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Ice hockey skating sprints: run to glide mechanics of high calibre male and female athletes

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Abstract

The skating acceleration to maximal speed transition (sprint) is an essential skill that involves substantial lower body strength and effective propulsion technique. Coaches and athletes strive to understand this optimal combination to improve performance and reduce injury risk. Hence, the purpose of this study was to compare body centre of mass and lower body kinematic profiles from static start to maximal speed of high calibre male and female ice hockey players on the ice surface. Overall, male and female skaters showed similar COM trajectories, though magnitudes differed. The key performance difference was the male's greater peak forward skating speed (8.96 ± 0.44 m/s vs. the females' 8.02 ± 0.36 m/s, $p<0.001$), which was strongly correlated to peak leg strength ($R^2=0.81$). Males generated greater forward acceleration during the initial accelerative steps, but thereafter, both sexes had similar stride-by-stride accelerations up to maximal speed. In terms of technique, males demonstrated greater hip abduction ($p=0.006$) and knee flexion ($p=0.026$) from ice contact to push off throughout the trials. For coaches and athletes, these findings underscore the importance of leg strength and widely planted running steps during the initial skating technique to achieve maximal skating speed over a 30 m distance.

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Introduction

In ice hockey, rapid skating acceleration and sprint speeds are tactically important in the game for an athlete to achieve correct positioning on the ice, catch and cover opponents, and win the race to the puck. Typically, coaches emphasise ‘power skating’ for skill development and training which can provide a quick, general performance assessment; however, specific skating technique factors for optimal performance have not been critically evaluated. For a comprehensive understanding of skate sprint locomotion mechanics, discrete body position-time measures are required. For example, in sprint running, centre of mass (COM) ‘speed curve’ profiles can detect key sprint phase transition points that correspond to changes in body segment angles (Nagahara, Matsubayashi, Matsuo, & Zushi, 2014). Similar analyses in ice hockey are necessary to gain a comprehensive understanding of the mechanics involved in the acceleration to maximal skating speed transition.

Previous ice hockey research has studied the kinematics and kinetics of maximal skating in various settings. For example, skating treadmill studies have highlighted differences between high and low calibre male athletes in terms of lower body joint range of motion and stride characteristics that relate to differences in forward skating velocity (Upjohn, Turcotte, Pearsall, & Loh, 2008). While skating treadmills are a great training tool to develop skating power and technique, there are substantial differences in stride rate, heart rate, and VO_2 max values when compared to on-ice skating (Nobes et al., 2003), and treadmills do not afford the ability to practice skate starts. Hence, to understand skate start factors that affect speed curves, it is necessary to study athletes skating on the actual ice surface. For example, push-off forces measured by wireless transducers in the skate worn on the ice identified differences in step mechanics between initial and latter skating steps when skating 35 m. Initial steps showed

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unimodal force-time profiles comparable to a sprint step, while latter steps exhibited a distinct bimodal force pattern (Stidwill, Turcotte, Dixon, & Pearsall, 2009), which is indicative of the run to glide transition (de Koning, Thomas, Berger, de Groot, & van Ingen Schenau, 1995). What defines the optimal skate start technique during this transition in ice hockey is not well known.

Recent studies have examined this issue further. For example, Buckeridge, LeVangie, Stetter, Nigg, and & Nigg (2015), using biaxial electro-goniometers secured to players skating on an ice surface, studied the hip and knee range of motion of high and low calibre male ice hockey skaters over 30 m. They found that high calibre skaters showed larger hip range of motions during the start to maximal speed transition. Other studies have demonstrated the use of motion capture technologies on the ice surface to quantify skate start techniques. For instance, Renaud et al. (2017) tracked lower body hip, knee and ankle kinematics during skate starts, and revealed that high calibre male players exhibited greater forward velocity and acceleration by way of faster joint movement speed, and greater ‘running’ vertical COM velocity (i.e. shorter stance time and higher COM vertical position) during the first four steps compared to low calibre players. More recently, Shell et al. (2017) studied lower body mechanics during the first seven skate start steps in elite male and female skaters. While previous studies have assumed that males and females perform the same skating stride (Abbott, 2014), Shell et al. (2017) showed clear sex differences during initial skate start technique, namely that females exhibited approximately 10° lower hip abduction and knee extension at ice contact than males, which may ultimately correspond to differences in full body COM acceleration. It remains unclear whether these sex differences persist into maximal skating, and how lower body kinematic profiles may influence key performance variables such as forward COM speed.

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Thus, the purpose of this study was to compare the skaters' full body COM 'speed curve' profiles through the skate start to maximal speed transition of high calibre male and female ice hockey players. Further, we aimed to identify when the skate start run to glide transition point occurs, and how this corresponds to changes in hip and knee movement patterns. Combining previous skate start data (Shell et al., 2017) with new data on the successive maximal speed steps from the same participant cohort, novel insight into the speed curve progressions over a longer distance (34 m) was explored. It was hypothesised that the skating run to glide transition would involve a progression from wide running step widths narrowing by the fifth step, after which gliding strokes would begin. Further, it was hypothesised that males would achieve a faster peak speed than females, with sex differences in maximal skating attributed to greater hip abduction and knee flexion of males during stance phases compared to females.

Methods

Participants

Nine high calibre male (age 22 ± 1 years, height 1.81 ± 0.08 m, weight 81.5 ± 8.4 kg, 16 ± 2 years hockey experience) and ten female (age 21 ± 1 years, height 1.72 ± 0.07 m, weight 71.2 ± 10.4 kg, 14 ± 1 years hockey experience) ice hockey players participated in this study. All participants played university varsity hockey (Canadian Interuniversity Sport league), were between the ages of 18-35 years old, and were free from any lower extremity musculoskeletal injury. Ethics were obtained from McGill University's Research Ethics Board II, and informed consent from all athletes was obtained before participation.

Instrumentation

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Kinematic data were collected on a National Hockey League standard arena ice surface using an eighteen-camera (two T40S, eight T20S, eight T10S cameras) Vicon Motion Capture system (Vicon Motion Systems Ltd., Oxford, UK; Figure.1). The maximal skating data were collected in the same test sessions as the Shell et al. (2017) study that focused only on the skating starts. The infrared system captured an approximate volume of 3 m wide by 15 m long by 2 m high. The capture rate was set at 240 Hz, and the cameras captured data from 14 mm passive-reflective markers with an image error <0.2 pixels per camera. Each participant wore dark, tight fitting compression clothing so that the retro-reflective markers were placed as close to the anatomical markers as possible. A whole-body cluster marker set was used, consisting of eighty-one spherical markers, with sixty-seven on the body and fourteen on the equipment (Shell et al., 2017). Participants were given skates in their size (Bauer 1X, Bauer Hockey Ltd, Exeter, New Hampshire, USA) sharpened to a 3/8 in. hollow with a 9.5 radius (both standard) by the same technician prior to data collection, as well as a hockey stick corresponding to their height and handedness to mimic a game situation.

Experimental Protocol

Off-ice tests

Upon arriving at the arena, each participant was given an overview of the testing procedures. Anthropometric measurements, including barefoot standing height and weight in compression clothing, were measured (Table 1).

Participants performed a single-leg jump test: a proxy measure of unilateral lower extremity strength (Reiman & Manske, 2009) which predicts running sprint and change of direction task performance in University-aged males and females (Meylan et al., 2009), and on-

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ice performance of Midget to Junior-aged (15-22 years) male hockey players (Farlinger, Kruisselbrink, & Fowles, 2007). Participants performed three jumps on each leg, and the final score was the average jump distance on each leg.

On-ice tests

Participants were given a 5-minute warm-up period on the ice. Two sets of skating trials, the start phase (Shell et al., 2017) and maximal speed (sprint) phase, were performed on the ice surface in a randomised order. Each participant performed five trials of each condition with a one-minute rest period between trials. The start and maximal speed phases of the skating sprint were assessed separately, as the cameras' capture distance was limited to 15 m. The initial phase consisted of the first seven steps from 0 to 15 m (Shell et al., 2017) and the maximal speed phase consisted of four steps from 19 to 34 m.

To measure the start phase of the skate sprint, the participant began on the first blue line within the capture area and performed a maximal-effort sprint to the opposite blue line (Shell et al., 2017). To measure the maximal speed phase, each participant started on the goal line (19 m before the capture area) and skated through to the opposite blue line (Figure 1). Speed curves were estimated by combining the two skating phases from 0 to 34 m.

Data Processing

Data were labelled and gap-filled using Vicon Nexus 2.1.1 (Vicon Motion Systems Ltd., Oxford, UK), using a combination of Woltring and rigid-body filling. A low pass, 4th order Butterworth filter with 8 Hz cut-off frequency was applied.

Visual3D software (v5.01.23, C-Motion, Germantown, Maryland, USA) was used to detect ice-contact and push off stride events. The skate ON events (when the skate contacts the ice) were detected at the point of maximal vertical acceleration of the heel marker (Zeni, Richards, & Higginson, 2008), and the OFF events (when the skate ends ice contact) were detected at the point of maximal jerk of the heel marker in the forward direction (Hreljac & Marshall, 2000). Visual inspection confirmed the instances of all events based on the marker trajectory data. The upper and lower body, trunk, and head markers were used to calculate the body COM within Visual3D based on the methods of Dempster (1955).

For the start trials (Shell et al., 2017), seven steps (from ON to OFF for the same leg) were recorded within the capture area, representing five strides (from ON to subsequent ON for the same leg). For the maximal speed trials, four steps were recorded representing 2 ½ complete strides. COM movement was calculated for each step through the acceleration phase (0-15 m, steps 1-7) and maximal speed phase (19-34 m, steps 10-14). The number of steps in each phase represents the minimum number of steps taken by all participants within the 15 m area and were chosen to complete event-based comparisons between groups.

Data Analysis

Skate sprint speed curves from start to 34 m were generated by concatenating body COM forward speed measures at each ON event during the start and maximal speed trials for each participant. An estimated group logarithmic line of best fit (and R^2) was calculated (Excel 2016, Microsoft) of forward skating curves from start to 34 m.

Custom MATLAB (Mathworks, Natick, MA, USA) scripts, including the biomechZoo toolbox (Dixon, Loh, Michaud-Paquette, & Pearsall, 2017), were used for data analysis. For all COM measures and joint angles, the maximum, minimum, and range of motion values during each stride were extracted from the waveforms.

In MATLAB R2014a and after visual inspection of each trial, the Step 1 (S1) side was defined as the leg first within the capture area with the first ice contact (i.e. ON event). The Step 2 (S2) side was then the opposite leg, or the leg with the first OFF event. Therefore, the time scale for kinematic measures were normalised to S1 and S2 sides regardless of whether the participant first contact the ice with the left or right foot.

All kinematic data were calculated for all stance (ST) phases through the start (ST1-ST5) and maximal speed phases (ST9-ST11). The kinematic variables included COM position in the side-to-side (x) and vertical (z) directions, COM forward (y) speed and acceleration, frontal hip joint angle (adduction/abduction), sagittal knee joint angle (flexion/extension). Additionally, spatiotemporal variables including peak speed, task completion time (the absolute time from the first to last event within each task), and step widths (the distance from the ipsilateral proximal foot to the contralateral proximal foot, perpendicular to the direction of primary motion; only in the maximal speed phase) were assessed.

In addition to the discrete measures, all kinematic data are also presented using bootstrap resampling. This technique illustrates differences between groups by calculating the variability over 1000 samples along each curve, using a 95% confidence interval (Dixon, Stebbins, Theologis, & Zavatsky, 2014). The colour bar alongside the waveforms represents the effect size (Cohen’s d) of each difference, with larger differences in black and smaller differences in white (Dixon et al., 2014).

Statistical Analysis

Group means and standard deviations were calculated for all variables, and significance level was set at $p < 0.05$ for all tests. A two-way repeated-measures ANOVA (SPSS Statistics, IBM Corporations, Somers, USA, Version 23.0) was used to examine the influence of the main effects of sex (male or female) and stance number (ST1-5; ST9-11), and their interaction on the dependent variables. Data sphericity was tested using Mauchly's test, and if data was non-spherical, a Greenhouse-Geisser correction was applied. Independent samples t-tests were completed for peak speed, task completion time, and single leg jump distance, since they were not influenced by step number. A Pearson's r correlation was used to determine the strength of the relationship between the single leg jump test, peak skating speed.

Results

Off-ice tests

During the single leg jump test, males jumped further than females on both the right (2.06 ± 0.28 m vs. 1.79 ± 0.13 m, respectively, p=0.015) and left (2.17 ± 0.16 m vs. 1.77 ± 0.14 m, respectively, p<0.001) legs (Shell et al., 2017). Peak skating speed was strongly correlated with peak (left) leg strength (R^2=0.81).

On-ice tests

Males completed the start task in less time (p=0.031) than females (1.82 ± 0.12 s vs. 1.97 ± 0.17 s, respectively) (Shell et al., 2017); however, in the maximal speed task, males and females completed the task in similar (p=0.461) amounts of time (1.06 ± 0.10 s vs 1.11 ± 0.16 s, respectively). The entire skating sprint from 0 to 34 m was completed in 4.94 ± 0.49 m/s for males and 5.24 ± 0.48 m/s for females (p=0.772). With regards to step widths, no significant main effects of step or sex, or their interaction, were found during the maximal speed phase (Table 2).

COM movement

Sinusoidal COM movement progression was evident through the skating sprint. For peak side-to-side motion, a significant main effect of step was detected ($p<0.001$), while the main effect of sex ($p=0.411$) and their interaction ($p=0.208$) were not significant. There were increasing step-to-step differences in side-to-side COM movement during the start phase up to 0.07 ± 0.06 m, which stabilised to 0.09 ± 0.04 m during maximal skating (Figure 2). For vertical COM motion, no significant main effects for step ($p=0.054$), sex ($p=0.807$), or their interaction ($p=0.767$) were detected. The vertical COM oscillation peaked during the second start step (0.03 ± 0.05 m on average for both males and females), then attenuated to ± 1 cm during maximal skating (Figure 2).

Forward COM Speed Curves

By concatenating the start and maximal skating phases, forward COM speed-time progression curves from 0 through 34 m were produced for males and females (Figure 3). Logarithmic lines of best fit strongly agreed with the data for both sexes ($R^2=0.9988$). On average, both males and females entered the maximal speed capture area (19 m) on their 10th step (or 5th stride) at approximately 4 seconds and exited after their 14th step (or 7th stride) at 5 seconds.

The forward speed progression was non-linear, with incremental increases in speed coinciding with each push-off (Figure 3). Over the entire skating trajectory, significant main effects of step ($p<0.001$), sex ($p=0.003$), as well as their interaction ($p=0.004$) were detected for forward speed. Over the first seven steps (15 m), males reached a faster speed than females (6.7 ± 0.4 m/s vs 6.0 ± 0.4 m/s). At 19 m and entering the maximal speed phase, a males and females had reached respective velocities of 8.4 ± 0.4 m/s vs 7.5 ± 0.3 m/s. At the end of 34m, males and females had reached peak speeds of 8.96 ± 0.44 m/s vs 8.02 ± 0.36 m/s, respectively (Figure 3).

Corresponding forward acceleration sex differences over the 34-m sprint occurred (Figure 3). Significant main effects of step (p<0.001) and sex (p=0.014) were detected, as well as their interaction (p=0.034). The interaction displays sex differences at the third and fourth steps. Forward accelerations during the initial skating phase were unimodal, with peak values of 9.6 ± 2.0 m/s^2 for males and 7.8 ± 1.6 m/s^2 for females during the first push-off. At maximal skating speed, peak forward accelerations of 2.9 ± 0.9 m/s^2 for males and 2.7 ± 0.7 m/s^2 for females occurred, and each stance phase exhibited a bimodal acceleration pattern. Technically, the skaters did not reach their ultimate maximum speed even after 34 m, as marginal increases in speed (acceleration) still occurred (Figure 3).

Lower Body Joint Angles

Males and females exhibited different hip joint movement patterns through each skating phase, highlighted by the bootstrap colour bars (Figure 4). For hip adduction, significant main effects of step (p<0.001) and sex (p=0.007) were detected, while their interaction was not significant (p=0.106). Hip abduction followed a similar pattern in which the main effects of step (p<0.001) and sex (p=0.006) were significant, while their interaction was not (p=0.708). The combination of hip adduction and abduction show that females were more consistently more adducted through all stance phases. However, for hip range of motion, a significant main effect of step was found (p<0.001), as well as an interaction effect (p=0.006), while the main effect of sex was not (p=0.834).

Sex differences can also be seen at the knee joint, particularly at ice contact events, highlighted by the bootstrap colour bars (Figure 5). For knee flexion, there were significant main effects of step (p<0.001) and sex (p=0.026), while their interaction was not significant (p=0.079). Males were more flexed (by approximately 7°) at ice contact and during the stance phases than

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females. For knee extension, only the main effect of step was significant (p=0.028), while the main effect of sex (p=0.727) and their interaction (p=0.256) were not. Both males and females ended their stance phase at approximately 20° of flexion. Similarly, for knee range of motion, only the main effect of step was significant (p<0.001), while the main effect of sex (p=0.060) and their interaction (p=0.107) were not.

Both males and females exhibit a similar ‘knee extension plateau’ phenomenon, in which a temporary cessation of knee extension occurs at ice contact. However, females exhibit this phenomenon more prominently. The average absolute time for the knee extension plateau was 0.08 s for males and 0.12 s for females, so this phenomenon was not visible to the naked eye.

Discussion and Implications

This study aimed to compare high calibre male and female skaters’ COM ‘speed curve’ and lower body joint profiles through the skate start to maximal speed transition, and to identify when the skate start run to glide transition point occurs. Overall, male skaters achieved faster peak skating speed at 34 m, as well as greater hip abduction and greater knee flexion in relation to females, as hypothesised. These variables collectively afforded males with greater hip-knee push-off range of motion, which in combination with their greater lower body strength and higher initial acceleration, contributed to male skaters’ greater forward skating speed. The run to glide transition can be identified at approximately the third stride (fifth step), where marked differences in forward COM acceleration and step widths occurred.

To the authors’ knowledge, this is the first study to map in detail the skaters’ speed curve progression in ice hockey skate sprints. As such, this can provide a template for coaches and athletes in terms of skill development goals. Coaches can use and apply this information to maximise their athletes' performance by increasing lower extremity strength to augment forward COM speed and performance. Coaches and trainers of female athletes could also use this knowledge to introduce training techniques to optimise skating technique, i.e. strengthen the muscles around the knee and hip as well as emphasise explosive and wide skating steps during the running start.

On-Ice Tests

All participants completed the 34-m skating sprint in approximately 5 seconds. This is comparable to Buckeridge et al. (2015) who reported a task completion time of 4.42 seconds for male high calibre ice hockey players while skating over 30 m. Both males and females were still accelerating at the end of the 5 seconds and 34 m (Figure 2). This is consistent with the theoretical skating speed-time curve generated by van Ingen Schenau, de Koning, and de Groot (1994) that showed skater speed increases even after 10 seconds. However, pointed differences between speed skating and ice hockey skating, such as longer distances travelled, longer skate blades, fewer distractions, and a larger forward trunk angle, would result in different peak speeds for each sport. In theory, skaters would reach their ultimate maximal skating speed once they reach their anaerobic threshold (Droghetti et al., 1985). It is unlikely that an ice hockey athlete would perform an all-out sprint to exhaustion, especially in a game setting, so these athletes may never achieve their ultimate peak speed. The peak speeds determined in this study are arguably representative of an in-game context.

No differences were found in maximal skating phase step widths between males and females. This is counter the findings of Shell et al. (2017) who found sex differences in the first, second, fourth, and sixth steps of the skating start tasks, whereby males displayed larger steps in these 4 steps. As skaters reach their maximal speed, step widths become smaller because there is less need to create lateral propulsion on the ice, and wider steps are less necessary to promote balance or stability on the ice. Potentially, step widths for both males and females become smaller and more similar in size between their 7th and 10th steps, which would further denote the transition from running to gliding.

COM movement

No differences between male and female skaters existed in the side-to-side and vertical COM displacements during the skate sprint. The skater's sinusoidal COM motion was evident throughout both run and glide phases, similar to that reported by van Ingen Schenau and de Koning (1999) for speed skating. Both sexes showed larger side-to-side COM excursion during maximal skating speed. Large vertical COM movements occurred during the run start phase then subsequently tapered to ± 1 cm oscillation for both male and female skaters in glide skating, comparable to those previously reported by Lee and Farley (1998). These dampened COM vertical oscillations emerged during the skate run to glide transition as forward momentum increased (de Koning et al., 1995).

Forward COM Speed Curves

Speed curves during the skating sprint were calculated by tracking the progression of the body's COM. A logarithmic speed to time function was observed (i.e. rapid gains in speed during the initial 4 steps ever decreasing towards maximal speed). The maximal skating speed was greater for males than females, though the step-by-step push-off speed gains were the same in the latter phase of the skate sprint. Hence, the male's greater acceleration in the first two start strides had a large effect on final speed. This agrees with early findings by Marino and Weese (1979) stating that the first 1.25 seconds during the skate start greatly affect maximal skating speeds. In this study, males achieved greater peak accelerations within 1.25 seconds. Given the strong correlation between participants' skating speed and leg strength ($R^2 = 0.81$) and the differences noted in male:female leg strengths, future studies should determine to what extent leg strength is a covariate of sex differences in skate start performance. On face value, these finding support coaches' emphasis on lower body power drills to improve performance.

Within each skating stride, positive and negative COM forward acceleration intervals occurred during the skating speed curve (Figure 3). Although net forward acceleration was positive, intervals of negative acceleration began after the first three strides (6th step), which encountered ice surface friction and air drag resistance (Humble & Gastwirth, 1988). The within-stride accelerations oscillated between +2 and -2 m/s^2 at maximal speed. The bimodal oscillations in forward acceleration align with the bimodal force-time curves reported by Stidwill et al. (2009), which showed distinct differences between the first three running-like strides and the latter gliding strides. Consequently, the transition point between skate running to gliding technique may be identified at the point at which the first negative forward acceleration interval occurs, and as hypothesised, occurred within the third stride (fifth step).

The skating sprint is unique when compared to the track and field sprint. In particular, the low ice surface friction significantly hinders the skater's acceleration during the first 10 m due to poor blade-to-ice traction; however, after the run to glide transition, the low ice surface friction augments speed gains by increasing stride (glide) distance (van Ingen Schenau et al., 1994). Skate sprint performance, as in running, is dictated largely by leg power and physiological factors of the ATP-PCr system under maximal anaerobic effort (Zupan et al., 2009). However, off-ice sprint tests cannot fully predict skating performance as skating technique variables must be considered (Behm, Wahl, Button, Power, & Anderson, 2005; Bracko & George, 2001;

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Durocher, Jensen, Arredondo, Leetun, & Carter, 2008). Hence, best estimates of skate sprint performance require concurrent biomechanical and physiological assessment on the ice surface.

Lower Body Joint Angles

Maximal skating displayed greater hip and knee range of motion during skate stance to push-off, when compared to the early accelerative strides. Both males and females exhibited abducted hips through the entirety of the skating stride, but males were significantly more abducted (by 7°) than females (Figure 4). The reduction of hip abduction in females may be in part a mechanism to reduce high knee abduction moments and in turn avoid valgus knee strain injuries (Sigward and Powers, 2007) and to lesser extent groin injuries (Abbott, 2014; Agel & Harvey, 2010). This may represent the optimal trade-off between skating push-off force and injury potential for female athletes.

In addition to the hip, differences in knee flexion were seen between males and females (Figure 5). Males displayed greater knee flexion than females, while females exhibited greater knee pre-extension upon ice contact, which is consistent with previous work comparing drop vertical jump mechanics between the sexes. In landing tasks, studies have suggested that females stereotypically tend to land with more knee extension and emphasis on energy-absorption at the ankle rather than the hip (Decker, Torry, Wyland, Sterett, & Steadman, 2003). This, coupled with a more erect body position, may increase females' knee injury risk due to the landing strategy that moves entirely proximally (Decker et al., 2003). The greater initial crouched knee posture of males may allow for a shallower knee extension plateau. Females may benefit from learning how to contact the ice differently to improve energy absorption and decrease lower body injury.

Both males and females exhibit a knee extension plateau during acceleration and maximal skating, but females displayed this more prominently. During this 0.08 to 0.12 second time interval, the orientation of the tibia segment remains relatively fixed in relation to the ice surface, possibly for balance control or stability while undergoing the transition from one base of support (i.e. narrow blade edge) to the other over the slippery ice surface. Joint stability and force absorption are related to muscle stiffness, and males typically have higher stiffness in their active muscles than females (Granata, Padua, & Wilson, 2002). In combination with higher strength output, more stiffness in the male lower body muscles would translate into higher force production. This would help explain the attenuated male knee plateau phenomenon because males may be strong enough to contact the ice and continue pushing through the stride. Conversely, females may be weaker and show less stiffness upon landing, ultimately pausing knee extension at ice contact before beginning the push phase. Further research is needed to determine the function of the knee extension plateau and how it affects skating stride propulsion.

Limitations and Future Advancements

The limitations to the current analysis include the fact that collection of the start and maximal skating trials was non-continuous, so the complete speed curve was obtained through logarithmic projection. Additionally, despite best efforts to mimic in-game ice hockey conditions including holding a hockey stick and skating on the ice surface, participants wore unfamiliar skates and compression clothing without body protective padding, which may have altered their natural in-game skating technique. Future kinematic analysis would be beneficial to understand sex differences in other skating tasks such as backward skating or change-of-direction tasks. Additionally, the inclusion of upper body joint kinematics (i.e. shoulder joint) would provide a more holistic view of sex differences in skating technique. Further development of lower cost

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and real-time movement tracking technology is warranted to afford practical tools for ice hockey trainers.

Conclusion

This study quantified ice hockey COM speed curves and lower body kinematics of skating sprint to maximal speed. Males achieved greater maximal skating speed than females due to their greater acceleration during the first four starting steps, which may be attributed to increased lower body strength and skating technique differences, including greater hip abduction and knee extension. The COM is an important parameter of athletic performance as it defines how the body is moving through space, and this represents the first study to comprehensively describe and compare the forward body COM speed curves and lower body joint kinematics of male and female ice hockey players.

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Table 1: Participant Characteristics (adapted from Shell et al., 2017).

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

*Indicates significant difference between sexes ($p < 0.05$).

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Table 2: Average step width (± SD**)** of maximal skating.

Parameter	Sex	Stance 9	Stance 10	Stance 11
Step Width (m)	Female	0.07 ± 0.04	0.04 ± 0.03	0.09 ± 0.07
	Male	0.07 ± 0.03	0.09 ± 0.05	0.07 ± 0.04

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Figure 1: On-ice system setup. The Vicon cameras are represented by the black triangles, and the light grey shaded area represents the calibrated capture area on the ice. The grey arrow indicates the trajectory for the maximal speed (sprint) trials, and the black arrow represents the start trials.

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Figure 2: The body COM side-to-side (x) position [top] and vertical (z) position [bottom] during the start [left] and sprint [right] phases for males and females. S1 black, S2 grey; Step ON solid, Step OFF dashed lines. Times normalised to respective task interval durations. The male-female differences for specific phases are indicated in the colour spectrum bars (0 white to 1 black).

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Figure 3: The body COM forward (y) speed curve [top], step-by-step speed progression [middle] and step-by-step forward acceleration [bottom] during the start [left] and maximal speed [right] phases for males and females. S1 black, S2 grey; Step ON solid, Step OFF dashed lines. Times normalised to respective task interval durations. The male-female differences for specific phases are indicated in the colour spectrum bars (0 white to 1 black).

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Figure 4: Hip joint angle in the frontal plane (adduction + abduction -) during the start [left] and maximal speed [right] phases for males and females. S1 black [top], S2 grey [bottom]; Step ON solid, Step OFF dashed lines. Times normalised to respective task interval durations. The male-female differences for specific phases are indicated in the colour spectrum bars (0 white to 1 black).

Figure 5: Knee joint angle in the sagittal plane (flexion + extension -) during the start [left] and maximal speed [right] phases for males and females. S1 black [top], S2 grey [bottom]; Step ON solid, Step OFF dashed lines. Times normalised to respective task interval durations. The male-female differences for specific phases are indicated in the colour spectrum bars (0 white to 1 black).

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