (left to right). These events have been used to define the variables within the results section. Darker circles depict Leg 1 events, lighter circles depict Leg 2 events. Solid circles are ON events, dashed circles are OFF events. Darker and lighter solid horizontal bars show when Leg 1 and Leg 2 were in contact with the ice surface

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2.6 Statistical Analysis

Mixed-ANOVAs with between-subject factor of player calibre (High/Low) and within-subject factor of Step number (S1ON, S2ON, S3ON, S4ON) were used to perform statistical comparisons of the spatio-temporal and CoM dependent variables (step length, step width, double support time, and CoM position, velocity and acceleration). Within-subject factor stride (SP1 and SP2) were used to perform statistical comparisons of the lower body angles dependent variables (hip flexion / extension, abduction / adduction, internal / external rotation, knee flexion / extension, and ankle plantar / dorsi flexion). A Bonferroni [24] correction was applied to post-hoc comparisons. Group means and standard deviations were calculated for all variables. Data sphericity was tested using Mauchly's [25] tests: these indicated the need to apply Greenhouse-Geisser [25] corrections to measures of forward and vertical acceleration, as well as forward velocity. A Pearson's r correlation test was performed between maximal forward skating velocity and mean average double support long jump. Significance level for all tests was set at α =0.05. All statistical analyses were performed in SPSS Statistics Ver 19.0 (IBM Corp., Armonk, New York, United States).

3 Results

Within this section, the CoM and kinematic time series graphs (Figs. 6-9) have solid vertical lines which depict ON events (S1ON, S2ON, S3ON) and dashed vertical lines which depict OFF events (S2OFF, S3OFF, S4OFF). Darker vertical lines depict Leg 1 events, and lighter vertical lines depict Leg 2 events.

3.1 Start Acceleration Performance

HC (1.03±0.08 s) skaters performed the skate start in significantly shorter time than LC (1.20±0.18 s) skaters (p = 0.037). Leg strength (as estimated from long jump distances) did not significantly correlate with forward skating velocity at the four skating start steps ON events (p > 0.05). Step length and step width measures were similar between groups. However, a main effect of step was found for step length, wherein both groups demonstrated significant increases in step length with each consecutive step (Fig. 5). HC skaters showed higher stride rates than LC skaters (1.95 vs 1.7 strides/s, respectively, p = 0.043). A main effect of calibre was found for double support time; these double support times were very short for each group (less than 0.01 seconds, Table 1), indicative of a running gait pattern. Indeed, HC skaters' double support times were negligible to non-existent for the 2nd to 3rd step.

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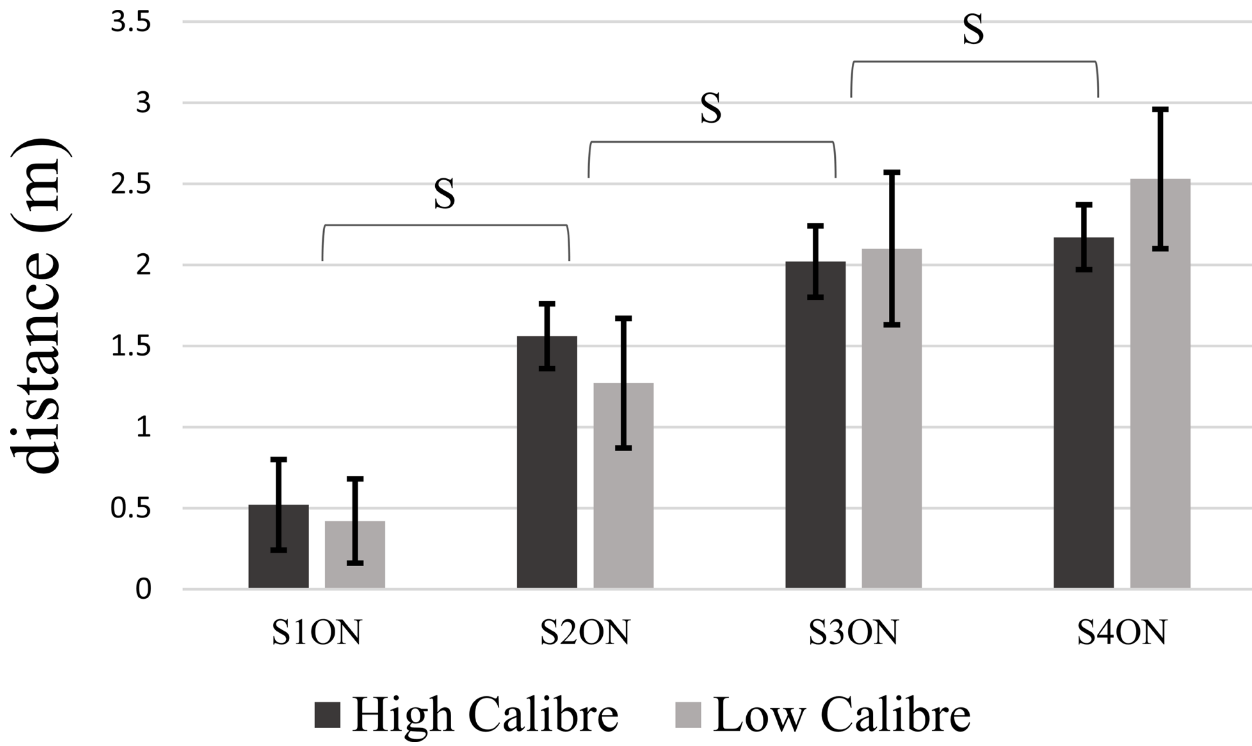

Fig. 5 Mean step lengths for each respective step by skating calibre (±SD bars). [S]Step lengths increased for each consecutive step

Table 1 Skating double support time in seconds for both high and low calibre skaters for 1st to 3rd steps. Mean (SD)

Step	High Calibre	Low Calibre
S1ON	**0.036 (0.042)**	**0.098 (0.063)**[C]
S2ON	**-0.015 (0.029)**	**0.040 (0.046)**[C]
S3ON	**0.003 (0.029)**	**0.038 (0.028)**[C]

[C]significant difference between calibre ($p \leq 0.05$)
Note: a negative value denotes a flight phase (i.e. no double support)

3.2 Estimation of Body CoM movement

Side-to-Side CoM excursion was substantial (i.e. ± 0.7 to 0.9 m from midline) from step to step; however, no differences were found between calibre groups over the skate start duration. Mean CoM Vertical position over the four start steps' ice contacts for HC skaters were significantly higher than compared to LC skaters (Fig 6 and Table 2).

Skating start CoM velocity and acceleration measures are presented in the Side-to-Side (X), Forward (Y) and Vertical (Z) directions in Table 3 as well as Figs. 7 and 8. In general, skaters increased their forward velocity from 2 m/s at step 1 to 5 m/s at step 4, with peak step forward accelerations of 11 to 20 m/s^2. HC skaters achieved larger mean forward velocities and accelerations than LC skaters over the four start steps ($p \leq 0.048$). In the vertical direction, over the first three steps, HC skaters generated peak accelerations of 9.3 to 10.6 m/s^2 compared to LC skaters' 3.8 to 8.4 m/s^2: this corresponded to the greater elevation of HC' CoM movement path and transient flight phase between steps 2 and 3. In terms of side-to-side motion, both calibre groups showed substantial peak reversal accelerations ranging from 6.8 to 13.7 m/s^2: considerably higher than seen in walking or running gait [26].

Table 2 Vertical (Z) CoM position in cm for both high and low calibre skaters at each step ice contact. Mean (SD). Zero vertical reference height taken from participant's initial start position

Step	High Calibre	Low Calibre
S1ON	**-2.0 (3.3)**	**-4.8 (2.7)^C**
S2ON	**3.3 (2.7)**	**-4.3 (4.3)^C**
S3ON	**3.2 (2.8)**	**-3.9 (2.8)^C**
S4ON	**1.1 (2.7)**	**-4.8 (3.2)^C**

^{C}significant difference between calibre ($p \leq 0.05$)

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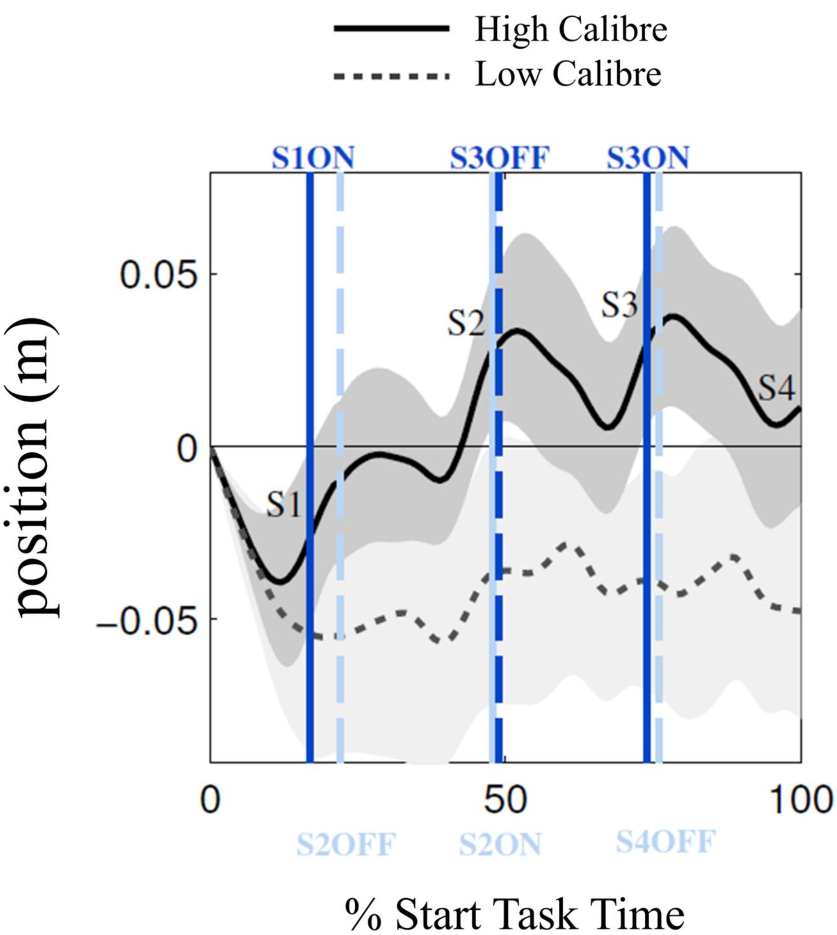

Fig. 6 Mean Vertical (z) CoM position during skate start strides

Table 3 Maximum skating velocity and acceleration for both high and low calibre skaters in the Side-to-Side, Forward, and Vertical axes at each step ice contact. Mean (SD)

Velocity (m/s)						
	Side-to-Side axis (X)		Forward axis (Y)		Vertical axis (Z)	
Step	High Calibre	Low Calibre	High Calibre	Low Calibre	High Calibre	Low Calibre
S1ON	**-0.63 (0.24)**	**-0.19 (0.23)**^{CxS}	**2.65 (0.49)**	**1.97 (0.55)**^{C,S}	0.25 (0.16)	-0.09 (0.20)
S2ON	0.70 (0.44)	0.48 (0.37)**	**3.89 (0.27)**	**3.58 (0.60)**^{C,S}	0.11 (0.23)	0.14 (0.27)
S3ON	-0.58 (0.40)	-0.50 (0.49)**	**4.84 (0.21)**	**4.47 (0.53)**^{C,S}	0.19 (0.19)	0.01 (0.29)
S4ON	**0.80 (0.56)**	**0.12 (0.37)**^{CxS}	**5.53 (0.15)**	**5.10 (0.61)**^{C,S}	0.10 (0.14)	-0.04 (0.29)
Acceleration (m/s^2)						
	Side-to-Side axis (X)		Forward axis (Y)		Vertical axis (Z)	
	High Calibre	Low Calibre	High Calibre	Low Calibre	High Calibre	Low Calibre
S1ON	**-12.88 (4.16)**	**-6.82 (2.84)**^{CxS}	**15.88 (2.00)**	**11.77 (4.04)**^{C,S}	**9.30 (2.95)**	**3.84 (2.29)**^{CxS}
S2ON	13.44 (6.36)	10.31 (2.89)**	**18.35 (3.54)**	**16.43 (2.84)**^{C,S}	9.48 (2.07)	7.96 (4.19)**
S3ON	-13.73 (4.97)	-11.26 (1.86)**	**20.05 (2.55)**	**16.60 (3.88)**^{C,S}	10.62 (3.75)	8.41 (3.75)**
S4ON	**12.77 (3.82)**	**8.85 (2.15)**^{CxS}	**18.20 (3.22)**	**15.81 (3.19)**^{C,S}	7.79 (3.37)	8.06 (3.46)**

significant difference ($p \leq 0.05$) between ^{C}calibre, ^{S}steps, and ^{CxS}calibre by step interaction

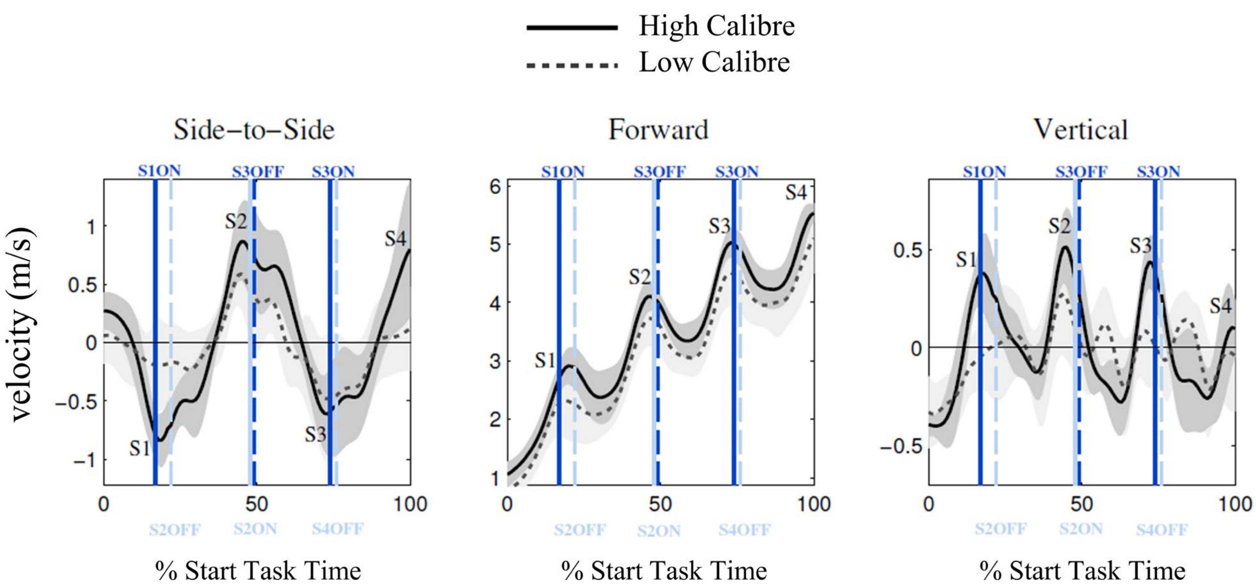

Fig. 7 Mean skating velocities in the Side-to-Side, Forward, and Vertical axes (x, y, z)

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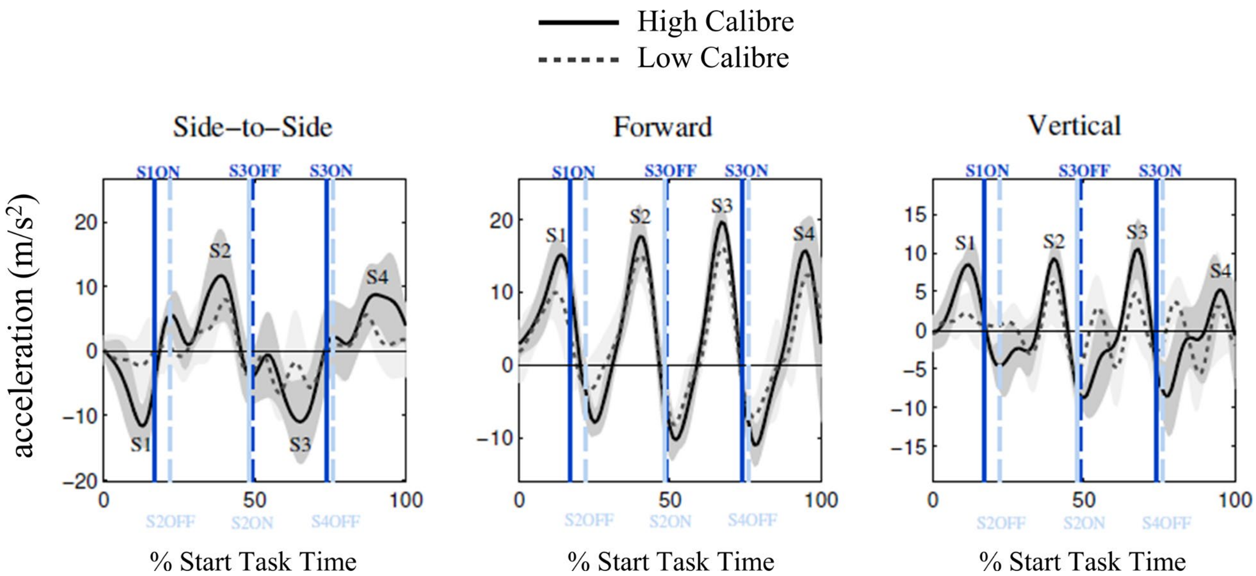

Fig. 8 Mean skating acceleration in the in the Side-to-Side, Forward, and Vertical axes (x, y, z)

3.3 Lower Limb Joint Angles

In general, no significant main effect of calibre or calibre x step interaction was observed for the first and second step leg joint angles during ice contact (Table 5). However, interaction effects in stride phases between HC and LC were detected in hip internal / external rotation for Leg 2 (p = 0.029); as well as a main stride phase effects in hip flexion / extension for Leg 1 (p = 0.002), and a main calibre effect of knee flexion / extension for Leg 2 (p = 0.026) (Fig. 9).

Table 4 Joint angles in degrees at skate-ice contact for both leg sides (Leg 1, Leg 2) for high (shaded grey cells) and low calibre skaters during the first and second strides. Mean (SD)

Angle			Hip flexion		Hip adduction		Hip int rotation		Knee flexion		Ankle dorsi flexion
Leg 1	SP1	HC	**64.5 (13.9)**	**C**	-32.7 (8.9)		-15.7 (22.2)		101.4 (6.2)		23.6 (8.9)
		LC	**64.0 (8.9)**		-28.1 (9.4)		-8.5 (7.4)		91.8 (14.0)		20.4 (5.8)
	SP2	HC	**75.3 (7.2)**	**C**	-22.3 (6.8)		-4.9 (7.6)		119.4 (9.3)		21.7 (8.0)
		LC	**75.8 (4.9)**		-17.4 (6.9)		-5.8 (5.5)		111.2 (10.4)		17.5 (4.7)
Leg 2	SP1	HC	66.4 (12.8)		-33.4 (12.6)		**-9.3 (9.5)**	**CxS**	**114.6 (9.1)**	**S**	24.5 (8.5)
		LC	71.5 (9.0)		-29.5 (10.0)		**-4.7 (8.5)**		**103.4 (7.6)**		18.4 (5.9)
	SP2	HC	74.9 (7.8)		-23.3 (7.2)		**1.0 (7.3)**	**CxS**	**114.6 (9.9)**	**S**	23.4 (8.2)
		LC	64.5 (21.4)		-18.7 (9.7)		**-4.9 (13.0)**		**104.9 (8.0)**		18.9 (5.2)

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(+ angles were hip flexion, adduction, internal rotation; knee flexion; ankle dorsiflexion); significant differences ($p \leq 0.05$) between ^{C}calibre, ^{S}stride phase, and ^{CxS}calibre by stride phase interaction

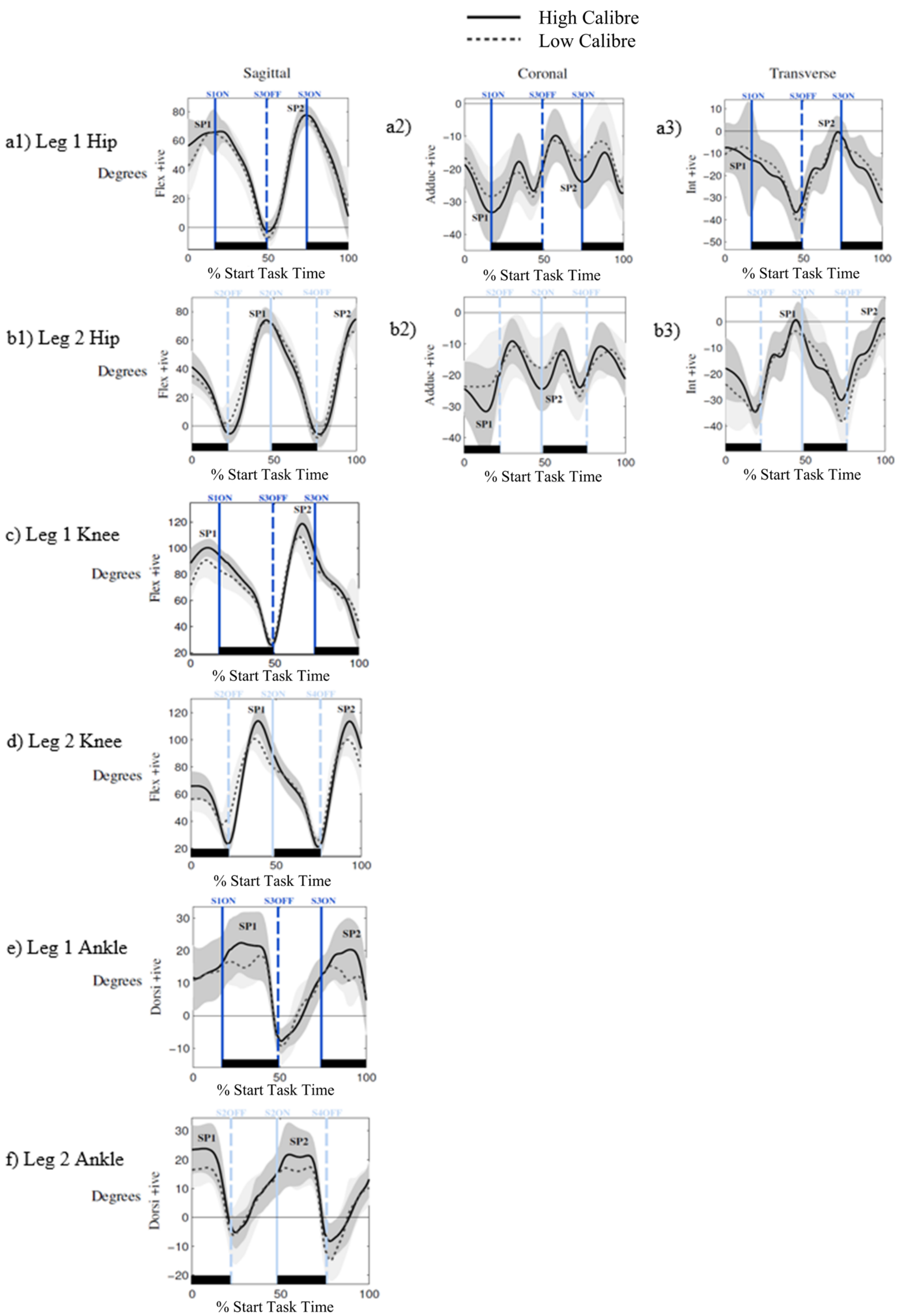

Fig. 9 Mean lower limb joint angles during the skating start at skate-ice contact. The solid black vertical bars at the bottom of each angle-time graph indicate the skate-ice contact support duration

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4 Discussion

This study examined the kinematic movement technique of ice hockey skating starts in relation to skater calibre level. Detailed 3D kinematic measures of skaters' lower body kinematics and estimated CoM progression during the first four steps were obtained in situ on the ice surface. Different from over ground sprint start kinematic technique [27], these skating starts showed greater concurrent hip abduction, external rotation and extension, presumably for ideal blade-to-ice push-off orientation for propulsion. This finding agrees with Stull et al. [12] three-dimensional analysis of skate starts performed on a synthetic ice surface. HC skaters covered 6.25 m in shorter time (1.03 vs 1.20 s) and faster speed by the 4th step (5.53 vs 5.10 m/s) than LC skaters. In practical terms, HC skaters completed the task one step (literally) ahead of the LC skaters, a major tactical advantage in the game of ice hockey. The fact that HC skaters had higher accelerations in the side-to-side and vertical directions during their first step, as well as higher velocities in the side-to-side direction for the first step, seems to give them the ability for larger initial propulsion. Buckeridge et al. [7] reported similar calibre differences. Given that step lengths were similar between calibre, the HC skaters' faster speeds were achieved by way of higher stride rates than LC skaters (1.95 vs 1.7 strides/s, respectively). This stride rate difference was previously noted by Upjohn et al. [10] between HC and LC skaters during steady state skating on a skating treadmill.

With respect to skill level, HC and LC skaters presented similar lower body strength profiles as well as comparable hip, knee and ankle joint gross movement patterns across skaters. This is contrary to past forward skating studies [10,7,4,28] that have found an association between greater skating speed and amplified hip and knee range of motion. We speculate that the HC skaters' higher speed was achieved by a more rapid "running" start compared to the LC's slower stepping advancement. In addition, when comparing HC skaters to LC skaters, their CoM "bounce" was 5 to 7 cm higher, they had shorter skate contact time, and they had increased vertical and forward peak push-off velocities. These biomechanical findings seem to be in agreement with the "spring-mass" concept of running [13, 29]. Differences in skating start velocities could also not be attributed to dry-land leg jump strength differences per se, as these were equivalent between calibre groups. Rather, the rate of lower limb movement appears to be the defining difference in technique between calibre groups, also observed by Upjohn at al. [10]. It may well be that this technique afforded HC skaters greater reaction force between the blade and ice surface that in turn gave more traction (surface frictional force) for forward propulsion.

In addition to the above, some unique joint kinematic patterns were observed. For example, both legs showed synchronized hip frontal plane profiles; however, both hips always remained in some state of abduction. This finding, in combination with greater skate start step widths (20-11 cm) compared to walking (~10 cm) [29] and running (~4 cm) [30] may be a result of the need to attain greater stability by means of a large base of support on the ice surface. This could also permit sufficient blade-to-ice angles to catch ("bite") into the ice for propulsion.

Similarly, greater hip external rotation values were found throughout the first four steps during the skate start. The range of internal (+) and external (-) hip rotation was from 0 to -35°. These values are substantially higher than what was found by in steady-state skating on a skating treadmill by Upjohn et al. [10]. The findings of the current study show that the hips were both substantially abducted and externally rotated during the start phase. This is counter to Buckeridge et al. [7] postulation that the transition from the acceleration phase to steady skate skating was defined solely by the change from hip extension to hip abduction. Conversely, the present study found that concurrent hip abduction, external rotation and extension seems to be essential in skating acceleration.

Furthermore, ankle plantar / dorsi flexion profiles were observed to be distinct from running; all skaters demonstrated substantial dorsiflexion (20 to 30°) during each of the skating step ice contact phases. This greater pre-dorsiflex position of the ankle may in turn contribute to a greater "plantar coil reflex" action, which in turn may yield greater and faster vertical CoM flight. This could also allow each consecutive step to be larger than the last, as observed in this study. These ankle findings are similar to those found using electrogoniometers by Pearsall et al. [31] and Buckeridge et al. [7].

As stated above, in general, the lower limb kinematics were similar between the groups. However, closer inspection showed some asymmetries between the leg side kinematics, as well as a few calibre differences. These differences are not easily explained, however they may be attributed to the respective roles of the first and second steps in initiating forward motion: the first step (defining Leg 1 side) achieves a forward stable base of support, while the opposite leg (Leg 2 side) contributes the first large push-off effort followed by the second step. For example, the starting leg side (Leg 1) increased hip flexion from 1st to 2nd stride (64 to 75°) but not for the opposite side (Leg 2). Also, differences between calibre and leg side were seen; for examples, for Leg 2 side, (1) a decreased hip internal rotation from 1st to 2nd stride (-9 to 1°) for HC was measured but not LC (-4 to -5°), and (2) HC increased knee flexion (115°) during the second stride, whereas LC did not. This asymmetry persisted to a lesser extent into the subsequent 3^{rd} and 4^{th} steps, and presumable symmetry in latter skating strides would be achieved. Given the major challenge in maximizing traction, HC may well have learned to maximize concurrent hip external rotation and knee flexion on second step side (Leg 2) to generate faster skating velocities.

In terms of practical coaching implications, this study's results suggest that kinematic tracking of the estimated body's CoM may be a key variable for performance outcomes. Thus, in addition to maximal outward placement and rotation of their step legs, coaches may want to emphasize to athletes to achieve high stride rates to propel the skater's body both forward and upward during the skate start.

Future studies should include analysis of full-body kinematics and larger sample sizes are warranted to confirm the asymmetrical differences found in hip and knee kinematics. Though muscle strength (as estimated from long jump trials) was not related to skating start velocity future studies should focus on muscle power. This could be achieved by adding more off-ice measurements to the testing protocol. Vertical and lateral jump tests, as well as other explosive plyometric tests could perhaps reveal the difference in muscle power between high and low calibre skaters. A more detailed examination of the skate start's ankle motion is also warranted. Furthermore, studies combining skate force sensors [32] and 3D whole body kinematic data would allow for an inverse dynamic analysis which would provide a better understanding of the respective ankle, knee and hip joint power contributions during the skating start. Additionally, further study on ice hockey skating speed transition is needed to observe the changing movement patterns from acceleration to steady-state skating. Finally, future on-ice analysis should include a broader range of participants spanning developmental age as well as examining differences attributable to gender.

This study in itself is a substantial achievement in terms of measuring ice hockey skating performance, as it demonstrated the feasibility of using sophisticated motion tracking technology within an ice arena's cold, humid environment. Though labor intensive in terms of the repeated camera setup / take down between ice testing sessions, the precision as well as the internal and external validity of the results from these measures is far more comprehensive to that of prior ice hockey skating studies. Installation of permanent infrastructure to mount cameras, cabling and computer links as shown by Bruening and Richards [33] who have already demonstrated this for figure skating jump analysis would make future direct on-ice kinematic analysis of skating skills more time efficient. This would have definite and far reaching practical implications for athlete skate training. Future studies are conceivable

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with inclusion of more cameras to create a longer skating corridor to analyze the ice hockey skating start through to steady-state transition, as well as other tasks such as backwards skating, turning, shooting, and stickhandling.

5 Conclusion

This study successfully demonstrated the use of a 3D motion capture camera system in an arena on the ice surface to record detailed lower body kinematics of ice hockey skating. Overall, HC skaters completed the task faster and with larger overall forward velocity than LC skaters. Though the gross movement patterns of the lower limbs were very similar between groups, HC skaters displayed higher stride rates than LC. In turn, the HC skaters achieved a higher vertical CoM velocity and shorter double support times during the “running” start steps that may have contributed to their greater forward acceleration. The differences noted cannot be attributed to leg strength discrepancies, as both groups had similar leg strength profiles. The difference between HC and LC skaters is more likely attributable to faster joint movement to elicit greater muscle power and possibly greater traction to the ice. In contrast to over ground sprint start kinematic technique, greater concurrent hip abduction, external rotation and extension seems to be essential for skate-to-ice push-off orientation needed for propulsion.

Conflict of Interest

The authors declare that they have no conflict of interest.

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